Risks to West Coast Vancouver Island fisheries from a mega-earthquake at the Cascadia subduction zone.

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ABSTRACT

Changes to British Columbia's marine environment due to catastrophic events such as earthquakes is a threat not yet adequately addressed by fisheries scientists. The Cascadia subduction zone, located offshore from Vancouver Island, has been quiescent for the past 300 years. With a large rupture recurrence interval of 200-600 years, there is substantial risk of a mega-earthquake (Mw >9) in the near future. The goal of this study is to increase the awareness of the potential impacts of a mega-earthquake on western Vancouver Island fishing industries and to aid in post-earthquake management.

An analogue approach was utilised to determine what commercial fisheries of west coast Vancouver Island (WCVI) can expect when Cascadia ruptures. Southern Alaskan is the most similar subduction zone to Cascadia, with respect to oceanographic, geophysical and geomorphic characteristics, and had a Mw 9.2 mega-earthquake in 1964.

Alaska, experienced intense shaking, an average of 2 m vertical deformation and tsunami waves reaching several meters inland. These forces caused sudden modification of shoreline morphology resulting in population declines, as large numbers of inter- and sub-tidal organisms were displaced and valuable habitats were lost or damaged. Fisheries data bracketing 1964 indicate that this disturbance negatively impacted their commercial fisheries. Prince William Sound and Cordova Bay regions experienced declines in pink, chum and coho salmon catch rates. Various species of clams experienced excessive mortality followed by slow recovery in Cordova Bay and Kodiak Island regions.

Geologists estimate that WCVI will experience up to 1.6 m of vertical deformation and tsunami waves reaching 10 m inland. Organisms that depend upon the coastal habitats, such as pink and chum salmon, clams and crab will be the most affected. The potential for population extinction along the WCVI is great for many salmon populations are classified as endangered or of special concern. It is these stocks that will be of greatest concern following a mega-earthquake.

I surveyed the perception of mega-earthquake risks among fisherman, aquaculturists, fisheries managers and fisheries biologists on WCVI. Questionnaire returns were poor, indicating a low level of concern. Most respondents underestimated the magnitude and consequences of a mega-earthquake with respect to the marine resources. However, recommendations for post-earthquake management of fisheries along WCVI can be made based upon an assessment of the vulnerability of the habits and habitats of the commercial species.

Dedication

In loving memory of my mom; the strongest and bravest woman I know.

Thank you.

Acknowledgements

I would like to thank my supervisor, Ian Hutchinson for taking me under his guidance. My appreciation for his patience and understanding over the years, especially through a difficult time, can never be fully expressed.

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I must thank Renaissance Coffee for suppling a cheery smile with every much needed cup of coffee. I am indebted to the Coastal Girls, Jessabean and Jenn, for their never ending support and much needed laughter over the years. I can never say thank you enough for the love and support I received from my siblings and the King. I am forever grateful that my love, Craig, was with me through it all, proving to me that it really is "too easy".

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CHAPTER 1

INTRODUCTION

INTRODUCTION

On March 27th 1964, the second largest earthquake ever recorded, with a moment magnitude (M_w) of 9.2, rocked Alaska. One hundred and thirty-one lives were lost and over $1.7B (2001 US dollars) in property damage resulted (Plafker and Savage, 1970). This event caused extensive damage throughout southern Alaska and shaking was felt along the west coast of North America.

Earthquakes of this size are rare, making it difficult to predict not only their timing but also their effects. These mega-earthquakes are a feature of subduction zones where a continental plate is overriding an oceanic plate. In subduction zones where older oceanic slabs are subducted, energy is released in frequent small earthquakes, while young subducting slabs lock for long periods, releasing the built-up energy suddenly and with potentially disastrous consequences. Around the margins of the Pacific Ocean are several locked subduction zones. These areas are the sites of the largest earthquakes on record (Rogers, 1988).

Cascadia is one such locked subduction zone, marking the collision of the North America and the Juan de Fuca plates (Figure 1.1). Located on the west coast of North America from British Columbia to northern California, this region is subject to periodic mega-earthquakes ($M_w \geq 9$) (Rogers, 1988; Atwater, *et al.*, 1995; Clague, 1997; Hutchinson, *et al.*, 2000; Kelsey, *et al.*, submitted). No mega-earthquake has occurred in recorded history, which means that the potential for such an event is increasing. As the time between mega-thrust events increases, so does the potential magnitude of the eventual rupture. It is probable that the rupture will be equal in magnitude to that of the 1964 Alaskan event.

Geological studies on the Cascadia margin have provided a record of such events in the late Holocene, with the latest event occurring on January 26, AD 1700 (Yamaguchi, *et al.*, 1997). Given the length of time since the last event and the cyclic nature of mega-earthquakes, there is a potential for a mega-thrust event in the near future. The long period of time between earthquakes allow for large amounts of potential energy to be stored in the locked plates. When these plates slip, releasing the energy, the effects include violent ground shaking, sudden vertical land deformation, landslides, and liquefaction. Subduction earthquakes also trigger tsunamis that can surge hundreds of meters inland, have heights of 10 m or more and cause substantial loss of life and severe property damage (Ng, *et al.*, 1990; Clague and Bobrowsky, 1994).

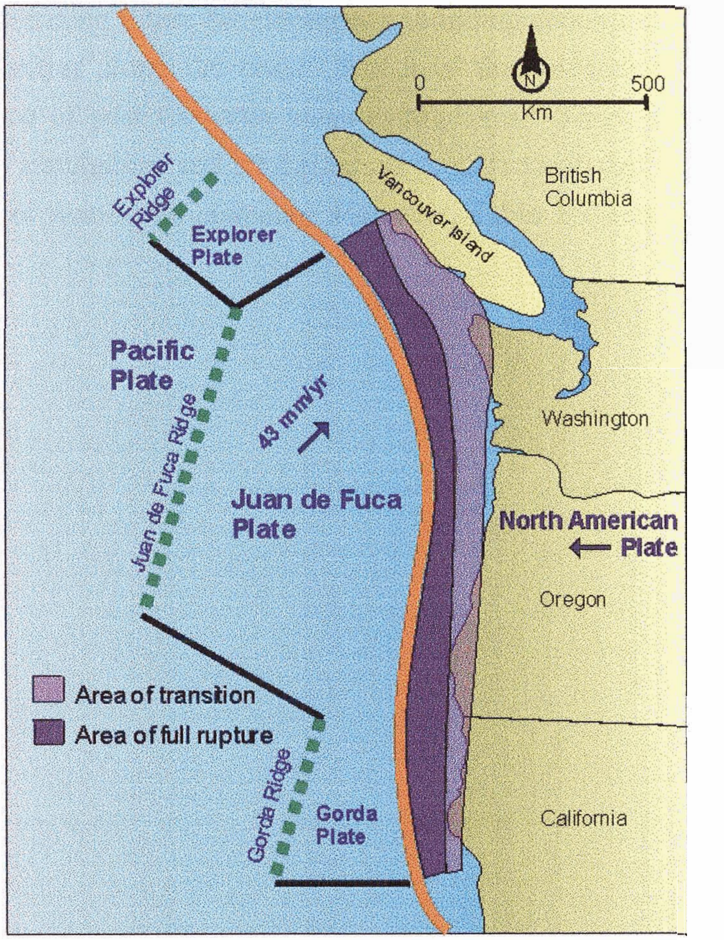


Figure 1.1 The Cascadia subduction zone, approximately 1000 kilometres in length, is made up of three separate plates subducting under the continental plate. The Juan de Fuca Plate with its shallow dip, has a relatively wide locked zone, measuring 40-100 km as indicated by the shaded areas. The dark shading indicates the area where the plates are locked and rupture will occur. The light shading indicates the area where the plate is in transition from brittle to ductile behaviour. This geometry concentrates future seismic activity to a broad area reaching to the edge of Vancouver Island. (*Based on Obermeier, 2000*)

Table 1.1 presents a listing of the present earthquake research for the Cascadia region. The first column identify the seismic phenomena that occurs as a result of a mega-earthquake. The second column indicates the hazard or what is at risk which is followed by the list of studies that have addressed that issue. To date, the primary focus has been to investigate the recurrence of these events from geological evidence. The majority of this research has been conducted by examining sediments in tidal marshes and coastal lakes for evidence of subsidence and tsunamis in order to date and measure the extent of paleo-events. This research is vital for establishing the historical record of events and may provide valuable information for the prediction for future events. This record will also determine future development of building codes and emergency plans for cities and communities along the coast. Much of the research is historic in nature; examining evidence of past Cascadia mega-earthquakes. There are also a number of studies that utilise simulations and mathematical models to predict future seismic events and the reactions of man-made elements. However, Table 1.1 demonstrates the lack of research on the potential effects of a seismic event on coastal marine resources and aquaculture.

Table 1.1 Summary of research on seismic hazards at the Cascadia subduction zone.

Seismic Phenomena	Hazards/at risk	Studies
Shaking	buildings and city infrustructure	Adams *et al.*, 1999; Resources Inventory Committee, 1994; Crouse, 1991; Heaton and Hartzell, 1987; Heaton *et al.* 1995; Obermeier and Dickenson, 2000; Tremblay, 1998
	people	Hutchinson and McMillan, 1997, McMillan and Hutchinson, 2002; Priest, 2001
Crustal deformation	buildings and city infrustructure	Resources Inventory Committee, 1994
	marinas, docks, boats	Stein, *et al.* 2001
	coastal habitats	Atwater and Yamaguchi, 1991; Atwater, 1992; Atwater and Hemphill-Haley,1997; Benson *et al.*, 2001; Clague, 1997; Darienzo and Peterson, 1990; Hemphill-Haley, 1995: Hughs and Mathewes (in press); Kelsey *et al.* 2002; Nelson *et al*, 1996; Peterson *et al.*, 1997; Yamaguchi *et al.*, 1997
	aquaculture facilities	
	coastal resources (commercial fisheries)	
Tsunami	buildings and city infrustructure	Clague *et al* 2003
	people	Hutchinson and McMillan, 1997, Priest, 2001
	coastal lakes	Hutchinson *et al.* 2000; Lopez and Bobrowsky, 2001
	harbours, marinas, docks, boats	Clarke, 2002; Hwang and Lin, 1969; Koshimura and Mofjeld, 2001; Murty and Boilard, 1969; Ng *et al.*, 1990; Stein, *et al.* 2001; Whitmore, 1993; Wood and Stein, 2001
	coastal habitats	Atwater, 1987;Benson *et al.*, 1997; Clague, *et al.*, 2000; Williams and Hutchinson, 2000
	coastal erosion	Dawson and Shi, 2000
	aquaculture facilities	
	coastal resources (commercial fisheries)	
Liquefaction	buildings and city infrustructure	Clague et al., 1997; Naesgaard and Clague, 1992; Resources Inventory Committee, 1994; Stein, *et al.* 2001
	coastal habitats	Haseegawa and Finn, 2002; Kelsey, 2002; Obermeier *et al.*, 2000
	coastal resources (commercial fisheries)	
Landslides	buildings and city infrustructure	McCalpin, 1997; Naesgaard and Clague, 1992; Resources Inventory Committee, 1994
	harbours, marinas, docks, boats	Stein, *et al.* 2001
	coastal habitats	Goldfinger, *et al.*, 2000
	coastal resources (commercial fisheries)	

The main purpose of this study is to assess the potential effects of a Cascadia mega-earthquake and the associated tsunami on the local fisheries, specifically the west coast of Vancouver Island (WCVI). The 1964 Alaskan event demonstrated the hazard that a mega-earthquake presents for coastal communities. Aside from the damage that occurred onshore during the Alaska event, there were substantial changes to the continental shelf and intertidal habitats. These disturbances, while not the traditional foci of risk assessment, represent significant hazards to communities that are economically dependent on marine resources.

Many of the communities on the coastline of Cascadia have economies that are dependent on marine resources and are, therefore, at risk of potentially deleterious effects of mega-earthquakes. The hazards from earthquakes include vertical movement of the coast, the movement of sediments and the movement of the water, all of which will have direct and indirect impacts on the biota. Vertical deformation would directly impact organisms, as they would be shifted out of their habitat. Sediments brought onshore or carried away from shore would scour or bury organisms and the mass movement of the water column would result in organisms being carried up from depth or brought up on shore. Indirect impacts from these hazards would result in habitat changes as intertidal zones are uplifted or downdropped, substrates are changed and areas are flooded. If there are negative effects upon the biota, then a mega-earthquake could prove to be a major threat on WCVI as many of these fish stocks are under increasing pressure due to human activities (Waldichuk, 1993; Slaney, *et al.*, 1996; Hall, *et al.*, 1998; Lackey, 2003). These reduced populations are susceptible to drastic and sudden habitat disturbances caused by mega-earthquakes. For these reasons, it is important to understand potential effects on the biota as a result of a catastrophic rupture on the Cascadia boundary. An assessment of the effects of such an event is usually phrased in terms of the "status quo", i.e. "what would happen to urban infrastructure, port facilities etc. if such an earthquake occurred tomorrow?" This study also adopts this perspective. In doing so, however, I recognise that marine resources on the coast are in a state of flux.

KNOWLEDGE GAPS

For many coastal areas, marine resources are the most valuable economic resource and as such have generated substantial research efforts examining the anthropogenic and environmental threats to the fisheries. Local threats such as over-harvesting, habitat changes/losses, urban development and the impacts of introduced species on native species have all been extensively investigated (Nehlsen, *et al.*, 1991; Waldichuk, 1993; Slaney, *et al.*, 1996; Boersma and Parrish, 1999; Cury, 1999; Leveque, 1999; Bradford and Irvine, 2000; Brodeur, *et al.*, 2000; Volpe, *et al.*, 2000). In addition, several studies have focused on broader threats such as global warming (Beamish, 1993; Beamish and Bouilon, 1993; Hare and Francis, 1995; Ware, 1995; Downton and Miller, 1998; Freeland and Beamish, 1998). One of the common themes in this research is the susceptibility of coastal environments to minor environmental change. While the anthropogenic and environmental fronts have been studied, there is a lack of published research that addresses the changes to the marine environment due to catastrophic events such as mega-earthquakes.

While research has been conducted on the potential of a mega-earthquake and the effects this event will have on land, there is a scarcity of information on the hazards that such an event poses for marine resources. This dissertation seeks to fill this gap between the geophysical and biological realms with respect to mega-earthquakes and resource management. By combining the information from marine resources studies with the associated risks from the geological literature, the hazards to marine resources from a mega-earthquake can be ascertained.

METHODS

The lack of an event in the historic period is the primary problem in seismic risk assessment. Several sources of data (simulations and/or analogues) can help fill the gaps but each of these has limitations. Archaeological information and oral traditions are valuable as they document the effects of prehistoric events on local populations. For the Cascadia region, oral traditions have proven useful for substantiating and enhancing archaeological evidence (McMillan and Hutchinson, 2002) which shows that native villages were frequently abandoned in the aftermath of Cascadia earthquakes (Hutchinson and McMillan, 1997). However, native traditions recording natural disasters associated with earthquakes are often an unreliable source of information as they are qualitative and temporally vague.

Simulations are often used to predict the impacts of large earthquakes. Mathematical and computer simulations are used to estimate seismic wave propagation in various substrates (e.g. Tremblay, 1998), for tsunami propagation (e.g. Ng, *et al.*, 1990; Whitmore, 1993; Koshimura and Mofjeld, 2001) and for the development of building codes (Resources Inventory Committee, 1994). However, simulations use global parameters and apply them in a regional context, adding uncertainty and error. This method of research may be valid for the prediction of simple behaviours (soil stability, long-wave theory) but models of perturbation responses in complex systems (e.g. marine and coastal ecosystem) are not reliable (Ricklefs, 1993).

An alternative method is the use of spatial analogues. Process-response models of complex systems developed in one region can be extrapolated to other areas in another region, assuming that the areas have similar templates. Although there is some uncertainty, as an analogous region may not be exactly the same as the study site, it can fill in some of the knowledge gaps so that potential consequences can be anticipated. This method of research has less uncertainty when there is greater similarity between the analogous and study region.

For this thesis, simulations and models were considered to be too simplistic to predict with any confidence what would happen to coastal ecosystems in the event of a mega-earthquake. Therefore, the consequences of a megaearthquake for WCVI will be assessed using an analogous region.

ANALOGY

The use of a template restricts the choice of analogues to geophysically and ecologically similar regions. Rogers (1988) identifies the subduction zones that are comparable to Cascadia as: the North and South Nazca, North Cocos, Riviera, and the Nankai plate boundaries. Table 1.2 presents a summary of the oceanographic, geophysical, and geomorphic criteria for plate margins around the Pacific Rim where the subducting slab is <20 Ma in age (Rogers, 1988). Although the Aleutian subduction zone is not a young subducting plate, it was included in Table 1.2 as it occurs in the same oceanographic ecoregion as Cascadia. From this table, it is evident that there are only a few regions that could be used for comparison. The South Nazca, Nankai and Aleutian zones are all similar in their oceanographic, geophysical and geomorphic nature (scores of 14 or 15/17). The limiting factor was the availability of data. In order to assess the risks to the marine ecosystem, data regarding the physical and biological effects as well as fisheries data for the time period before and after the event were critical

Table 1.2 Oceanographic, geomorphic and geophysical characteristics of subduction zones analogous to Cascadia. Values for Cascadia are within parentheses. A checkmark indicates that the fault is similar to Cascadia and the X indicates it is not similar. Those marks within a box indicate a characteristic that is imperative for comparison. The fault with the highest score and with the boxed characteristic is the best choice for this study.

	Cascadia WCVI	South Nazca Chile	North Nazca Columbia	North Cocos Mexico	Rivera Mexico	Nankai Japan	Aleutian Alaska
Oceanographic Criteria	Oceanic circulations (upwelling)	✓	✓	✗	✗	✓	✓
	Sea surface temperature (7-15 degrees Celsius)	✓	✗	✗	✗	✓	✓
	Narrow continental shelf	✓	✓	✓	✓	✓	✓
	Coastal habitats (estuaries, marshes, open coast, fjords)	✓	✓	✗	✗	✓	✓
	Aquaculture (fin and shellfish)	✓	✓	✗	✗	✓	✗
	Anadromous fish (salmon)	■	■	☒	☒	■	☑
Geomorphic Criteria	Fjord coastline	✓	✓	✗	✗	✗	✓
	Coastal substrate (rock, gravel, sand and silt)	✓	✓	✓	✓	✓	✓
	Minimal coastal protection	✓	✓	✗	✗	✓	✓
Geophysical Criteria	Young subducting plate <20 Ma (9 Ma)	✓	✓	✓	✓	✓	✗
	Shallow dip (0-12 degrees)	✓	✓	unknown	unknown	✓	✓
	Shallow rupture depth (25 km)	✓	✓	✓	✓	✓	✓
	Long fault length (1000 km)	✓	✗	✗	unknown	✗	✓
	Width of locked zone (100 km)	✓	✓	unknown	unknown	✓	✓
	Long recurrence interval (~600 years)	✗	✗	✗	✗	✗	✓
	Fault close to shore (<120 km)	✓	✓	✓	✓	✓	✓
	Convergence rate (~40 mm/yr)	✗	✗	✓	✗	✓	✓
	Subtotal (/17):	14	12	6	5	14	15

In order to determine what is important to look for in an analogue, it is necessary to examine the characteristics of the region in question. Chapter 2 examines the tectonic setting for the WCVI and chapter 3 examines the biological and oceanographic characteristics. It is this template that the analogue must fit. Chapter 4 isolates the plate boundary that is best suited to be the analogue for this study. This chapter discusses the analogous region in terms of its geomorphic, geophysical and oceanographic characteristics. Then there is an examination of the fisheries data bracketing the seismic event to determine if any negative effects can be attributed to the mega-earthquake. With this assessment the risks to the fisheries of WCVI can be ascertained.

RISKS

The primary risks include abrupt vertical deformation of coastal habitats and damage resulting from the subsequent tsunamis. This sudden and catastrophic modification of the coastal habitats may have numerous ecological effects including flooding, desiccation, scouring or burial of organisms (Baxter, 1971; Johansen, 1971; Hanna, 1971b; Plafker, 1990). A large magnitude Cascadia earthquake will certainly have impacts upon the fisheries along the WCVI. However, if the potential effects upon the fisheries are understood then it may be possible to mitigate negative after-effects from such an event.

In order to conduct an analysis of the risk associated with the Cascadia region a standard risk assessment procedure was used. The term "risk" refers to the probability that an outcome will occur (Geiger and Gharrett, 1997). It can also refer to a specific undesirable outcome or some measure of the effect of that outcome (Peterson and Smith, 1982; Francis, 1992; Fogarty, 1992; Hilborn, *et al.*, 1993; Geiger and Gharrett, 1997). This second definition is commonly used in the fisheries management literature and is used in this study with reference to declines in stock populations due to a seismic event.

There are three steps in risk assessment (Kates, 1978; Brunk, 2001; Garvin, 2001). The first step when dealing with earthquakes, is to measure the hazard with respect to damage to city infrastructure or danger to human populations. This narrow view of the risk associated with earthquakes may not be appropriate for areas like the WCVI where human populations are heavily dependent on a single resource (the fisheries) that can be adversely affected by seismic events. In order to estimate the risks to the fisheries, an inventory of the potential harm a mega-earthquake can inflict was conducted. By examining the physical evidence from an analogous event, an estimation of the potential physical changes was gathered.

The second step in the estimation of risk determines the magnitude of the risk and involves questions that seek to assess the probability of the hazard (Brunk, 2001). This involves estimating how the biological and ecological systems will function in the aftermath of the hazard. For example, what are the distributions of the species, what habitats would be adversely affected, what species would be affected by altered habitats, and what is the strength of the population prior to and post earthquake? Completion of this step provided a better understanding of the ecosystems and the geophysical parameters to enhance probability assessment.

The third step is to assess the severity of the hazards: what happens if this hazard occurs (with respect to which species are affected and the spatial extent of the effects)? How sensitive is the population to change? There is little agreement on the proper method of evaluating the loss of a species or species assemblages. For some it may be catastrophic, but for others it may be a minor event in the long evolutionary history of the systems. There is room for debate on this aspect of risk assessment (Brunk, 2001). For this study the questions were simple. Is it detrimental to fish after an earthquake? If fishing does continue, where and how much can you fish?

These ecosystem estimates are all subject to environmental variability and uncertainty. The magnitude of the variability and uncertainty decreases the reliability of the estimate (Brunk, 2001). Uncertainties are endemic in the assessment of risk due to the lack of understanding regarding the interactions in complex systems and the probability of things going wrong. However, awareness of danger may lead to effective precautionary action plans by government agencies but without awareness and action by the general population, the damage as a result of a hazardous event may be much greater (Burton and Kates, 1964). Citizens within communities are often uninformed regarding existing hazards and are, therefore, unaware of how to minimise the risks and reduce damage (Anderson, *et al.*, 1990). Underestimating the damage resulting from a hazard can lead to further damage. For example, if the damages from a mega-earthquake are underestimated or ignored, then over-exploitation of fish populations in post-mega-earthquake fishery openings could further damage stocks. Therefore, in order to complete an assessment of the risks to the fisheries, a survey was conducted to estimate the present state of awareness among the stakeholders who live and/or work in the study region. This identifies what is necessary for the stakeholders to learn in order to prevent further damaging the stocks on which they depend.

Summary

The coastal environment is a complex system of food webs with links between the physical and biological environments with the communities that rely on its productivity. Risks to the physical environment from a mega-earthquake continue to be well studied. However, risks to the coastal fisheries have not been appraised. The absence of a mega-earthquake at Cascadia in recorded history means it is necessary to rely on archaeological, geological data and simulations to assess the physical effects. Because these tools are unable to estimate the susceptibility of the biota to the various seismic hazards, additional knowledge can be derived by studying events in other analogous regions.

This study is designed to ascertain the effects of a catastrophic seismic event at the Cascadia subduction zone on fishing resources of WCVI. In order to assess the risks to the fisheries caused by a mega-earthquake, this study explores the physical and biological effects and evaluates the level of awareness among the local stakeholders. The physical analysis uses reports from analogous regions as well as historic literature from Cascadia. The biological assessment utilises reports as well as fisheries data from an analogous region. The level of stakeholder awareness is assessed with a survey. The purpose of this study is to fill the knowledge gap regarding seismic effects upon the local biota in order to minimise harm to stocks that may be heavily impacted by a mega-thrust seismic event.

CHAPTER 2

TECTONIC SETTING OF THE WCVI

INTRODUCTION

Much has been learned in the last two decades regarding mega-thrust events at the Cascadia subduction zone. However, with the lack of a recent event and the infrequency with which they occur, information gaps remain. In this chapter, the potential seismic hazards at the Cascadian subduction zone are reviewed. I investigate the physical evidence left by historic large or mega-earthquakes at the Cascadia subduction zone. From this geological information the amount and extent of land deformation, as well as the extent and impacts of tsunamis that have occurred in the past can be discerned. This information can then be used for predictive purposes. Many studies attempt to estimate the physical effects that will occur during or in the aftermath of the next mega-earthquake (Ng, *et al.*, 1990; Whitmore, 1993; Tremblay, 1998). In this study, geological information is used to assess the risks that a mega-earthquake poses on the biota.

Subduction zones generate the largest earthquakes, having the potential to exceed a moment magnitude (M_W) of 9.0. Where continental and oceanic plates converge, the lighter continental plate will slide over the denser oceanic plate. When the oceanic and continental plates are locked, there is gradual strain accumulation on the plate boundary causing the area above the locked zone to be uplifted (Nelson, *et al.*, 1996). This also causes the seaward edge of the continent to be pulled down. Instantaneous rupture of large segments of the plate interface produces great ($M_W \geq 8$) or mega ($M_W \geq 9$) earthquakes. When the plates rupture, the interseismic pattern of deformation is reversed, causing abrupt subsidence and uplift. During the largest earthquakes, the region nearest the plate boundary (60-160 km wide and hundreds of kilometres long) is uplifted: at the same time a parallel zone, landward of the zone of uplift, suddenly subsides (Figure 2.1). The fault then relocks, and strain once again begins to accumulate. It is this deformation of the surface during the rupture that could have negative effects on the coastal biota as their habitats change suddenly and dramatically.

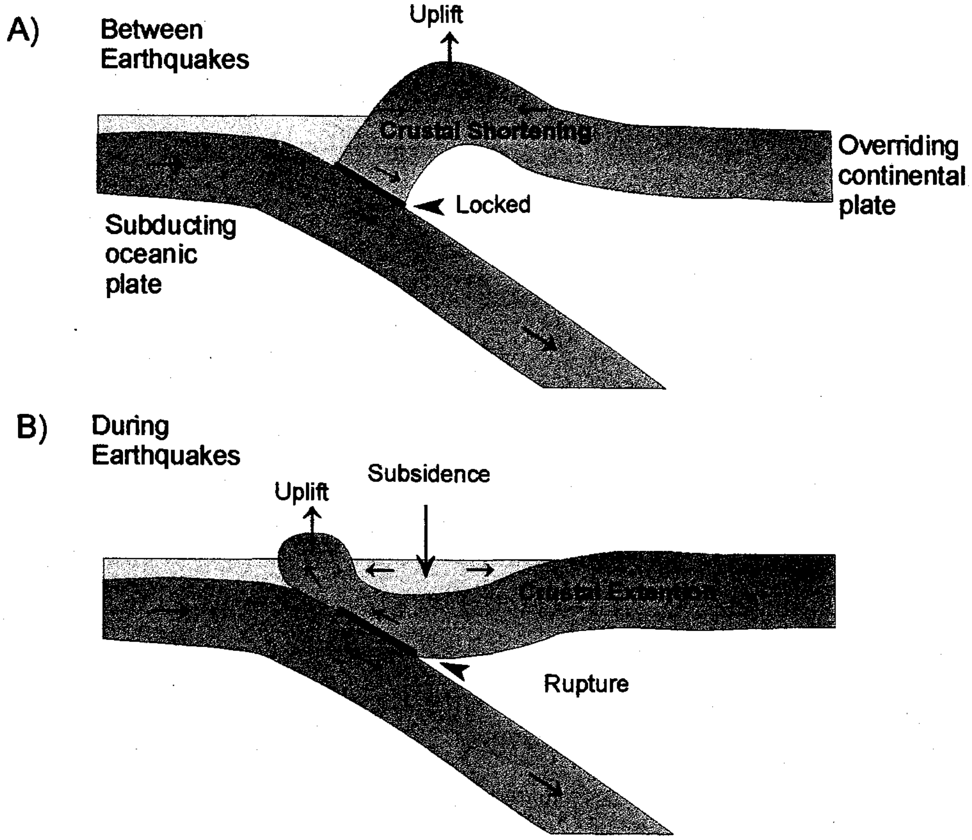


Figure 2.1 When the plates are locked there is a compression of the continental edge, leading to the shortening and uplift of the coast (A). Once stress forces exceed the fictional forces, plate rupture occurs, leading to the extension, uplift and subsidence of the coast (B). There is severe vertical exaggeration in the graphics to emphasis deformation processes. *(Adapted from Clague, 1997)*

TECTONIC SETTING

The Cascadia subduction zone extends over 1000 km along the coast from central British Columbia to northern California (Figure 1.1). This plate boundary marks the convergence of the oceanic Juan de Fuca plate, bordered by the Gorda plate to the south and the Explorer plate to the north, and the continental North American plate. The Juan de Fuca plate is produced by the spreading of new oceanic crust from a ridge located several hundred kilometres offshore. The relative plate motion between the North American and Juan de Fuca plates is approximately 40 mm yr^{-1} (Atwater, 1987; Dragert, *et al.*, 2001).

Geodetic measurements over the past decade at sites on the Cascadia margin have confirmed that this boundary is currently locked (Hyndman and Wang, 1993; Clague, 1997). This causes elastic bending and buckling of the crust as seen on the Washington coast which is actively rising relative to sea level, indicating an accumulation of strain in this region (Savage and Plafker, 1991; Parsons, *et al.*, 1998; Adams, *et al.*, 1999). Rates of uplift along the coast of the Cascadia margin average 1-4 $mm \cdot yr^{-1}$. The uplift rate decreases to near zero 100 km inland from the coast, indicating the location of the hinge line (Clague, 1997). The horizontal deformation in the Cascadia coastal region is approximately 10 $mm \cdot yr^{-1}$, effectively shortening the seaward crust (ibid.) (Figure 2.1A).

The angle at which the oceanic plate is pulled under the continental plate determines the landward extent of the seismic source zone. The dip of the subducting Juan de Fuca plate is well defined: the oceanic crust encounters the deformation front at about 120 km from shore, where its dip increases from 0° – 2° to 3° – 5° (Parsons, *et al.*, 1998). At 35 km offshore, the Juan de Fuca slab steepens from a 5°-7° dip to 12°, which persists for a distance of 50 km to 75 km inland (Parsons, *et al.*, 1998; Oleskevich, *et al.*, 1999). This subduction geometry concentrates the potential locked interplate contact to offshore regions. Future seismic activity is therefore concentrated in the broad area (because of the shallow dip) extending from the coastline to the deformation front ~120 km offshore and is restricted to a shallow depth of 25 km below the surface (Hyndman and Wang, 1993; Parsons, *et al.*, 1998).

The width of the inferred locked zone has been estimated by geodetic data with mathematic models of deformation (Clague, 1997; Dragert, *et al.*, 2001). From variations in the pattern of uplift and shortening along the coast, it is suggested that the width of the locked zone is approximately 100 km off the coast of northern Washington and only 40 km wide off central Oregon (Dragert, *et al.*, 1994). The locked zone is of intermediate width adjacent to southern Vancouver Island and northern Oregon. The easternmost extent of the potential rupture zone is thought to be 0-20 km offshore along the central portion of the subduction zone in southwestern Washington and central Oregon (Dragert, *et al.*, 1994; Oleskevich, *et al.*, 1999). However, GPS measurements suggest that the locked zone may extend much farther inland (Obermeier and Dickenson, 2000) (Figure 1.1).

History

Earthquakes are common in Cascadia, with several earthquakes occurring in any given week; however their size is rarely greater than M_w 4. These events are rarely felt by the population and are significantly smaller than the great (M_w 8) or mega- earthquakes ($M_w > 9$) that could result should the entire Juan de Fuca – North American plate boundary rupture simultaneously.

Recent studies of the Holocene geologic record indicate that great subduction-zone and/or large upper-plate earthquakes have repeatedly affected the Cascadia region. There is evidence of subsidence, tsunamis and liquefaction in many areas along the Cascadia margin. Over the past 5500 years, 11 large earthquakes have affected the coast of Cascadia (Kelsey, *et al.*, 2002) of which seven occurred within the past 3500 years (Atwater, *et al.*, 1995). Sudden subsidence and tsunamis, due to earthquakes, are known to have occurred because soil profiles with buried soils, sudden shift in microfauna and sand layers provide the physical signatures.

Evidence of Subsidence

Through the examination of soil profiles and changes in microfossil assemblages (diatoms, foraminifera and pollen) evidence of historic large or mega earthquakes can be provided. Sudden changes in these biological markers indicate that drastic changes to the environment occurred due to vertical changes to the land. In addition, these tools give an indication of how much land deformation occurred during a seismic event. This information can then be used to estimate the amount of land deformation that will occur along the WCVI, affecting the biota.

Buried soils within many estuaries along Cascadia are continuous over distances of tens to hundreds of meters (Clague, 1997). These buried wetland soils are a result of sudden subsidence and are present in more than a dozen estuaries on the Pacific coast between central Vancouver Island and northern California (Atwater, 1987; Darienzo and Peterson, 1990; Atwater and Yamaguchi, 1991; Atwater, 1992; Clague and Bobrowsky, 1994; Atwater, *et al.*, 1995; Nelson, 1995; Nelson, *et al.*, 1996; Shennan, *et al.*, 1996; Clague, 1997; Shennan, *et al.*, 1998). In southern Washington, deposits containing tidal-flat diatoms lie directly over buried soils. This suggests that the shift from diatom-poor upland deposits to tidal-flat or low-marsh diatom assemblages occurred abruptly, bypassing assemblages that are associated with the intervening, distinctive high marsh (Hemphill-Haley, 1995).

Soil profiles can indicate the occurrence of large events but, also, using diatoms (Hemphill-Haley, 1995), foraminifera (Guilbault, *et al.*, 1996) or pollen (Hughes, *et al.*, 2002), general inferences can be made about the amount of coseismic subsidence. Different dominant diatom and pollen assemblages located on either side of a sand layer in the soil profile can indicate that zonation changes occurred as a result of sudden subsidence (Hughes and Mathewes, in press). These changes in microfossil assemblages allow a fairly precise estimate of tectonic deformation. From paleo-earthquakes, it is estimated that uplift can range from 1-2 m between events and that the coastal area can drop as much as 0.5 – 1.0 m during an event (Hutchinson, *et al.*, 2000). The records indicate that the amount of coseismic subsidence required to generate the paleoecological changes observed at various sites along Cascadia would have ranged from 0.5 – 3.0 m (Clague, *et al.*, 1982; Friele and Hutchinson, 1993; Hemphill-Haley, 1995; Hutchinson, *et al.*, 2000; Kelsey, *et al.*, 2002). In the studies along WCVI, coseismic subsidence during the last mega-earthquake has been estimated to have been about 0.5 m (Dragert, *et al.*, 1994; Guilbault, *et al.*, 1996; Hutchinson, *et al.*, 2000; Hughes, *et al.*, 2002). From these estimates, it can be expected that vertical change will be spatially variable but that it can produce substantial changes in coastal habitat distribution.

Evidence of Tsunamis

The thin sheets of sand overlying the buried soils at numerous locations along the coast of Cascadia, are generally recognised as tsunami deposits (Atwater, 1987; Atwater and Yamaguchi, 1991; Clague and Bobrowsky, 1994; Clague, *et al.*, 1994; Clague, 1997). The association of subsidence and sand deposition is a result of coseismic deformation of the continental margin, generating an offshore tsunami. The tsunami waves carry offshore or intertidal sediments towards the coast, depositing them as the wave train runs ashore. More than 50 sites along the Cascadia margin contain potential or confirmed tsunami deposits (Peters, *et al.*, 2001).

The size of tsunamis triggered by Cascadia plate boundary earthquakes has been estimated using numerical models (Ng, *et al.*, 1990; Clague, 1997). By measuring the distance sand is deposited inland and the thickness of the sediments deposited, it is possible to estimate an average wave run-up. Waves as large as 5 m in height or more may occur at some sites on the open coast (Clague, *et al.*, 2000). Evidence from the distribution of past tsunami deposits in Cascadia indicate these heights may be further amplified, by a factor of up to three, in bays and inlets (Clague, 1997).

Tsunami waves of this size hitting Cascadia shores have deposited sheets of sand ranging in thickness from less than a centimetre to over 70 cm (Clague and Bobrowsky, 1994; Benson, *et al.*, 1997). The grain-size distributions of tsunami deposits generally range from fine to very coarse sand, often containing silt and occasionally gravel (Peters, *et al.*, 2001). Each of the past 11 earthquakes was accompanied by tsunami waves that deposited sand from the beach and/or nearshore as far inland as 1 km to 10 km in estuaries and rivers (Peters, *et al.*, 2001; Kelsey, *et al.*, 2002).

Diatom analysis has demonstrate that these sand deposits have a marine, rather than a fluvial origin (Hemphill-Haley, 1995). For instance, the presence of open estuarine sand-flat diatom species in sandy laminae (5-10 cm thick) capping the 300 year old soil in Willapa Bay (Wa.) suggests a bayward source for the sand, and is consistent with deposition by a tsunami (ibid.). Hutchinson, *et al.*, (2000) discovered three high-energy depositional events in Deserted Lake in Nootka Sound that were identified as deposits from tsunamis generated by plate-boundary earthquakes. Similar studies conducted along the coast have resulted in the dating of six inferred great earthquakes at the Cascadia subduction zone during the past 3000 years (Table 2.1) (Atwater and Hemphil-Haley, 1997; Hutchinson, *et al.*, 2000; Williams and Hutchinson, 2000; Williams, *et al.*, in press).

PREDICTIONS

Significant information is available about plate geometry and movement together with information on earthquake occurrence, magnitude and the extent of land deformation. However, over the past 300 years no earthquake of $M_W \geq 8$ has occurred in the Cascadia region leading many geoscientists to argue that significant amounts of stored energy exist at the subduction zone.

The Cascadia subduction zone has been quiescent, accumulating strain energy, for the past 300 years, placing coastal British Columbia at substantial risk to the effects of a great or mega-earthquake in the near future (Atwater, *et al.*, 1995; Atwater, *et al.*, 2001; Priest, 2001; Stein, *et al.*, 2001). Geologic records show a series of six great earthquakes (M_W ≥ 8) in the past 3000 years occurring at the Cascadia subduction zone (Atwater, *et al.*, 1995). As Table 2.1 indicates, the intervals between them range from roughly 100-900 years, with an average of approximately 500 years (Atwater, *et al.*, 1995; Nelson, *et al.*, 1996; Hutchinson, *et al.*, 2000; Benson, *et al.*, 2001; Priest, 2001; Stein, *et al.*, 2001; Williams, *et al.*, submitted). The most recent mega-earthquake, estimated to be M_W 9.0 (Yamaguchi, *et al.*, 1997), occurred on January 26, 1700. This date was estimated from widespread geologic evidence of subsidence, shaking and tsunamis on the coast of Washington state (Atwater and Yamaguchi, 1991; Clague, 1997), was refined by tree ring analysis (Yamaguchi, *et al.*, 1997) and finally precisely dated by Japanese writings recording the subsequent tsunami (Satake, *et al.*, 1996).

Table 2.1 Ages of plate-boundary earthquakes at the Cascadia subduction zone as discussed in Figure 6: Williams et al. (Inpress). Earthquakes are identified by letters designating buried soils on the outer coast of Washington state (Atwater and Hemphill-Haley, 1997). Ages are calibrated years BP. The interval column indicates the number of years between the midpoint age of an event and its predecessor.

Earthquake	Age Range (cal. yr. BP)	Average Age	Interval
Y	280-430	January 26, 1700	812
W	960-1270	1115	105
U	1140-1300	1220	495
S	1330-2100	1715	735
N	2150-2750	2450	450
L	2800-3000	2900	

Due to the long recurrence interval in Cascadia, it is likely that a plate boundary earthquake have a magnitude ≥8 (Clague, 1997). Over a period of 500 years, the amount of plate convergence would total at least 17 m (McCaffrey and Goldfinger, 1995), equivalent to the slip during historic magnitude 9 earthquakes in Chile and Alaska, which averaged about 20 m (Plafker, 1969b; Plafker and Savage, 1970).

The variation in recurrence intervals in the late Holocene indicates that there is a 9 to 25% (90% confidence interval: 2-57%) likelihood of a great earthquake (M_W >8) occurring at Cascadia within the next 50 years (Stein, *et al.*, 2001). In the event of a mega-earthquake, there will be strong ground motion for a duration of at least 45-70 seconds (Tremblay, 1998). Ground shaking is estimated to reach peak accelerations of

0.3 g or more for regions within 10-20 km of rupture (Wong, 2000). Beyond this peak accelerations will decrease with distance from rupture. Within hundreds of kilometers of rupture areas may still experience at least 0.1 g, inducing massive landslides, in upland areas and liquefaction, particularly in coastal lowlands (Wood and Stein, 2001). This will be accompanied by 1-2 m of sudden coastal subsidence (Clague, 1997) and tsunami waves with heights on the order of 5 m above mean sea level (Wood and Stein, 2001).

SUMMARY

These estimations of historic rupture areas are consistent with information on the pattern and extent of sudden subsidence inland from the coast along the Cascadia margin. During the most recent earthquake in AD 1700, subsidence extended at least 25-35 km inland (Atwater, 1992). These minimum distances are limited by the extent of wetlands capable of recording the subsidence, not by the width of the zone of subsidence itself (Atwater, *et al.*, 1995). Rupture lengths of tens to hundreds of kilometres are implied by the presence of correlative buried soils over such distances in southern Cascadia (Atwater, *et al.*, 1995). Stratigraphic correlation and radiocarbon ages of plants killed during the AD 1700 earthquake indicate a single rupture along 900 km of the Cascadia subduction zone (Nelson, 1995), implying a magnitude exceeding M_w 9 (Clague, 1997).

Numerous studies have concluded that mega-earthquakes have occurred at Cascadia and they result in significant land deformation. Tsunami wave inundation is also recorded in many locations along the coast of Cascadia. Numerous researchers continue to work on predicting the timing of the next mega-earthquake, its extent and potential magnitude. Information on the geophysical interactions of the tectonic plates is important for accurate predictions of future events. However, it is also important to understand past biogeographical changes resulting from tectonic activity to prepare for changes to coastal resources. Information on biogeographical effects from earthquake is limited to coastal marshes and lakes. Because of the lack of recent events research is limited to biotic evidence that do not easily decompose (i.e. diatoms, foraminifera and pollen). It is evident that coastal habitats and infrustructure along Cascadia are at risk of a mega-earthquake.

CHAPTER 3

OCEANOGRAPHIC SETTING OF THE WCVI

INTRODUCTION

For the purpose of this study, the general oceanographic characteristics of the coasts of the northeast Pacific ocean are discussed to emphasise the complexity of the region and the ecosystems within. This oceanic region extends from the tip of the Aleutian Islands to northern California (Thomson, 1981; Kozloff, 1996) and is demarcated by relatively uniform oceanographic and morphological conditions and supports a complex but relatively uniform array of biological communities. Rather than examine all of these features, this chapter focuses on the oceanic and coastal characteristics that support some of the economically important species. I examine the habits and habitat for salmon, crab and clams to provide insight to which coastal areas are of economical significance and what times of the year these habitats are utilised. It is important to examine these factors to provide the means for an assessment of the potential damages to certain species resulting from a major earthquake affecting WCVI.

Firstly, it is important to describe the WCVI coastline, as this is significant for the focus of this study with respect to the hazard and the risks for coastal biota from a mega-earthquake. Ocean circulation, shoreline morphology and coastal habitats are the basis for the biological communities that the peoples along the WCVI rely upon. These factors are also important to consider when isolating a subduction zone in an analogous region with which to compare.

PACIFIC NORTHEAST ECOSYSTEM

There are two distinct water masses in the northeast Pacific Ocean: the Central Pacific Gyre, and the Subarctic Alaskan Gyre. These gyres are a result of a divergence in the prevailing wind pattern, which controls the surface circulation of the northeast Pacific (Thomson, 1981; Pond and Pickard, 1983; Duxbury and Duxbury, 1997). The North Pacific Current travels east across the ocean and divides into two branches: the Alaska Current curves northeast into the Gulf of Alaska, and the California Current curves southeast along the coast to California (Figure 3.1). These wind driven currents cause coastal upwelling.

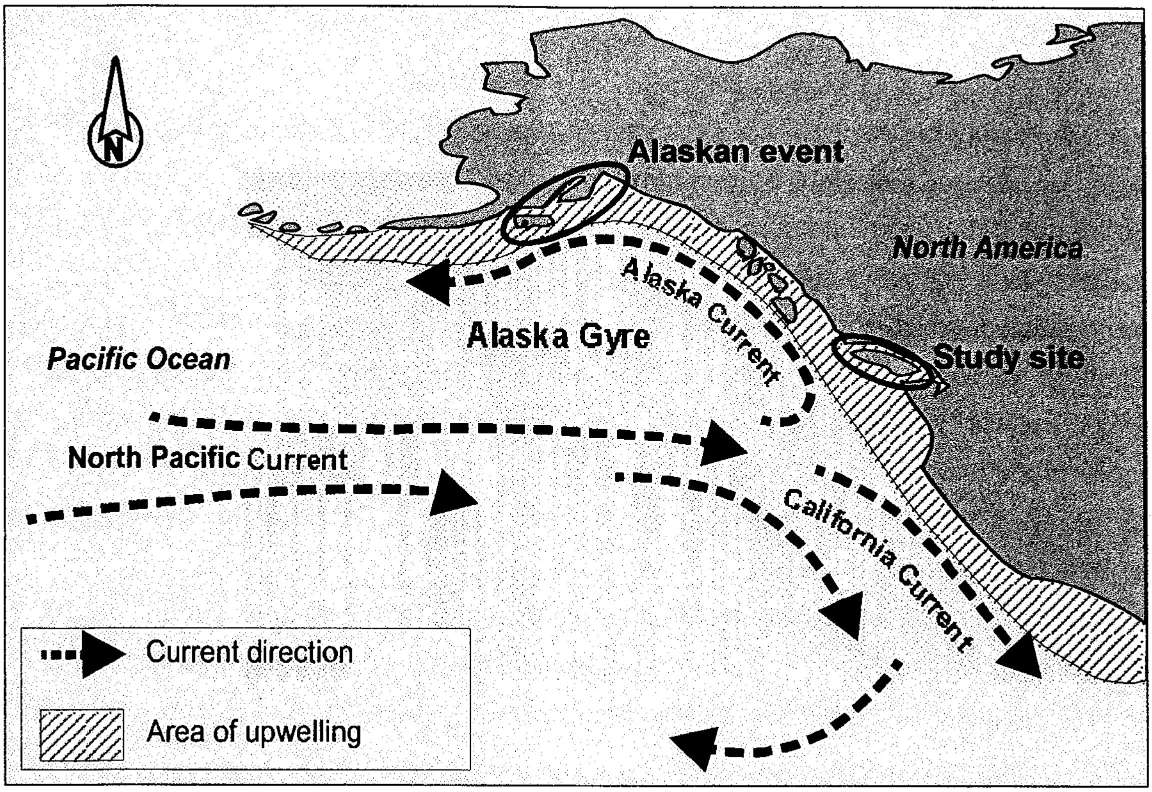


Figure 3.1 The general circulation pattern in the northeast Pacific Ocean. The study area in northern Cascadia is indicated, as is the location of the Alaskan 1964 mega-earthquake.

Upwelling encourages the growth of marine life, producing fishing yields that are at least a thousand times greater than in non-upwelling oceanic regions (Segar, 1998). This high productivity is a result of the process that brings deep, nutrient-rich water upward to the photic zone. In this zone, nutrients and solar energy are available for photosynthesis, leading to high phytoplankton and euphasid biomass (McFarlane, *et al.*, 1997). These in turn provide the basic food source for all marine animals. Although only comprising 0.1% of the total area of the oceans, upwelling regions are estimated to yield more than half of the total fish harvested (all species) (Thomson, 1981).

In the northeast Pacific, cold, nutrient-rich waters rise from ocean depths to the surface as the currents reach the North American continental shelf (Pickard, 1979; Thomson, 1981; Pond and Pickard, 1983; McFarlane, *et al.*, 1997). As a consequence, the coastal waters of the northeast Pacific support high biological productivity and biodiversity. One such biological "hot spot" that has the ability to support great numbers of fish is the entrance to Barkley Sound on WCVI (ibid.).

Coastline Characteristics

Below the waters off the coast of North America is a vast and varied seascape. The seabed adjacent to the west coast of North America comprises four distinct areas characterised by depth and slope: abyssal plains, continental rise, continental slope and the continental shelf. Abyssal plains are deep ocean plains that gradually shallow into the continental rise, which has a gentle slope with thick sediment accumulations. These sediments are transported by the turbidity currents that originate from the adjacent continental slope (Thomson, 1981). The slope, marking the seaward margin of the continent, is covered with land-derived deposits. The continental slope, adjacent to the coast of northern Cascadia, is approximately 90 km wide off the southern coast and 45 km wide off the northern tip of Vancouver Island. This area has highly variable terrain with bumps, knobs and steep-sided canyons, reminiscent of the topography of the adjacent terrestrial landscape (ibid.). The narrow continental shelf lies east of the continental slope, and is the most productive area for fisheries (ibid.).

Landward, the coast may be characterised by a series of steep banks with low undercut bluffs with narrow sand or pebble/cobble beaches. Rocky headlands and outcroppings are common, with nearshore sediments being primarily sand. In the lee of many offshore islands, such as the sheltered areas of Barkley Sound, wave effects are diminished and trees can grow down to the high water level. There are also large stretches of coast consisting of unconsolidated sediments where wave erosion creates flat broad expansive beaches of fine sand between headlands. These areas are typically 10 km long and 200-300 m wide, such as Long Beach. There are also extensive mud flats and marshes in more quiescent areas, such as Orca Bay. Aside from Barkley Sound, where there is a narrow sandy coastal plain, and a few isolated beaches, the coastline is largely rocky, with rugged fjords and skerry shorelines.

The coast is a complex network of fjords, straits, passes, sounds and narrows. Fjords are generally described as long, narrow channels bounded by steep mountainous terrain. The WCVI fjords have a mean water depth of 100 m, a length of 10-20 km, a width of 1.5-2.0 km and a length/width ratio is 10-20 (Pickard and Stanton, 1980). Many of the shorter fjords open into larger ones, which then open to the ocean. On Vancouver Island, fjords commonly open directly to the ocean. The fjords are products of the large valley glaciers that carved out the land below modern sea level. A typical fjord along the coast is U-shaped with a glacial mud bottom, a river at the head, and an underwater ridge (sill) across the mouth (Trites, 1956; Thomson, 1981; Duxbury and Duxbury, 1997; Segar, 1998).

When the glaciers began their final retreat some 15,000 years ago, the piles of rubble, or moraines, left behind formed ridges, creating relatively shallow depths at the entrances to most inlets. The changes in water depth from one side of the sill to the other can be quite pronounced, as much as 300 m, as sill depths are typically 20-50 m (Pickard and Stanton, 1980). Some basins have more than one sill; each marks a former terminus or interstitial deposit of some glacier. These sills impede the exchange of cold, salty Pacific Ocean water with the inner portion of the basin, creating anoxic conditions in the fjords (Thomson, 1981).

There is one important characteristic that must be addressed regarding WCVI fjords: the orientation of the fjords to the plate boundary as it relates to the amount of protection there is from high energy tsunami waves. Fjords, in general, have natural resonance periods that amplify any tsunami that enters the inlet. Those inlets without the protection of islands have a higher risk of tsunami exposure. Inlets located at the head of Nootka Sound and Clayoquot Sound are likely to have moderate to strong amplification of tsunami waves, as is the Barkley Sound area (Hutchinson and McMillan, 1997). The drastic and steep change in depth at the sill will result in a rapid shoaling of waves, which will cause the wave energy to be transferred to wave height. Fjords on WCVI tend to run perpendicular to the coast, open directly to the sea and are not morphologically complex. The consequence of this is that fjords are not well protected from tsunami waves generated at the local subduction zone. There are two fjords of particular concern because of their distinctive morphology and the size of the communities that live in the area: namely Tofino Inlet and Alberni Inlet which are located within Barkley Sound (refer to the inset in Figure 5.1 for location).

Tofino Inlet does not open directly to the coastal shelf region of Clayoquot Sound as Meares Island protects it. Therefore, there are two channels through which Tofino Inlet exchanges water with the coast. There is the northern channel where water is carried into Bedwell Sound through Father Charles Channel. From there it passes through Matlset Narrows and Dawley Pass before reaching the inlet. The southern channel is more direct. In this instance water passes through the shallows of Browning Passage to reach the inlet. Tofino Inlet is 21.3 km long, 4.6 km wide and has a maximum depth of 130 m (Coote, 1964). Within Tofino Inlet there are several sills at 66 m, 21 m and 33 m depth, creating several basins located at the head of the inlet (ibid.). Within Matlset Narrows there is a 28 m sill. Dawley Pass has a 33 m sill and there is a 7 m sill in Browning Passage (ibid.). These depths have been reduced to lowest normal tides, and at high tide the water level can be 4-5 m greater.

Alberni Inlet bathymetry is typical of glacial fjords in that there are a series of long, narrow, flat-bottomed straight channels of equal widths but with different depths (Buckley, 1980). This inlet has 3 regions consisting of the outer end, which opens to the ocean, having a depth of 100 m, the inner basin with a depth of 100 m and the shallow harbour at head (Buckley, 1980). There is a single sill rising to within 40 m of the surface separating the outer and inner basins (ibid.).

These inlets are a concern because of the relatively high density of people that live and work in and at the head of the fjord as well as the important marine habitats that are present. The morphology of these fjords is such that waves will rapidly shoal, increasing the risks to those people, organisms and habitats found in the fjord. The sills create a situation where the natural harmonics of the fjord matches the period of the incoming waves created by a subduction earthquake. As the first wave is reflected off the head of the inlet and reaches the sill it is reflected back into the inlet however, this time it will be compounded by the second wave that is entering the inlet (Hwang and Lin, 1969). Consequently, habitats within the inlets are at greater risk of damage from tsunami waves than the open coast.

Biological communities

The rich variety of sea life along the Pacific coast is due partly to the many different habitats that are represented (Nybakken, 1997). There are rocky shores with reefs, tide pools, and boulders; sandy beaches exposed to heavy surf; quiet bays in which the substratum ranges from sands to anoxic, black mud; and estuaries in which the salinity may fluctuate widely. The high diversity is also due to upwelling and the numerous rivers that drain into the sea (ibid.). These phenomena replenish nutrients necessary for the photosynthetic activities of phytoplankton and macro algae. As the phytoplankton and algae flourish, animals prosper and serve, in turn, as food for larger animals.

Plants, animals and microorganisms are linked to one another by their feeding relationships and other interactions, forming a complex biological community. Interrelationships within the community govern the flow of energy and the cycling of elements within and between ecosystems. This interrelationship also influence population processes, thereby determining the relative abundance of organisms

(Ricklefs, 1993). The ecological and evolutionary impact of a population extends in all directions throughout the trophic structure of the community by way of its influence on predators, competitors, and prey. This in turn passes through each successive link in the chain of interaction (ibid.). Therefore any negative effects from a mega-earthquake and tsunami will, to some degree, impact the entire food web.

Community structure of the shallow-water and subtidal benthic associations is a complicated matter that includes both physical and biological factors. Physical factors include water temperature, salinity, wave action, substrate type, exposure, etc. Some of the biological interactions include direct and indirect competition or predator/prey relations. The interaction of species may include one or more of these factors and is fairly obvious, such as seastars preying on mussels. More often, however, the interactions are subtle, and most of them are still not understood (Nybakken, 1997).

The forms of plants and animals communities vary in accordance with the conditions of the environment. As a result, biological communities in different climate zones take on different appearances. The distribution of all types of plants and animals are confined to a narrow range of climate zones to which the organisms are particularly well suited. This can relate to the spatial extent of a species along an entire coastline or a single species on a beach. Plants and animals of the Cascadia region are commonly distributed throughout the Pacific northeast, from northern California to the Aleutian Islands. Based on dominant algal genera, this region is classified as a *Macrocystis* or brown kelp-dominated ecosystem. On a smaller scale, the distribution of an individual species of algae found on a beach is restricted to its intertidal range, related to exposure times. The first spatial restriction is due to water temperature and nutrient availability. The second spatial restriction is due to exposure time, as the photosynthetic ability of the algae as well as its water concentration and nutrient uptake would be affected. To move it to a different region or intertidal zone will limit its ability to survive. Because algal beds are a fundamental basis of coastal communities and are distributed according to intertidal zonation, seismic caused coastal deformation could prove devastating for foodwebs.

Throughout the cold temperate regions of the world, kelp bed communities inhabit areas with hard subtidal substrates. Kelps obtain their nutrients directly from the seawater and therefore depend on the constant movement of water to avoid nutrient exhaustion (Sze, 1998). Turbulence, upwelling, and runoff from land replenish nutrients. Kelp beds are extremely productive and provide the framework for the community. Associated with these dominants are many other species of algae, invertebrates, marine birds, mammals and fishes. Grazing herbivores only occasionally destroys adult plants, but kelp beds are vulnerable to destruction by mechanical forces, mainly wave action. Since they occur in shallow water, often on open coasts, storm waves can have a devastating effect (Nybakken, 1997).

Storms, especially severe ones, may be devastating to kelp beds. They also effect the subsequent community, as the economy of kelp beds depends on the continued existence of the kelps themselves (Nybakken, 1997). For instance, after a storm the canopy of *Macrocystis* may be removed but other algal species remain intact. The storm may also have removed the drift algae that sea urchins feed on. The urchins then consume most of the remaining living kelp. This, in turn, weakens the other parts of the food web and leads to further declines in kelp forest associates, such as invertebrates, fish, and mammals. The effects of a storm will be severely magnified by tsunami waves.

Storms also impact coastal habitats such as eelgrass beds (*Zostera marina*), mussel beds, and various benthic communities all of which are important habitat for various species of fish, invertebrates and birds. The destruction of these habitats, as a result of vertical deformation and tsunami wave action, would be devastating to the organisms that are a part of these ecosystems.

One method of measuring the hazards of habitat destruction is to measure changes in marine productivity. The concern with habitat destruction is generally the effects it has on fish populations. To measure marine mortality, it is general practice to examine the size of commercial fish populations. Since it is impossible to census fish populations directly, fisheries statistics are commonly based on catch data (Beamish and Bouilon, 1993; Hare and Francis, 1995; Downton and Miller, 1998). Fisheries are managed using Total Allowable Catch rates which are based on a percentage of the estimated population (i.e. fisherman may be allowed to catch 10% of the population). Knowing how many fish were taken out of the sea, a number is calculated and projected onto the entire population (Parsons, 1993). Therefore, to detect any effects that habitat destruction has on fish populations one must look at fisheries catch data pre- and post-hazard. It is also useful, in predicting effects a hazard may have on fisheries, to examine habits and habitats of commercial species as it provides insight to times and areas that may lead to the greatest devastation to the fisheries of interest.

COASTAL FISHERIES

Communities dependent upon the productive fishing grounds offshore have sprung up along the WCVI. Despite the widespread decline of fishing industries on the west coast of Canada in the 1990's, commercial fishing is still the fourth largest primary industry in BC after forestry, mining and agriculture. In 2000, sales of fish and shellfish were worth $698 M to the provincial economy. Wild salmon and shellfish accounted for $203.4 M and $153.5 M respectively of that total. Farmed salmon and shellfish generated $320 M and $21.5 M respectively in wholesale value, making BC one of the top producers in the aquaculture industry behind Norway, Chile and the United Kingdom (Ministry of Agriculture Food and Fisheries, 2001).

This region has come to depend various fisheries, both commercially and recreationally. This study however, due to time and data restraints concentrates on a few dominant commercial industries: salmon, Dungeness crab and various clam fisheries as well as aquaculture. Although there are many other species that are harvested in this region (e.g. hake, herring, halibut, eulachon, etc.) the aforementioned fisheries that are examined in this study have an abundance of information available. An examination of habits and habitats utilised by these fisheries will indicate critical coastal areas and seasons (time of use). This will provide the means for assessing the potential damages to major commercial species resulting from an interplate earthquake affecting WCVI.

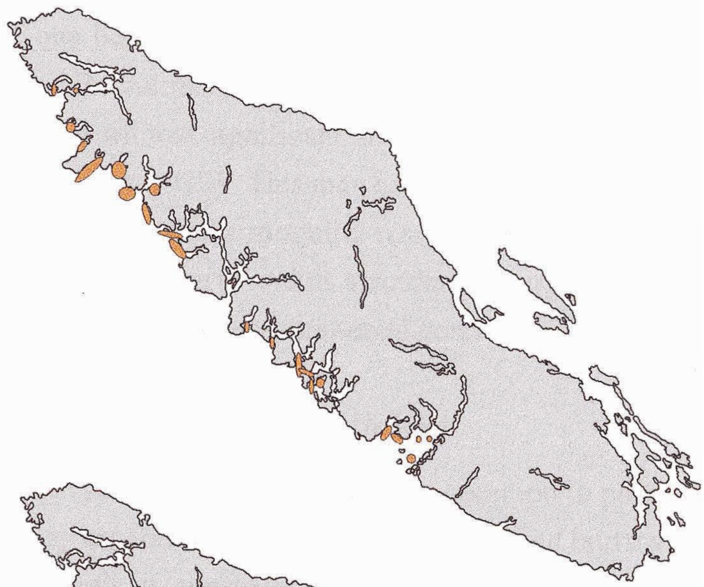
Clams

There are over 400 species of clams found along the west coast of North America. About five have been harvested commercially since the early 1900s. The commercially harvested species of intertidal clam include the razor clam (*Siliqua patula*), manila clam (*Venerupis philipinarum*), littleneck clam (*Protothaca staminea*) and butter clam (*Saxidomus giganteus*), all of which are found on WCVI (Alaska Department of Fish and Game, 1964a; Department of Fisheries and Oceans, 2000; Bendell-Young, 2002).

The clam fishery is managed with staggered openings throughout the year (e.g. open for 5 days, closed for 1-2 weeks) in order to provide a year-round supply of fresh clams to the market. Harvest efforts are generally concentrated in the spring, summer and early fall when low tides are prevalent during daylight hours.

The total value of the BC clam fishery in 1999 was $5.1M (Department of Fisheries and Oceans, 2001e). As of 2001, there were 1190 licenses available for the commercial intertidal clam fishery, divided into 7 clam management areas (Department of Fisheries and Oceans, 2001e). Mariculture of manila clam (*Venerupis philippinarum*) is a relative new industry. In the last decade the seeding of BC's foreshores with hatchery raised clams has increased immensely (Bendell-Young, 2002). Figure 3.2 shows the location of the most productive clam beds that are harvested and Figure 3.4 shows the location of mariculture licenses held on the WCVI (Ministry of Agriculture Food and Fisheries, 2001).

A)



B)

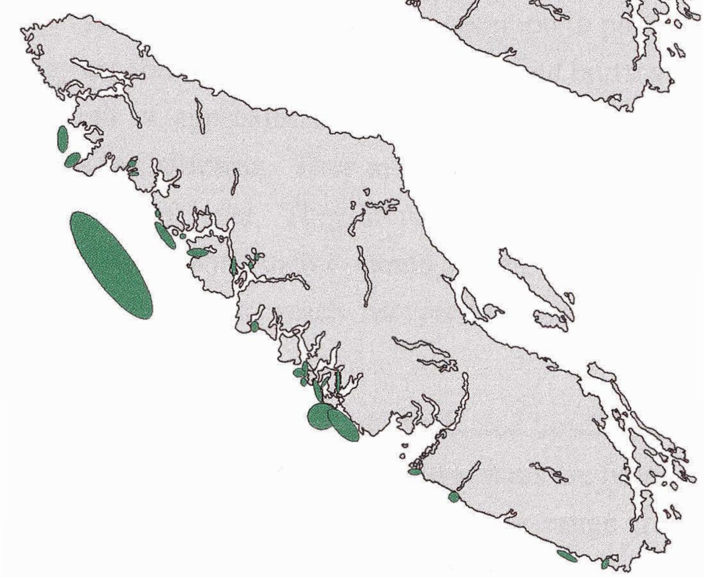


Figure 3.2 The location of the main harvest areas for **A)** shellfish and **B)** dungeness crab for west coast Vancouver Island are shown (Ministry of Agriculture Food and Fisheries, 2001).

General Biology

All intertidal clams have separate sexes and are broadcast spawners, which means that both sperm and eggs are released into the water column where fertilisation takes place. Spawning generally occurs between mid-June and September. After a planktonic period of 3-4 weeks, depending on species, temperature and available food, the larvae settle and take up an infaunal existence (Department of Fisheries and Oceans, 2000). The clams are sexually mature in approximately 2 years and reach the minimum legal harvesting size between 3 and 4 years of age (Department of Fisheries and Oceans, 2000).

Exchange of adults among beaches does not occur, i.e. adult clams do not move from one beach to another although there may be mixing of clams within a single habitat. Recruitment into a population is variable and in some cases a number of years can pass without significant influx of new animals to a harvestable population (Quayle and Bourne, 1972). This may be due to poor settlement of larvae at a beach or due to a high rate of juvenile mortality that reduces the number of clams growing large enough to enter the fishery. Adult abundance is controlled mainly by poor juvenile recruitment due to adverse environmental conditions, predation or competition.

Specific Distribution and Habitat

Manila clams, an exotic species, are common in protected beaches in bays and estuaries. They are found in sand-gravel beaches and burrow just below the surface to a maximum depth of approximately 10 cm. These clams range from the Queen Charlotte Islands to California. They are found within the 1 m intertidal zone to well above the mid-intertidal level. They do not inhabit subtidal areas, as they are limited by spatial competition with native clams (Kozloff, 1996). Manila clams require approximately 3.5-4 years to reach harvestable size (Department of Fisheries and Oceans, 2000).

Littleneck clams are common in protected beaches in bays and estuaries, and near rocky outcrops on the outer coast. These clams are found in firm, gravel beaches, often in association with the butter clam. They range from the Aleutian Islands, Alaska to South Baja California. They burrow to a maximum depth of 15 cm, but are usually only 3-8 cm below the surface. They are normally found slightly in or above the mid-intertidal to subtidal zones but may occur subtidal to a depth of 12 m (Kozloff, 1996). These clams are of harvestable size in approximately 3.5-4 years (Department of Fisheries and Oceans, 2000).

Butter clams are common in protected beaches in bays and estuaries along the coast. They are found in a variety of substrates but typically are found on beaches of porous sand, broken shell, gravel and mud. They may occur in association with littleneck clams and burrow to a maximum depth of 25 cm. These clams are found from Alaska to Monterey, California. They are normally found in the lower third of the intertidal zone but may occur to a depth of 15 m (Kozloff, 1996). They are commercially harvestable after approximately 6 years (Department of Fisheries and Oceans, 2000).

Crab Fishery

For all crab fisheries, management is based upon size, sex and season. The Dungeness crab fishery in particular has size limits of 165 mm across the maximum breadth of the carapace as the primary conservation measure (Winther, 2000). The size limit is designed to protect sexually mature male Dungeness crab for at least one year prior to harvest (Department of Fisheries and Oceans, 2001d). Female Dungeness crab rarely exceed the commonly used 165 mm size limit but are also protected through a sex restriction as only male crabs can be harvested (ibid.). Harvest seasons are created yearly because crab populations are not consistent with moulting times across an area or from year to year (Winther, 2000).

The Dungeness crab (*Cancer magister*) is the most important species of crab harvested in British Columbia and is exploited by commercial, native and sport fishers coastwide. The inception of the commercial fishery occurred before the turn of the century with the first recorded landings in 1885. There are currently 222 commercial crab fishing licenses available for issue in BC earning, in 2001, $4.4M (Department of Fisheries and Oceans, 2002a) (see Figure 3.2 for location of harvest grounds).

General Biology

Mature female crabs molt between May-August, with mating occurring immediately after the female has molted but before the new exoskeleton hardens (Butler, 1960; Kozloff, 1996). Breeding occurs in inshore waters and females may move to deeper waters to hatch the eggs (Butler, 1960). In October or November, eggs are fully developed, extruded and fertilised; remaining attached to the female's abdomen until they hatch in late winter (ibid.). During this period, females often bury themselves in sand as the eggs develop. Once the eggs are developed, the larvae are planktonic and are dispersed by currents. This larval phase lasts approximately 4 months until May to September at which time the crab larvae settle and metamorphose into juveniles that looks much like the adults (ibid.). The juvenile crabs will then remain in lower intertidal or shallow subtidal waters and overwinter in shallow, estuarine waters (Kozloff, 1996).

Specific Distribution and Habitat

Dungeness crab are found in the eastern Pacific Ocean and range from the Aleutian Islands to Mexico, from the intertidal zone to depths of 180 m (Hart, 1982; Kozloff, 1996). They are common and widespread in sandy areas along the coast. Although they may occur on mud and gravel, they are typically found in estuarine environments such as river deltas (ibid.). Juveniles remain in intertidal and shallow subtidal waters hiding beneath or among plants, rocks and shell debris until their second summer (Butler, 1960). They are often found at low tide in sandy and muddy bays buried just below surface of sand, especially where there is good growth of eelgrass (Hart, 1982; Kozloff, 1996). Dungeness crab requires 2-3 years to reach maturity (Department of Fisheries and Oceans, 2001d).

Salmon Fishery

Commercial fishing for salmon began shortly after the arrival of Europeans on the West Coast. Despite declines in catch rates in the 1990's the salmon fishery remains one of the region's prominent economies.

The timing of salmon runs varies between species, individual stocks and latitudinal regions. Runs begin in the northern region of the Pacific in Alaska and then reach the coast of BC, Oregon and Washington. Stocks located in Alaska are in good health however there are stocks in the lower latitudes (BC, Oregon and Washington) that have not been harvested during the last few years due to low stock abundance (Department of Fisheries and Oceans, 2002c).

General Biology

Five salmon species are found in the northeast Pacific: pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), chinook (*O. tshawytscha*), and coho (*O. kisutch*). Figure 3.3 shows the location of salmon streams on WCVI. This figure does not indicate the strength of the populations, simply the known location of stocks. Of course, some species are of greater economic value however, the economic importance of once species over another is not a focus of this study. For this reason, all species discussed in this study are considered to be of equal importance.

There are variations between salmon species although the general life cycles are similar (Rogers, 1986). Eggs are deposited and buried by the spawners in nests called redds, which are normally constructed in gravel in freshwater streams (Rogers, 1986; Department of Fisheries and Oceans, 2002c). The embryos are incubated and hatch within the redd, and remain in the gravel until they have used up their yolk supply (Department of Fisheries and Oceans, 2002c). Normally fry will emerge in the spring and, depending on the species, will remain in the freshwater streams or lakes for periods from a few hours up to two years prior to migrating to the ocean (ibid.).

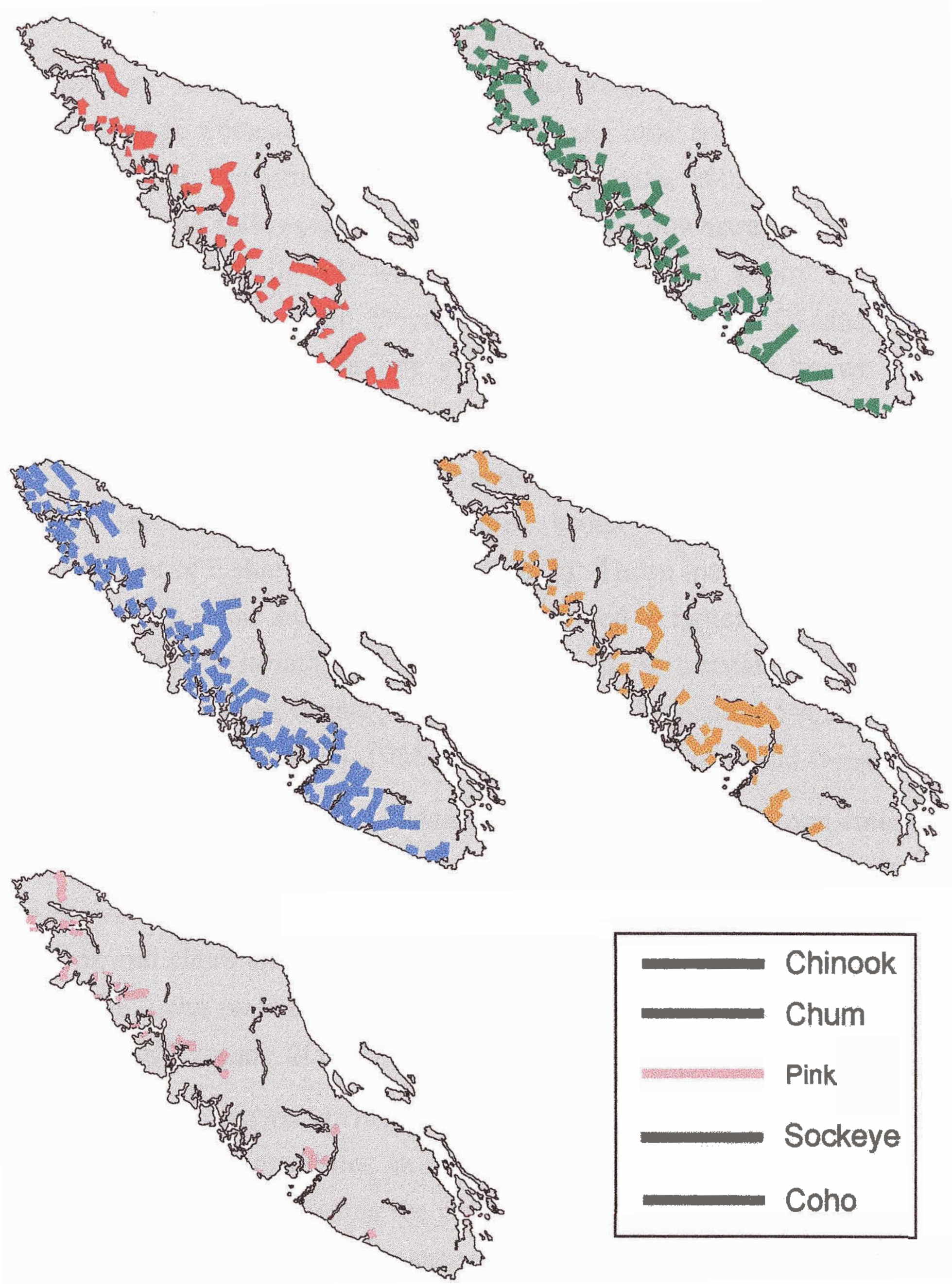


Figure 3.3 This series of images indicate the streams on the west coast of Vancouver Island that are known to be used by salmon (Ministry of Agriculture Food and Fisheries, 2001). It does not indicate the strength of the runs, only that it is utilized. Overall, pink salmon utilise fewer streams than other species and coho populates most of the coast.

Specific Distribution and Habitat

Pinks are found spawning in areas between Puget Sound, Washington, and Bristol Bay, Alaska. They migrate to their home stream from July to October, and while some go a considerable distance upstream, most spawn in waters close to the sea (Rogers, 1986; Department of Fisheries and Oceans, 2002c). They emerge from the gravel beds the following spring and go directly downstream to the ocean. During their first summer in salt water, they stick close to shore, moving offshore in September (Rogers, 1986; Department of Fisheries and Oceans, 2002c). Pinks typically remain at sea for one year prior to returning to spawn (Department of Fisheries and Oceans, 2002c).

Chums enter southern BC streams and rivers to spawn, usually in late autumn and in some instances in late winter, usually spawning close to tidal waters (Department of Fisheries and Oceans, 2002c). Those spawned in short coastal streams move directly to the sea, whereas those spawned in larger river systems stay in fresh water for several months (ibid.). They remain in coastal waters until mid or late summer before going farther offshore. Chum will spend 2.5-4.5 years at sea before returning to spawn (Rogers, 1986; Department of Fisheries and Oceans, 2002c).

Pink and chum migrate seaward almost immediately upon emergence from the gravel. These species are less dependent on freshwater habitats; droughts or poor water quality during the summer period have little effect on overall population health. As pink and chum are less capable of surmounting obstacles, they tend to make more use of the lower reaches of streams, spawning even in intertidal areas (Department of Fisheries and Oceans, 2002c).

Sockeye spawn in rivers that feed into lakes, or in the outlets and spring-fed beaches of lakes, sometimes as far as 1600 km inland. Sockeye run from June to November and after spawning the young emerge from the gravel and spend up to three years in lakes, generally downstream from their spawning grounds (Rogers, 1986; Department of Fisheries and Oceans, 2002c). Migrating juveniles travel down to the ocean during May and June. Upon reaching the sea, they move rapidly outward or along the shore. The majority of sockeye spend 1-4 years at sea before returning to spawn (Alaska Department of Fish and Game, 1964a; Department of Fisheries and Oceans, 2002c).

Chinook are frequently dubbed "spring" salmon, because they return to rivers earlier than the other four species of Pacific salmon. Some river systems have more than one stock of chinook, with stocks migrating in spring, summer and fall (Rogers, 1986; Department of Fisheries and Oceans, 2002c). The early runs usually go farthest upstream, with those in later migrations spawning closer to salt water (Rogers, 1986; Department of Fisheries and Oceans, 2002c). While the majority of chinook salmon head for sea a few months after they emerge from the gravel, some remain in their home stream for one or two years. The time chinooks spend at sea is variable, lasting anywhere from 1.5-4.5 years (Department of Fisheries and Oceans, 2002c). Chinook, like sockeye, cluster their spawning distribution, which can be risky if spawning grounds are subjected to catastrophic perturbations (ibid.).

Juvenile coho are highly adaptable and can have varied life histories. Most stay from one to two years in coastal streams before migrating seaward as smolts. But other fry remain in lakes or coastal estuaries. While most coho tend to remain close to the coast, they have been found as far as 1,600 km from shore (Department of Fisheries and Oceans, 2002c). Coho spawn and rear in small tributaries and channels in low gradient areas. Like the pink salmon, coho prefer relatively warm water, often moving south in the fall and winter months (ibid.). After 0.5-1.5 years at sea, mature coho return for spawning (ibid.).

Aquaculture

The physical and geographic characteristics of the WCVI coastline make it suitable for salmon aquaculture and shellfish mariculture. Salmon farming began in BC during the 1970's raising chinook, coho and sockeye. As of 1998, 16 salmon farming companies operated 79 active salmon farm grow-out sites in BC (Environmental Assessment Office, 1998). There were 122 site tenures, not all of which are being used to actively raise salmon to maturity (a proportion of sites are routinely in fallow) (ibid.). In the fall of 2002, the BC provincial government lifted the moratorium on new aquaculture facilities. This is likely to lead to a dramatic increase in site tenures in the coming years. Figure 3.4 shows the location of present licenses held for aquaculture and mariculture on WCVI.

A)

B)

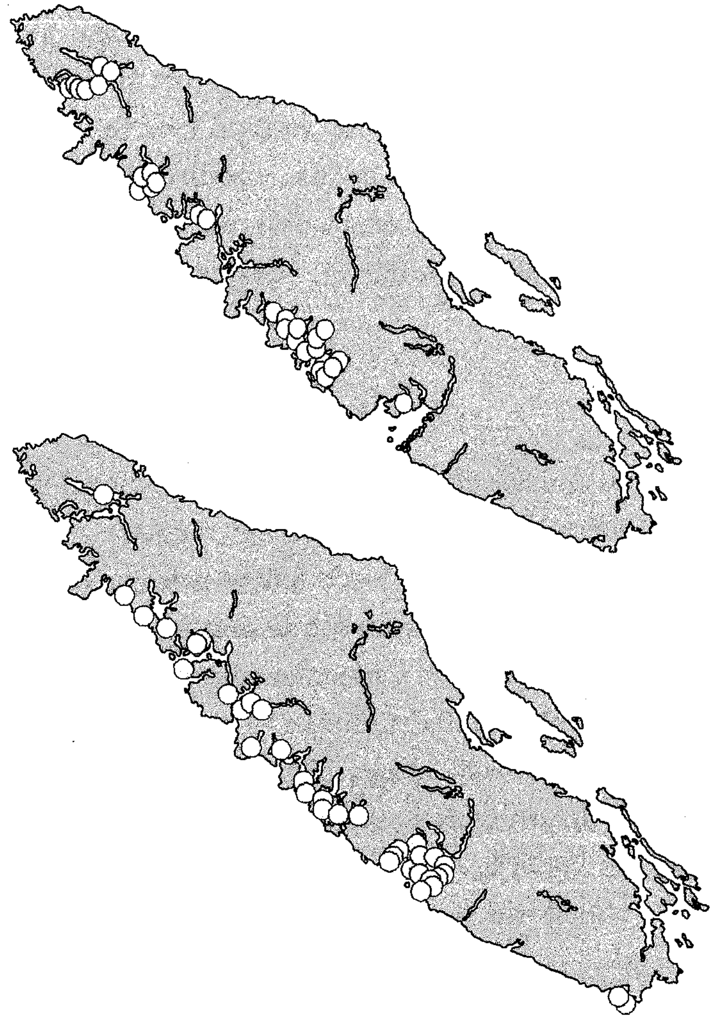
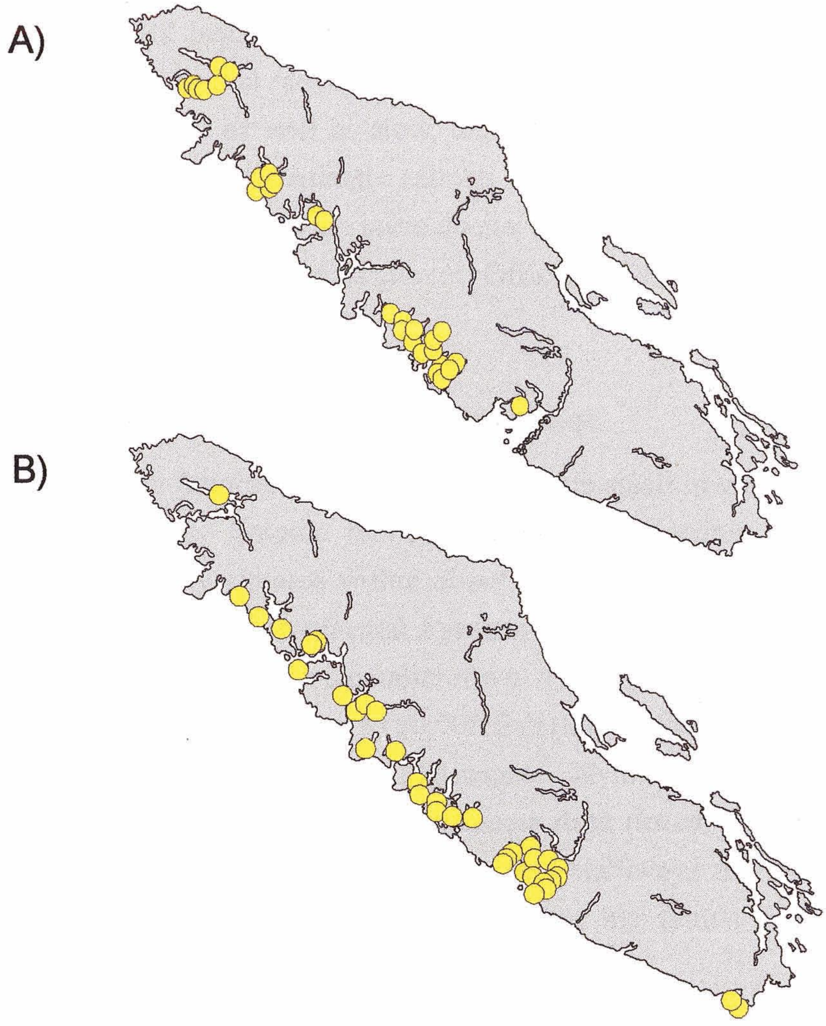


Figure 3.4 Shows the location of the **A)** salmon and **B)** shellfish aquaculture sites on west coast Vancouver Island. There are approximately 32 salmon and 46 shellfish sites as of 2003 (Ministry of Agriculture Food and Fisheries, 2001).

With increased investment in the aqua and mariculture industries, there will be greater concern for displaced fish as a consequence of seismic activity. The main concern for this aspect of the fisheries is not necessarily the deformation of the seabed but rather the potential damage associated with tsunamis. As will be discussed in a later chapter, the characteristics of the coast that are considered to be ideal site locations for these farms may in fact be of high risk with respect to tsunami wave impacts.



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Species

Farmers began having problems with raising sockeye and coho salmon, including low survival rate upon entry to saltwater, stress leading to mortality or poor productive quality as well as slow, unpredictable growth. These problems led BC farmers to start raising Atlantic salmon in the mid-1980s, because they have better growth and survival rates, are more docile, and as a product are in strong international demand (Environmental Assessment Office, 1998; Department of Fisheries and Oceans, 2002b).

Site Selection and Set-up Description

Salmon farming sites are normally quite small in area, usually occupying less than 10 hectares. Salmon farms are commonly floating, self-contained facilities. They are typically situated within about 100 m of the shore, occupying an area of about one-hectare (Environmental Assessment Office, 1998). There can be as many as 10-30 cages deployed in two parallel rows. The cages are normally 12x12 m or 15x15 m, with each cage holding up to 20,000 fish (ibid.). Floats of hollow fibreglass, foam or lightweight concrete support the cages. Nylon nets are hung from each cage, usually to a depth of 15 m. A main access deck (usually four to six feet wide) runs between the cage layouts, and minor access walkways run between adjacent cages. Pens are held in place by anchors securing the farm's geographic position and minimise billowing of nets.

In terms of site location, restrictions exist to minimise impacts upon wild species and habitats. Farms are not allowed within 1 km of the mouth of a salmonid stream and must be at least 125 m from an existing shellfish lease or license or a significant wild stock shellfish bed (Environmental Assessment Office, 1998).

SUMMARY

The process of upwelling along a narrow continental shelf and the jagged glacially carved inlets, create a diversity of habitats. These habitats are able to support a variety of biological communities that include species such as salmon, crab, clam and aquaculture fisheries. These biological communities are complex entities that have habitat and organisms relying upon one another. Disturbances to one can directly or indirectly affect the other, creating a negative feedback loop. Knowing the requirements of the species that are economically important it is possible to assess the effects a mega-earthquake may have on these species. Once the hazards are identified then it can be assessed whether or not the damage is such that it can be reflected in the fisheries. Through an examination of an analogous region, information regarding the impacts a mega-earthquake will have on the habitats and the species can be ascertained. From that information, along with catch data the effect on the fisheries can be established. It is therefore important to isolate a region that not only is similar to Cascadia geophysically but also biologically.

CHAPTER 4

ANALOGOUS REGION: SEISMIC EVENT AND FISHERIES ANALYSIS

INTRODUCTION

Mega-earthquakes and tsunamis along BC's coast occur with such large recurrence intervals that the assessment of the potential earthquake hazard for BC's fisheries is very challenging. This chapter aims to gain an understanding of the physical and biological changes may occur in northern Cascadia when the next mega-earthquake occurs. With no historic event of this magnitude at Cascadia, it is necessary to look to other sources of information. As discussed in chapter 1, there is minimal archival information and mathematical models are unable to adequately deal with the complexities of the marine ecosystem. Therefore, this chapter discusses the effects a mega-earthquake had on the physical and biological environment in an analogous region. With similar oceanographic, geophysical, and biological characteristics it is not unreasonable to assume that similar outcomes will occur at Cascadia.

In order to choose the best analogous region, a scoring system was utilised. A number of subducting plate boundaries surrounding the Pacific ocean were compared and given a point for every characteristic that was similar to Cascadia. For the purpose of this study, the North and South Nazca, North Cocos, Riviera, Nankai, and Aleutian plates are compared in order to isolate the subduction zone that is most similar to Cascadia. Rogers (1998) discusses the similarities between the first five of these subduction zones. They are comparable to Cascadia because they are comprised of young oceanic plates (<20 Ma) subducting beneath the continent. However, I included the Aleutian subduction zone even though it is older than 20 Ma for two reasons: it had a recent rupture that exceeded M_W 9.0 and it is in the same oceanic region.

Off the west-central coast of Mexico two plates, the North Cocos and the Rivera are subducting beneath the America plate. The convergence rate between the northern Cocos plate and the North American plate is about 55 $mm \cdot yr^{-1}$ (Rogers, 1988). The age of the subducting plate ranges from 5 Ma in the north to 20 Ma at the southern end (ibid.). The most recent large event at this boundary was on September

19, 1985, measured M_W 8.0, and caused a great amount of damage in Mexico City (Nunez-Cornu, *et al.*, 2002). The dip of the subducting plate is not confirmed, but researchers estimate it to be anywhere from 10-14° for 110-150 km from the trench (Lemoine, *et al.*, 2002). It is sub-horizontal at a depth of 50 km and 110 km from the trench (ibid.). This shallow dip of the subducting plate causes there to be shallow to intermediate depth earthquakes (~30 km) (ibid.). Overall, this region scored 1/3 in the geomorphic criteria and 4/8 in the geophysical criteria (Table 4.1).

Table 4.1 This continuation of Table 1.1 further eliminates the possible analogous subduction zones. The additional four criteria: a recent event, available data from the event, data availability regarding biological impacts, and the availability of fisheries data, allowed for the Alaska subduction zone to be identified as the best region to use for this study.

	Cascadia WCVI	South Nazca Chile	North Nazca Columbia	North Cocos Mexico	Rivera Mexico	Nankai Japan	Aleutian Alaska
Oceanographic Criteria	Oceanic circulations (upwelling)	✓	✓	✗	✗	✓	✓
	Sea surface temperature (7-15 degrees Celsius)	✓	✗	✗	✗	✓	✓
	Narrow continental shelf	✓	✓	✓	✓	✓	✓
	Coastal habitats (estuaries, marshes, open coast, fjords)	✓	✓	✗	✗	✓	✓
	Aquaculture (fin and shellfish)	✓	✓	✗	✗	✓	✗
	Anadromous fish (salmon)	☒	☒	■	☒	☑	■
Geomorphic Criteria	Fjord coastline	✓	✓	✗	✗	✗	✓
	Coastal substrate (rock, gravel, sand and silt)	✓	✓	✓	✓	✓	✓
	Minimal coastal protection	✓	✓	✗	✗	✓	✓
Geophysical Criteria	Young subducting plate <20 Ma (9 Ma)	✓	✓	✓	✓	✓	✗
	Shallow dip (0-12 degrees)	✓	✓	unknown	unknown	✓	✓
	Shallow rupture depth (25 km)	✓	✓	✓	✓	✓	✓
	Long fault length (1000 km)	✓	✗	✗	unknown	✗	✓
	Width of locked zone (100 km)	✓	✓	unknown	unknown	✓	✓
	Long recurrence interval (~600 years)	✗	✗	✗	✗	✗	✓
	Fault close to shore (≤120 km)	✓	✓	✓	✓	✓	✓
	Convergence rate (~40 mm/yr)	✗	✗	✓	✗	✓	✓
	Subtotal (/17):	**14**	**12**	**6**	**5**	**14**	**15**
Other	Recent mega/great-earthquake event	☑	☒	☑	☑	☒	☑
	Earthquake/tsunami data available	☑	☒	☒	☒	☒	☑
	Studies available re: effects on biota	☑	☒	☒	☒	☒	☑
	Fisheries data available	☒	☒	☒	■	☒	☑
	Overall total (/21):	**17**	**12**	**7**	**6**	**14**	**19**

The Rivera- America boundary has a convergence rate of about 25 mm•yr^{-1} and is approximately 10 Ma old (Rogers, 1988). The largest known earthquake at this boundary was on June 3, 1932 measuring M_s 8.2 (Rogers, 1988; Nunez-Cornu, *et al.*, 2002). The dip angle is hypothesised to range from 12-21° and the length is unknown (Nunez-Cornu, *et al.*, 2002). The regional tectonics are largely undocumented. The lack of monitoring stations in the region creates a situation where inferences about local tectonics are primarily based on world-wide seismic data (Nunez-Cornu, *et al.*, 2002). This region scored 1/3 and 3/8 in the geomorphic and geophysical criteria (Table 4.1).

Although tectonically similar to Cascadia, the oceanographic characteristics of the Pacific coast of central Mexico contrast strongly with those of Cascadia. Upwelling is inhibited by the onshore flow of warm surface water from west to east resulting in warmer waters with temperatures averaging 28° (Duxbury and Duxbury, 1997; Wang and Enfield, 2003). Shallow bays dominate the Mexican coastline and parts of the coast are protected by coral reefs (Rivera-Arriaga and Villalobos, 2001). The dominant fisheries (anchovies, sardines, and tuna) have different habitats and habits from the fish that are present in Cascadia. These are schooling fish whereas salmon are not. Therefore, these two subduction zones may not be suitable for comparison with the Cascadia zone. In the oceanographic criteria the Cocos and Rivera regions each scored 1/6 (Table 4.1)

The Nankai plate boundary has a similar convergent rate at 46 mm•yr^{-1} and a shallow dip angle of 8° increasing to 20° approximately 50 km landward from the trough (Park, *et al.*, 2002). This subduction zone has a recurrence interval of 100-200 years between large events and has a documentary record of activity dating back to AD 684 (Rogers, 1988) with the most recent great earthquake being the 1946 Nankaido event (M_W 8.3) (Park, *et al.*, 2002). This region scored 2/3 in the geomorphic criteria and 6/8 in the geophysical criteria (Table 4.1).

Japan has similar fisheries as Cascadia, being dependent upon chum and pink salmon species. This is not surprising, as these two regions are very similar, oceanographically. Table 4.1 shows Japan scoring 6/6 in these criteria. However, their salmon populations are mostly hatchery born in order to supply the fisheries and are unable to return in great numbers and spawn successfully (Nagata, 2003). For this reason, effects from habitat destruction would not be easily detected by examining the catch data, should this data have been available. Aside from that, the geological and geophysical characteristics of the Japanese coast are very similar to Cascadia.

However, with no history of mega-earthquake and the state of their fisheries, this subduction zone may not be the best fit for this study.

The North Nazca plate boundary is converging with South American plate at a rate of 80 mm·yr^{-1} which leads to great thrust events (Rogers, 1988; Lemoine, *et al.*, 2002). The last time this zone ruptured along the entire length was on January 31, 1906 (M_w 8.8). The dip angle is variable, initially ranging from shallow to 30°, then, at 100 km depth runs horizontally for a distance of 300 km (Lemoine, *et al.*, 2002). This region's geophysical characteristics set it apart from Cascadia. The convergence rate is twice that of Cascadia and the length is much shorter. Great earthquakes frequently rupture but mega-earthquakes are likely rare. This region also differs in oceanic characteristics. It is an upwelling area (Duxbury and Duxbury, 1997; Segar, 1998) however, just like Mexico, the dominant fisheries are based on warm water, schooling species.

The South Nazca plate, which subducts beneath southern Chile, is tectonically similar to Cascadia. It has a convergence rate that exceeds that of Cascadia (95 mm·yr^{-1}) but it is equal in rupture length (1000 km), and dip angle (12-19°) (Plafker, 1972a; Rogers, 1988; Oleskevich, *et al.*, 1999). This zone is capable of mega-earthquakes although the recurrence interval is much shorter (128 years) than Cascadia (Rogers, 1988). The most recent occurred on May 22, 1960 and measured M_w 9.5, making it the world's largest instrumentally recorded event (Plafker and Savage, 1970). This region has a similarity score of 3/3 in the geomorphic criteria and 5/8 for the geophysical criteria (Table 4.1).

Oceanographic characteristics also prove to be similar to Cascadia. This region is a cold water, upwelling-driven system with a coastline dotted with fjords (Paskoff and Manriquez, 1999). As in Cascadia the Chilean region lies within the brown kelp region (*Macrocystis*) (Nybakken, 1997). The main coastal industries here are based on fisheries as well as aquaculture, however the fish species that are commercially important are not anadromous. This makes comparisons with Cascadia difficult, as the coastal biological communities have different structures. This region has a similarity score of 5/6 for the oceanographic criteria (Table 4.1).

The last potential subduction zone is that of Alaska. This region lies in the same oceanic region as Cascadia, has a coastline consisting of fjords and experiences upwelling. This region has the same habitats and species as Cascadia and therefore has the same biological communities and structure. Alaska meets all the requirements except for the presence of aquaculture and the age of the subducting plate (>40 Ma).

The last mega-earthquake (M_w 9.2) occurred in 1964. The geophysical characteristics are such that there is a shallow dip angle (8-15°) (Plafker, 1972b), an equal rupture length (1000 km) and width (100-200 km) (Plafker, 1972a; Atwater, 1987; Atkinson, 1997) as that of Cascadia. This allows comparison and projection of information to be executed with a greater amount of confidence than if any other subduction zone were used.

There are however, two important factors that have not yet been addressed: the availability of seismic information and fisheries data from the time of the last earthquake. Originally there were a number of subduction zones that appeared to be suitable for this study (Table 4.1). The three that had the highest scores after comparing their oceanographic, geophysical and geomorphic nature were South Nazca (score of 14/17), Nankai (14) and Alaska (15). Even though much can be learned from using any of these regions there is the limiting factor of data availability. In order to assess the risks to the marine ecosystem, data regarding the physical and biological effects as well as fisheries data for the time period before and after the event are critical.

It is evident that Alaska is the best choice for this study for it has the greatest similarity score. In addition, the effects of the 1964 earthquake are thoroughly documented. Immediately following this seismic event, surveys were conducted throughout the affected region to assess changes to local hydrology, biology and geology, as well as the impacts on people and property. These reports provide baseline data on seismic events of this type and magnitude, which could prove important for hazard mitigation in other regions that experience large interplate earthquakes.

Alaska also has fisheries catch data, from the years bracketing the mega-earthquake that are available to the public. And finally Alaska is located in the same northeast Pacific ecoregion as Cascadia and therefore has the same fish species, which makes for simple comparisons. Information availability regarding seismic effects on marine organisms and fisheries archival data constrained this study to examine only the commercial salmon, crab and shellfish fisheries.

It is evident therefore, that the March 1964 event in Alaska is a very useful analogy for an earthquake at the Cascadia plate boundary. In this chapter I examine the reports that were completed post-earthquake in Alaska, and discuss the physical and the biological changes relevant to the Cascadia case. In addition, I examine Alaskan catch and escapement data from earthquake-affected areas for the time period bracketing the earthquake event to ascertain the impacts of seismic activity on fish stocks.

RATIONALE FOR USING ALASKA AS AN ANALOGY FOR BC

The earthquake event that occurred in Alaska on March 27th, 1964 holds important clues for BC as Alaska shares physical, biological and seismic characteristics with Cascadia (Clague and Bobrowsky, 1994; Clague, 1997). By analysing the Alaskan experience, insight can be gained into what may occur in the event of a megaearthquake at the Cascadia subduction zone.

As will be discussed in the following sections, there are several similarities between the plate boundaries located off the coasts of Alaska and WCVI. Seismically, these two areas can both fit the generic elastic dislocation model of coseismic deformation associated with great subduction earthquakes (Plafker, 1969b; Plafker, 1972a; Plafker, 1972b; Plafker, 1990; Clague and Bobrowsky, 1994; Dragert, *et al.*, 1994; Dragert and Hyndman, 1995; Clague, 1997). Seismic rupture on Cascadia is expected to be equal in displacement (100-200 km wide and up to 1000 km long) as the 1964 Alaskan event (800 x 250 km) (Plafker, 1972a; Atwater, 1987; Atkinson, 1997). Therefore, Cascadia can expect similar land deformation, ground motion and hazards to those experienced in Alaska.

The Alaska experience can also provide information regarding the magnitude of land deformation that occurs; the types of habitat that may be negatively affected; and the biological effects that can ensue. The 1964 event can indicate how sensitive these commercial species are to habitat destruction from large-scale seismic activity. The initial reports produced by the Committee on the Alaska Earthquake (1971) provide a first approximation of the effects a megaearthquake might have on the west coast of BC, specifically WCVI. Revisiting and updating such predictions allows for planning and preparation prior to such an event.

ALASKA

Tectonic Setting

The Pacific plate moves in a northwesterly direction at a rate of 50 to 70 mm·yr^{-1} (Plafker, 1972b) and is subducting beneath the North American plate in the Gulf of Alaska. This convergence causes the crust of southern Alaska to be compressed and warped, with some areas along the coast being depressed while other areas inland are being uplifted. At intervals of hundreds of years, this compression is relieved by the sudden motions of large sections of the continental plate moving back in a southeasterly direction over the subducting Pacific plate.

The Alaska-Aleutian Trench lies approximately 250 – 300 km from the Alaskan coastline (Plafker, 1972b). The area of highest seismic activity along the eastern Aleutian Arc occurs along a broad zone that dips northward from the Alaska-Aleutian trench at a shallow angle of 8° (Plafker, 1972b). Below the continent, the dip remains less than 15° as at the Cascadia subduction zone (ibid.).

History

Although the March 27th, 1964 earthquake was an extreme event, the stacked sequences of uplifted marine surf-cut terraces along the outer Alaskan coast suggest that similar abrupt movements have occurred at intervals of 800 years or more in the late Holocene (Geophysical Institute, 2002). The last major tectonic earthquake that displaced shorelines in the Prince William Sound region appears to have been about 930-1,360 years ago (Plafker, 1972b).

A SPECIFIC EXAMPLE - THE 1964 EARTHQUAKE

The epicentre of the 1964 earthquake was located at 61.04° N - 147.73° W (about 10 km east of the mouth of College Fjord, approximately 90 km west of Valdez and 120 km east of Anchorage). Vertical and horizontal displacement occurred over an area in excess of 285,000 km^2 in south central Alaska (Plafker, 1972b) (Figure 4.1). The earthquake was felt over approximately 1,300,000 km^2 including all of Alaska, parts of western Yukon Territory and British Columbia and the State of Washington. The locations of the Alaskan study areas are shown in Figure 4.2. In addition to widespread land deformation, local tsunami waves triggered by this earthquake were extremely destructive. A Pacific-wide tsunami was generated, damaging areas in southeastern Alaska, British Columbia, Oregon, California and the Hawaiian Islands. It was recorded by tide gages throughout the Pacific, including Japan, Chile, and the former Soviet Union (Dudley and Lee, 1998).

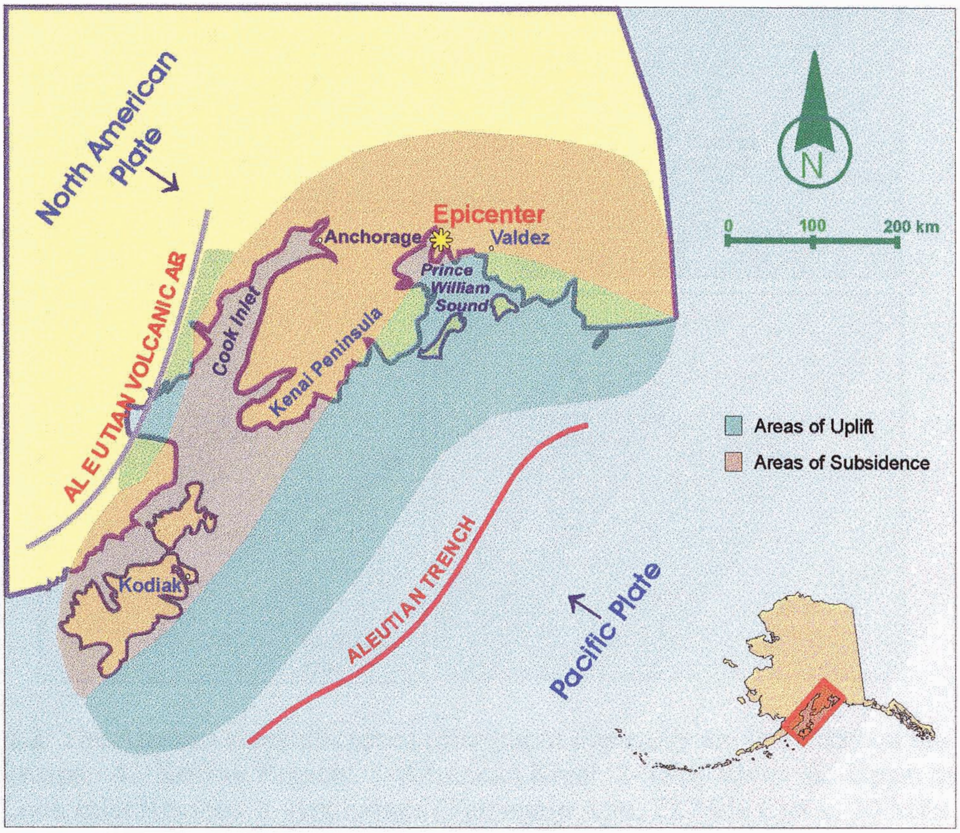

Figure 4.1 The magnitude 9.2 earthquake of 1964 had an epicentre located in Prince William Sound. With this came extensive land deformation in south central Alaska with as much as 3.0 metre subsidence and 15.0 metres of uplift occurring over 140,000 km . *(Adapted from Plafker, 1972)*

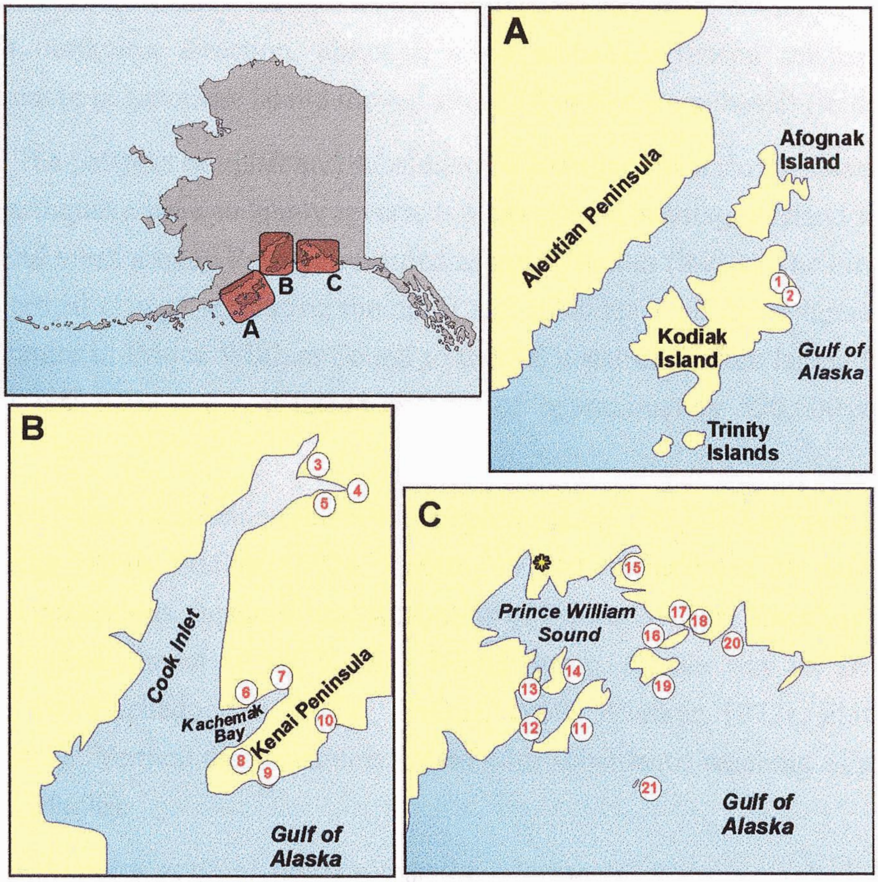

Figure 4.2 The Alaskan areas discussed throughout this study are indicated on the regional maps. **A.** Kodiak Region: 1-American River 2- Olds River **B.** Upper and Lower Cook Inlet Region: 3- Anchorage (Turnagain Arm, 22 Mile Creek, 20 Mile Creek and 6 Mile Creek) 4-Portage (Tutka Bay Lagoon) 5- Resurrection Creek 6- Homer 7- Kachemak 8- Port Graham 9- Port Dick 10- Seward **C.** Prince William Sound/Copper River Region: 11- Montague Island 12- Latouche Island 13- Chenega Island 14- Knight Island 15- Valdez (College Fjord) 16- Hawkes Island (Shipyard Bay) 17- Orca Inlet 18 - Orca Bay 19- Hinchinbrook Island 20- Copper Bay (Copper River) 21- Middleton Island The star indicates the location of the epicentre from the 1964 mega-earthquake.

Physical changes

The earthquake occurred at an estimated depth of 25 km and lasted approximately 4 minutes (Plafker, 1972b). The segment of the Alaska-Aleutian trench where slippage occurred was 800 km long and 250 km wide (Plafker, 1972b; Pararas-Carayannis, 2000; Geophysical Institute, 2002). Pre-earthquake strain suggested that the continental margin that ruptured had been elastically compressed and shortened by at least 19.5 m prior to the 1964 earthquake (Plafker, 1972b). As a result, the net horizontal movements of the Pacific plate under the North American plate averaged 9 m in a northwest direction, although some also experienced substantially more movement (e.g. Latouche Island moved about 18 m to the southeast) (ibid.).

The patterns of uplift and subsidence which had been slowly developing prior to the earthquake were suddenly reversed; areas around Montague Island were uplifted 4-9 m and areas around Portage subsided as much as 3 m (ibid.). The hinge line (line of no vertical change separating the uplift and subsidence zones) extended from near the epicentre in Prince William Sound to the SE coast of Kodiak Island (Figure 4.1). This vertical deformation affected an area of approximately 520,000 km^2 (Zirbes, 2002).

The zone of subsidence covered approximately 125,000 km^2 and averaged 0.8 m (Plafker, 1969b; Plafker, 1972a; Plafker, 1972b). It included the west part of the Chugach Mountains, the north and west parts of Prince William Sound, most of Kenai Peninsula, and almost all the Kodiak Island group, all the way to Trinity Islands (Plafker and Kachadoorian, 1969a; Plafker, 1969b; Plafker, 1972a; Plafker, 1972b) (Figure 4.1). Vertical displacements varied with subsidence reaching as much as 3 m (Plafker, 1969b).

The major zone of uplift along the continental margin reached a maximum amplitude of 4.6 m (Plafker, 1969b; Plafker, 1972b). The main zone of uplift on land, as determined by shoreline changes, included a narrow fringe of points, capes and small islands along the seaward side of the Kodiak group of islands and the majority of the Prince William Sound region. Direct indications of uplift of parts of the contiguous continental shelf are afforded by emergence of all the offshore islands and reefs, including Middleton Island near the edge of the continental shelf (ibid.). Uplift also occurred over much of the submarine part of the continental margin in a broad zone extending southwestward at least Kodiak Island (ibid.). It is also suggested that uplift occurred over much of the continental slope, extending to the toe of the continental slope (ibid.). For example, average uplift at Montague Island was 4-9 m while off the southwest end of the island, there was vertical displacement ranging around 13 - 15 m on shallow crustal faults (Plafker and Kachadoorian, 1969a; Plafker, 1969b; Plafker, 1972a; Plafker, 1972b).

Biological changes

An impact of subduction earthquakes that is seldom addressed is the effect on the flora and fauna of the coastal areas. However, a party of US Geological Survey investigators studied the Prince William Sound region, making post-earthquake observations of the intertidal areas. Intertidal species in the ocean are adapted to certain conditions within narrow bands defined by depths below mean high tide. If the water depths to which these animals and plants have evolved are changed, the organisms often die, as they are unable to move or adapt to the changed environment. The investigators from the USGS found that the 1964 earthquake caused changes to an extent and on a scale never previously imagined. Changes in the position of the shorelines relative to sea level directly affected coastal infrastructure, shipping as well as local ecosystems having repercussions felt in some of the finfish and shellfish industries along the Alaskan coast (Noerenberg, 1971).

The fishing industry experienced significant economic losses including damaged or destroyed fishing vessels and canneries. On Kodiak Island alone, there was nearly $14.5 million (2002 US dollars) worth of damages (Noerenberg, 1971). The approximate loss to the king crab fishery was $5.2 million (2002 US dollars) affecting both fisherman and packing industries (ibid.). The salmon industry was also affected as the San Juan cannery at Uganik was unable to function in 1964 due to damages. This was unfortunate as 1964 was predicted to be a successful salmon year during which the facility could have operated and earned as much as $23.3 million (2002 US dollars) (ibid.).

Although economic losses are commonly reported and quoted, habitat loss and increased mortality of fish and shellfish throughout the Alaskan region also occurred. In order to understand the cause of these changes it is necessary to examine the Alaska subduction zone together with the physical changes that occurred throughout the coastal area that resulted in the reported biological consequences. This chapter will cover the reported changes as well as any changes that were incurred by the fishing industry.

Coastal and offshore marine organisms and ecosystems were devastated as a result of two main processes. The sudden modification of shoreline morphology resulted in widespread mortality of intertidal biota. Large numbers of organisms were displaced into different intertidal zones (Baxter, 1971; Johansen, 1971; Hanna, 1971b; Plafker, 1990); pelagic organisms were killed as they are suddenly brought to the surface, causing fish bladders to rupture (Alaska Department of Fish and Game, 1965), and valuable rearing habitats were lost or damaged.

Organisms and habitats were also damaged by the resultant tsunamis. As tsunami wave trains approach the shore, they built up in height and energy. These waves mobilised sediments from the upper continental shelf and destroyed benthic communities. The erosion and deposition of sediments by increased wave action resulted in organisms and their habitats being buried or scoured (Baxter, 1971; Hanna, 1971b; Castilla and Oliva, 1990).

Vertical displacements of the shoreline strongly affected both the fauna and the flora over a vast coastal area of south central Alaska. Some of these effects were apparent within days of the earthquake; others, which depend upon the complex interrelations of one organism to another and to their habitat, were not apparent for a long time. These effects resulted in disruption to wild stocks over a number of seasons. Such changes can alter the ability of the marine ecosystem to function through loss of intra-specific diversity. The result can be lower long-term sustainable catch rates, enhancing overexploitation and fishing down the food web (Cury, 1999).

Effects of Subsidence

Land subsidence resulted in the loss of intertidal spawning areas that caused pink and chum salmon to spawn farther upstream. These "new" upstream spawning areas were however, susceptible to adverse environmental conditions such as flooding, silting, and low water flows. Some streams were reported to be carrying greater sediment loads as a result of landslides, stream-bank loosening and sloughing (Noerenberg, 1971). Sedimentation downstream also affects spawning success.

Subsidence of unconsolidated deposits also resulted in narrowing or complete submergence of beaches. Seawater inundated the lower reaches of some streams in subsided areas as much as 1,400 m inland from the former mouths (Plafker, 1972b). Former reefs and low-lying islands along the coast were submerged and some tombolo-tied points or capes became islands as wave action at higher sea levels caused rapid erosion of shorelines (ibid.).

Subsidence led to sessile intertidal marine organisms being submerged below their optimal habitat. Individuals near the species lower depth limit would be especially adversely affected by the changed conditions and would gradually be replaced by other organisms better adjusted to the deeper water environment. Some marine organisms encroached upward into the new littoral zone and it was not uncommon to find barnacles, limpets and algae living on or among the remains of land plants (Plafker, 1972b). Destruction of animals and plants in the littoral zone was less extensive in subsided areas as compared to uplifted areas (Hanna, 1971b). Within a year, organisms migrated upwards into their various zones although animals in the old zones seemed to be living despite being exposed to air for shorter periods of time (ibid.).

Effects on Finfish:

There was approximately 1.5 m of subsidence on Afognak Island and the north end of Kodiak Island, causing changes in salmon spawning habitat (Noerenberg, 1971). The permanent damage to spawning and rearing habitat occurred mainly in the intertidal zone and to a lesser degree in former freshwater portions of streams used by pink and chum (Noerenberg, 1971). Subsidence resulted in narrower, steeper intertidal areas at the stream mouths.

The Olds and American Rivers, which were major rivers on Kodiak for salmon spawning, were extensively damaged (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). The Kodiak- Afognak area also saw major changes to spawning and rearing streams of pink, chum, sockeye and coho salmon. Land subsidence and tsunamis waves were responsible for most of the damage. In the Kodiak area, at least two historic salmon fisheries did not produce in 1964. This could be due to migration pattern changes caused by sea floor alterations brought about by the earthquake or due to a normal evolution of the fishery (Alaska Department of Fish and Game, 1965).

In the Cook Inlet and Kenai Peninsula regions subsidence occurred along most of the coastline. It took two different forms: actual sinking of the entire landmass and compaction of soil materials (Noerenberg, 1971). Cook Inlet also experienced numerous coastal landslides. The most substantial changes and greatest detrimental effects however, were encountered in the southern and eastern area of Kenai Peninsula. The overall effect of the sinking was a direct loss of intertidal salmon-spawning areas in streams from Kachemak Bay to Port Dick and in Turnagain Arm (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). At Port Dick Creek, an area of 16258 m^2 of spawning gravel was lost due to subsidence (Noerenberg, 1971). The effects of the land subsidence and tsunami on the pink and chum salmon spawning streams from Homer to Port Dick were never accurately determined (ibid.).

In other areas, such as in the Portage area, land subsidence resulted in high tides extending 1-3 km farther upstream, resulting in considerable loss of freshwater habitat (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). As well, the mouth of Resurrection Creek subsided about 1.5 m, and an estimated 1,254 m^2 of pink salmon spawning area were lost (Noerenberg, 1971). Tutka Bay Lagoon and Port Graham River also lost intertidal spawning area as a result of subsidence (ibid.).

Effects on Shellfish:

The effects on commercial shellfish populations were however relatively minor. For example, in areas visited by Haven (1971) that had experienced 1-2 m of subsidence, there was low mollusc mortality and Noerenberg (1971) noted that losses to the crab populations in Cook Inlet region were minimal.

Effects of Uplift

The effects of uplift on the biota of the Alaskan littoral zone were more striking than those resulting from subsidence. Uplift caused complete extermination of organisms that were permanently elevated above their normal ranges. In areas where uplift exceeded the local tide range, as on islands in southern Prince William Sound, on parts of the mainland coast to the east of the Sounds, and on several offshore islands on the continental shelf, destruction of the sessile organisms was almost absolute. Even many of the mobile organisms, including seastars, gastropods, and small fish did not survive (Plafker, 1972b).

The rocky shores of Prince William Sound experienced considerable amounts of uplift, up to 10 m in some areas (Plafker, 1969b). The entire intertidal zone and considerable parts of the upper subtidal zone were lifted above the reach of the tides. There was virtually complete mortality of the uplifted intertidal and upper subtidal organisms (ibid.). The newly exposed littoral areas, covering many hundreds of square kilometres and once densely populated by a varied intertidal community, became completely desolated. Hanna (1971a-pg. 9 and b-pg. 20) described an area in Prince William Sound as having "turned black in desiccation or bleached white with so many marine plants having been destroyed. There were beaches with great accumulation of dried seastars and dried necks of clams forming a solid mass covering about a square yard". In some places a shovel could be used to collect almost pure concentrations of shells. The major effect of tectonic uplift was to shift the extreme high-tide line seaward and thereby expose parts of the littoral and at some places, the sublittoral zones (Plafker, 1972b). In the areas of maximum uplift, such as Montague Island, the emergent sea floor was as much as 550 m wide (ibid.).

Effects on Finfish:

Dewatering and the resultant loss of freshwater salmon habitat due to land uplift were noted at three places in Cook Inlet. The discharge of Kasilof River was significantly reduced for an undetermined amount of time following the earthquake; Ship Creek at Anchorage stopped flowing for an estimated 18 hours; and two of the Finger Lakes on the Kenai Peninsula lost water at a rate of approximately 10 cm per month (Noerenberg, 1971). The Copper River Delta experienced 2 m of uplift, resulting in the loss of many schooling areas used by salmon prior to moving upstream to spawn (ibid.). This led to many salmon dying in the shallow waters while attempting to go upstream. It was reported that virtually all the spawning that did occur was in the lower sections of the river where the substrate had been disturbed by the tsunami (Alaska Department of Fish and Game, 1965).

Surveys in July–September found that new spawning-bed material in uplifted zones varied considerably, from silt and small gravel to boulders and cobbles and even some mussel beds. Erosion had occurred in some streams and had occasionally caused them to flow underground. In uplifted areas, spawning salmon had shifted downstream (in subsided areas, they moved upstream).

Effects on Shellfish:

Molluscs occupy a narrow depth zone (see chapter 2), and any appreciable reduction in mean water depth will result in the desiccation of beds. Large areas in Prince William Sound contained extensive and highly valuable populations of clams. Where these areas were uplifted, the clams were destroyed. At the time it was estimated that these clam populations, which were 8-13 years old, would require many years to recover to pre-earthquake levels (Hanna, 1971b).

Prince William Sound has extensive mudflats, particularly in the vicinity of Cordova. There was extensive mortality of bivalves following the earthquake in both the moderately and maximally uplifted parts of the sound. Mortality estimates ranged from 11% with uplift of 1 meter to 100% in areas with uplift above 1.5 m. Species growing closest to the high tide limit had proportionally greater mortality. Mortality of commercial-sized cockles (*Clinocardium*) at Cordova was 36 per m^2, and that of *Macoma balthica* reached 3,240 per m^2 (Haven, 1971). The principal cause of clam mortality was exposure following raising of populations above their normal vertical ranges. This reduced submersion time for feeding and led to increased exposure to sub-freezing temperatures (Alaska Department of Fish and Game, 1965).

Prince William Sound lost at least 36% of the stock of commercially viable clams due to uplift (Baxter, 1971). Total loss of clam habitat in Prince William Sound, assuming an average land-level change of ≥2 m, was estimated at 43% (Haven, 1971). Hanna (1971b) estimated that the mortality of all types of shellfish, including commercially important razor clams, was as high as 90% in some areas. At many places where uplift exceeded the normal tide range of 3 m, the clam and mussel populations were completely wiped out. In these areas, the populations of birds, fish and other animals that normally fed on shellfish also declined because of the reduced food supply (Plafker, 1972b).

Shipyard Bay on Hawkins Island had densely populated clam beds. However an average uplift of 2 m resulted in the populations being completely wiped out, with most of the soft sediments having been washed away (Hanna, 1971b). Regardless of these losses in areas of maximum uplift, there was evidence of repopulation soon after the earthquake (Haven, 1971). It is possible that some of the living specimens and perhaps individuals of other species were pre-earthquake survivors, lifted from the subtidal into the intertidal zone. However, it was noted there was a strikingly smaller number and variety of animals in the lower midlittoral zone than before (ibid.).

Tsunamis

The associated tsunami caused significant destruction to the east coast of Kodiak and Afognak Islands. There was a series of five major waves reaching 6-7 m above the existing high tide level (Alaska Department of Fish and Game, 1965; Noerenberg, 1971; Lander, 1996). Several kinds of damage can occur to fishery resources from tsunamis. As the tsunami moves onshore it scours benthic communities. As wave energy is transferred to the shore causing the movement of gravel and sands in streams resulted in loss of salmon fry and clambeds. Freshwater habitat is also affected by saltwater intrusion. As the tsunami recedes, loss of energy results in deposition of sediments, resulting in the burial of habitat, salmon fry and clambeds.

Effects on Finfish:

Red rockfish floated to the surface in Valdez Narrows and near Chenega Island in sufficient numbers to cover the water (Hanna, 1971b). These mortalities were possibly a result of fish bladders rupturing as tsunami waves quickly brought them to the surface.

Tsunami deposits in the Olds and American Rivers, reached as far inland as 2.5 kms, killing many pink salmon fry that were emerging from the gravel in the river estuary (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). Approximately 1.4 km of the river, including three major spawning riffles, were lost, forcing the entire Olds River pink salmon run to spawn (some 32,800 fish) in less than 200 m of stream (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). The wave action within the streams was particularly critical because it coincided with pink salmon fry emergence from the gravel or migration to the creek-mouth estuaries (ibid.).

An area covering 5 hectares near the mouth of Kern Creek was completely destroyed by silting (Noerenberg, 1971). This process of re-deposition of silt and mud by the tsunami waves also removed 2.4 kms of Twentymile Creek from spawning habitat (ibid.) as it did throughout the south side of Cook Inlet (Alaska Department of Fish and Game, 1965; Noerenberg, 1971). An area of about 1,672 m^2 of gravel previously used by pink salmon was lost under mud deposits at the mouth of Sixmile Creek (Noerenberg, 1971).

The tsunami water surge at Port Dick reached inland as far as 24 km beyond the extreme high tide mark (Noerenberg, 1971). Several streams such as Island Creek in Port Dick sustained gravel movement caused by the tsunami, effectively changing the character of the streams and intertidal areas. The lower portion of the main spawning areas were buried under 0.5 m of gravel that had been scoured out of the upper portion of the stream, resulting in heavy mortalities among fry throughout the creek (ibid.). After the earthquake, surveys showed there were no fry present in the gravel anywhere along the stream (ibid.). At Seward, damage from the tsunami destroyed tide gates for major sockeye and coho salmon rearing habitat. Several streams experienced changes that resulted in mortality however it was noted that overall there was greater mortality of fry in the exposed tidal flats than upstream areas (ibid.).

Effects on Shellfish:

The removal of surface sediments, caused by the strong currents and waves associated with the tsunami, was another important cause of mortality on some mudflats. At several stations there were extensive beds of dead clams, upright in what remained of their pre-earthquake burrows (Haven, 1971). Areas were stripped of fine sediments, scoured by currents, leaving bivalves half buried in hard substrate (ibid.). The tsunami deposited sediments over spawning beds in four streams (Noerenberg, 1971).

SUMMARY

Throughout Prince William Sound the immediate or short-term effects of the earthquake were losses of pink and chum salmon eggs and fry in the gravel. Permanent damage to spawning and rearing habitat was caused mainly by subsidence and to a lesser degree by uplift and tsunami waves (Alaska Department of Fish and Game, 1965). The initial observed effects of this seismic event included: large portions of salmon bearing streams undergoing drastic changes to the streambeds; clam beds being moved out of their ideal zonation; the deposition of silt and debris in habitats or scouring of habitats through tsunami action; and the creation of riffles in the new intertidal zones by subsidence.

The Copper River Basin sustained damaged from shoreline sloughing and the forcing of sand and gravel into stream mouths by large blocks of sea ice. Thirteen salmon-spawning streams were either partly or totally blocked to fish movement by the ice action that pushed up ridges of sand and gravel (Noerenberg, 1971). Approximately 20 km of shoreline spawning gravel were covered by silt and debris as a result of shoreline damage; any fish in the underlying gravel, or in the area scoured by ice, were undoubtedly destroyed (ibid.).

The reports included here show that there was an increased amount of mortality among species that utilise the intertidal and subtidal regions of the coast. The visible damage was a direct result of land deformation and tsunami wave action. Some of the effects were apparent within days after the earthquake whereas others may have never been fully recognised. Cascading effects within the biological community may only appear years later, and further up the food chain. The changes that were experienced in Alaska may have had long-term sustainability repercussions as fisheries continued in most areas as normal. In the following section I analyse catch and escapement data for a 10-year time period bracketing the 1964 earthquake to detect any influences this event may have had on Alaskan fisheries.

EARTHQUAKE EFFECTS ON ALASKAN FISHERIES

Having examined the physical hazards associated with a megaearthquake as well as the initial biological damage, it is important to assess the potential long-term damage to commercial stocks. For large aggregates of fish populations, commercial catch data are commonly used as indices of the variability in abundance (Beamish and Bouilon, 1993; Hare and Francis, 1995; Downton and Miller, 1998). Therefore, it would be useful to examine catch data from the areas that are known to have sustained heavy damage in 1964. The inherent problem with using this type of data is that it is influenced by catch effort, which in turn is under political and market influence. The more fishermen there are, with greater technology, the greater the total catch can be, regardless of the actual population size. This can be misleading, as harvests may be more than the allowable catch. For this reason, when available, escapement data are preferred. Alaskan fisheries data were collected from the ARLIS Library in Anchorage, Alaska or directly from the biologists and managers in the Alaskan Fish and Wildlife Department.

A 10-year period is used for this study in order to limit complications from long term cycles that occur in the ocean that affect survival rates, such as the El Nino – Southern Oscillation, the Pacific Decadal Oscillation (PDO), as well as the compounding effects of fishing efforts. The PDO index provides a measure of basin-scale variations in sea surface temperature (SST) in the North Pacific. Warm (cold) phase conditions tend to coincide with years of positive (negative) polarity in the PDO (Mantua et al., 1997). As seen from the bottom graph in Figure 4.3, the PDO was predominantly positive between 1925-46 and 1977 to present and negative between 1947-76. When the PDO is in its positive polarity, coastal areas of central/southern Alaska tend to experience an enhanced cyclonic flow of warm, moist air, which produces heavier than normal precipitation (Mantua et al., 1997). The cyclonic wind pattern results in an intensification of downwelling along the coast and increased advection of oceanic plankton into nearshore areas (Brodeur and Ware, 1992).

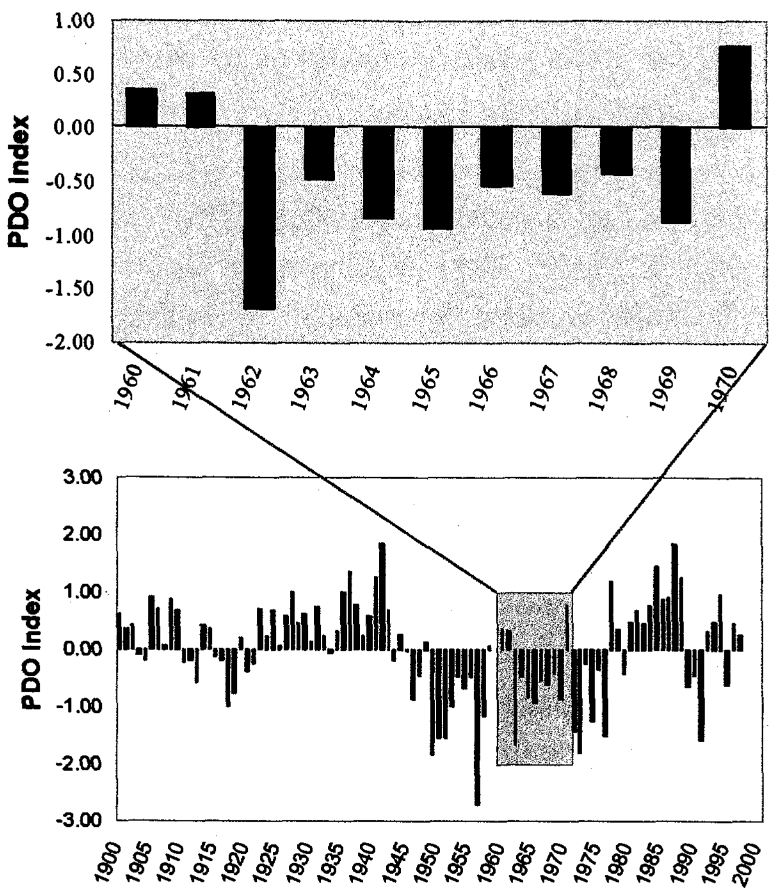

Figure 4.3 The Pacific Decadal Oscillation Index, 1900-2000, and inset, 1960-1970.
(Data from Mantua, et al., 1997)

Higher SSTs (positive PDO polarity) are positively correlated with higher recruitment levels in Alaska (Downton and Miller, 1998; Mueter et al., 2002). Mantua et al. (1997) however, points out that this correlation is not consistent in recent decades as Alaskan salmon catches and coastal SSTs have remained above average since the late 1970s despite the fact that the PDO has fluctuated severely since that time. Further analysis of survival rate anomalies from stock-recruitment curves have shown significant positive co-variation among stocks across local or regional scales of several hundreds kilometres, but not at larger scales (Myers et al., 1997; Peterman et al., 1998; Pyper et al., 2001). Regional SST (SST, within several hundred kilometres of a stock's ocean entry point) anomalies specific to each stock were found to be a much better predictor of survival rate than the PDO, suggesting that coastal conditions during the first few months at sea have larger effects on survival rate and subsequent recruitment of salmon than large-scale variability related to the PDO index (Mueter, et al., 2002). Further to this, Mueter et al. (2002) found that coastal SSTs during summer, when juvenile salmon are in the coastal ocean, are only weakly correlated with the PDO index.

There is obviously conflicting research regarding salmon survival and scale of SST effects on survival. The catch data in this study lie within the predominately negative regime and do not experience a PDO regime shift (Figure 4.3), although 1960-61 are slightly positive. If recruitment levels do reflect the PDO index, the data may be below long term averages however the entire data set will be consistently low with drastic declines having alternative causes. Regression analysis on the recruitment levels between the years of 1940-1970 and PDO index, showed no correlation within any region (Appendix B). Running the regression with data from a consistantly negative PDO regime (1950-1963) also failed to show any correlation with all R2-values being below 0.200. Correlation between recruitment and coastal SSTs however was not investigated as SSTs vary greatly (spatially and temperally) making analysis difficult due to lack of data. Therefore, for this study recruitment levels are assumed to be consistent and any sudden drop below average can then be attributed to the mega-earthquake.

The data covered the period 1960-1970 for the areas that were hardest hit by the earthquake and tsunami. These areas primarily include Prince William Sound but also Cook Inlet, and Kodiak Island. Unfortunately, there are gaps in the data. Missing data may reflect an absence of fisheries being managed over that time period; or the method in data collection may have changed, making years incompatible; or usable records were not accessible. Areas where one or more of these situations arose included Kodiak Island salmon fisheries, and escapement data for most of the Gulf areas.

Escapement data are utilised with greater frequency in population studies and are collected either in the river delta or further upstream. They are based on an estimate of the number of individual fish that return to their natal area to spawn. However, there are also problems with these data. The accuracy of the counts can be affected by water turbidity at the time of the count, the timing of the counts relative to timing of the run's peak and the temporal pattern of returns. These situations can result in spawning populations being over or underestimated, masking any population changes that may be occurring. Regardless of the difficulties with using catch and escapement data, it is the only data available. Examination of the data can still prove useful for examining sudden or immediate population changes following catastrophic changes to habitats.

Salmon in Prince William Sound were exposed to a great deal of habitat damage from the coseismic deformation and tsunami. A large area experienced subsidence, making it no longer usable by certain organisms (i.e. estuaries that experienced significant down dropping would no longer be available as a rearing habitat by migrating juvenile salmon). There was also a large amount of damage done by the tsunami waves causing changes to substrates as waves removed or deposited sediments. There was also the effects of uplift as habitats were shifted upwards out of the marine realm. It is expected that because fishermen were able to get their boats repaired in time for the fishing season that the catch values of 1964 would not reflect the occurrence of the earthquake. However, it is probable that any decline in populations would be reflected in catch levels in the years following the disturbance. It is expected that the effects of habitat change, affecting spawning success, would be evident in the years following 1964.

Prince William Sound

Pink salmon follow a two-year cycle with either the odd or even year dominating. Therefore, it is necessary for comparisons to be with either the odd or even years (i.e. 1963-1965-1967). The pink salmon population shows a decline, from the parent stock, in the year following the earthquake. The forecast for 1965 returns was optimistic however, the catch was significantly less than anticipated. Calculations of the expected 1965 return of pink salmon show an earthquake loss representing approximately 235,000 adults (Alaska Department of Fish and Game, 1965). There was also a significant drop in the 1964 run size (4,189,505) from the parent stock of 1962 (6,543,081) and catches continued to drop in 1966 (2,719,236) and 1968 (2,451,668). The Coghill district, in the Prince William Sound region, reported a lower than estimated catch rate following an average catch in 1964 (ibid.). Regardless, these years are still above average. Only the 1965 cohort drops below the 10-year catch average, possibly indicating increased mortality of the fry spawned in 1963. This decline in the 1964 cohort (seen in the 1966 and 1968 runs) could be in part due to habitat loss/change and/or as a result of the tsunami waves bursting the fish bladders during sudden rise to the surface (Figure 4.4).

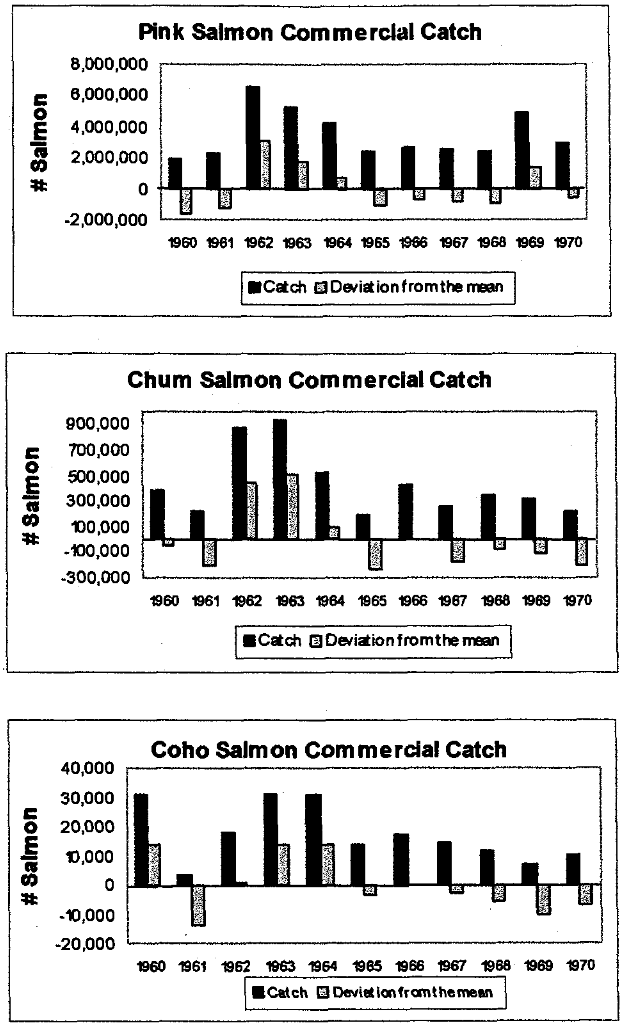

Figure 4.4 Catch rates for pink, chum and coho salmon in the Prince William Sound district are shown by the black bars. The difference from the ten year (1960-1970) mean is indicated by the gray bars, where negative numbers indicate a lower than average catch rate. The catch rates for the pink stocks remain below average for four years after the 1964 earthquake. Chum salmon also show four years of declined catch rates after the earthquake. There is also a significant decline in the 1964 coho cohort that return six years later to spawn in 1970.

Escapement data for Prince William Sound pink salmon show a declining trend in the years following 1964 (Figure 4.5). This trend of fewer spawners continues up to 1969, and in some districts, includes the 1970 cohort. The East district is the strongest run but in 1970 it remained at a level just above half of the pre-earthquake value

(371,690 and 650,660 respectively). North, Coghill and Southeast districts have fewer spawners over three generations following the 1964 earthquake. Montague district shows a slight increase in 1970 over the previous three years, however it is still significantly less than the 1962 level. Eshamy does not have strong spawning numbers with alternating strong and weak years.

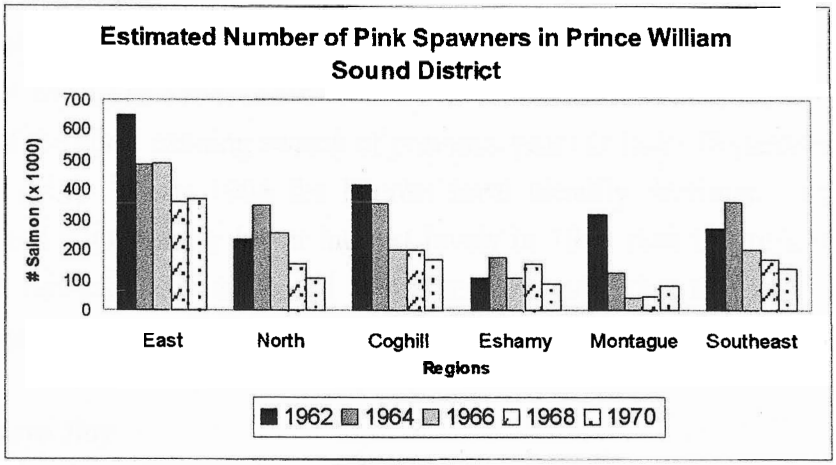

Figure 4.5 The escapement data for even-year pink salmon in the Prince William Sound district show varying trends through the six regions. The North, Coghill, Montague and Southeast regions all show declines for several years following the earthquake. This may indicate that any earthquake-caused stock losses are reflected in cohorts returns for more than one or two years.

Overall, chum salmon stocks were extremely strong in 1962-1964 (871,858, 933,133 and 521,711 respectively) but declined after the earthquake (≤429,636). Figure 4.4 shows this as an increase in catch values in 1964 (521,711) over the parent stock of 1960 (381,858), followed by a decline in 1968 (350,630), reflecting an increased mortality due to the marginal or lost habitat available for spawning in 1964. There is a low catch value in the 1965 and 1969 cohorts, reflecting in part the low numbers of parent stock in 1961.

Populations of coho salmon were also affected by the earthquake event as seen by the below average catch levels for the years following the 1964 (Figure 4.4). There are significant anomalies in catch levels post-earthquake compared to pre-earthquake. Looking at the 1964 cohort (30,914) six years later, there is a significant decline in the catch values (10,030), indicating a high mortality rate for that cohort. This decline in run size could be due to excess mortality of fry while in the stream due to habitat destruction during the earthquake. This loss of habitat may have left only marginal areas for spawning, resulting in heavy mortality of eggs.

Catch values for chinook and sockeye salmon are poor over this decade, with the last few years being the exception (Appendix C1). There is no discernible decline in runs after the earthquake. There is therefore, no evidence of the earthquake having any significant effect upon either of these fisheries.

Shellfish:

Prince William Sound Dungeness crab fishery hit a peak harvest of ≥ 1.5 M crabs (3.4 M lb.) in 1964. This was due to the crab cannery being open year-round, instead of the short canning season of previous years (Alaska Department of Fish and Game, 1964b). After 1964 the harvest level steadily declined. The razor clam experienced significantly lower harvest levels in 1963 than in pre-earthquake years however, this has been attributed to market demand rather than any environmental influences (Appendix C5).

Cordova Bay

Much of the salmon spawning habitat was damaged in the area of Copper River, within the Cordova Bay region. In 1962, it is apparent that the parenting stock for 1964 was relatively healthy as shown by the high catch value (1,880). The catch then declines in 1964 to 548 indicating there was a high mortality in the population. This decline is also reflected in the low returns of 1966 and 1968. There is however, a small increase in catch and almost no deviation from the average in 1970. If the 1966-68 decline is attributed to the earthquake then the 1970 run may indicate recovery (Figure 4.6).

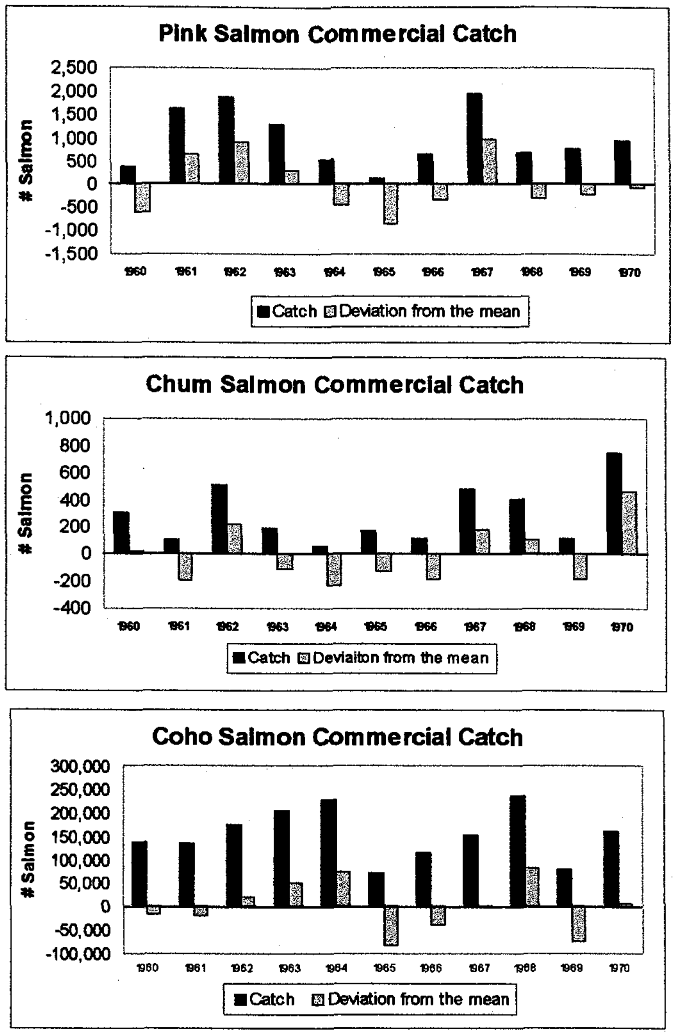

Figure 4.6 Commercial catch rates for 1960-1970 from the Copper River district. Catch values are in number of salmon per year. Catch rates are indicated by the black bars and deviations from the ten year mean are the gray bars where negative numbers indicate a lower than average catch. Pink catch rates decline after the earthquake with 1964 and 1965 being the lowest of the decade. The chum cohort that may have experienced excess losses due to the earthquake is that of 1964. Coho salmon in 1966 was a poor catch rate, indicating that the juvenile migrating out to sea in 1964 may have experienced high mortality rates.

Within the odd-year cohort, it is evident that there is a drastic decline in pink salmon populations immediately following the earthquake, with 1965 having the smallest catch of the decade (118). This appears to be an anomaly within the ten years, implying that runs with such low levels occur infrequently. This excessive amount of mortality however, is not carried through to the offspring cohort of 1967 as seen by the above average catch of 1,951 salmon. If there was an excess of fry mortality of the 1963 spawners due to the earthquake, it is possible that the habitat may have recovered in the two-year period, which could explain this apparent quick recovery of the population.

Chum salmon reach maturity in approximately 4 years, at which point they return to spawn. The graph for chum salmon shows there are poor catch values for several years within this 10-year window of which the 1964/69 runs appear to be the lowest (Figure 4.6). The 1960 parent run was considerably stronger with 317 salmon than the 1964 cohort (62) and slightly lower than the 1968 run (403). This decline may be attributed to excess mortality occurring along the coast from the tsunami waves at the time salmon would have been in the area preparing for spawning. The 1963 cohort (194) did not experience excess mortality however, as the 1967 returns are approximately four times stronger (483).

Coho salmon show a decline in population size in 1965 and 1969 (Figure 4.6). These two years are the weakest runs between 1960 and 1970. The odd year cohorts (1961, 1965, and 1969) were consistently the weaker runs. The varied life history of coho dictate that they spend anywhere from 1-5 years in freshwater before heading out to sea followed by an average of 18 months at sea before returning to spawn. Therefore the decline in the 1966 returns could reflect an increased mortality of the salmon on the migration out to sea during the spring of 1964 due to habitat changes or streams running dry.

Chinook and sockeye appear to have stable runs throughout this time period (Appendix C2). Since 1963 the Copper River district office has collected escapement data for sockeye salmon in both the lower and upper delta reaches of the watershed. Analysis of these data show that the upper reaches of Copper River had low spawning numbers in 1964 with a larger return in 1965 (Figure 4.7). In the fisheries reports for 1964, it was noted that spawning escapement was about one-half of the last four years average and the poorest in the previous 5 years (Alaska Department of Fish and Game, 1964a). The 4 years between 1966-1969 had low returns except for the two years of strong runs in 1965 and 1970. On the other hand, the delta portion of the watershed shows weak escapement numbers in 1967 and 1968. These years were attributed to the reported difficulties with in-stream counting due to weather extremes (ibid.). Therefore it appears that the earthquake did not cause a sufficient increase in mortality to affect population levels.

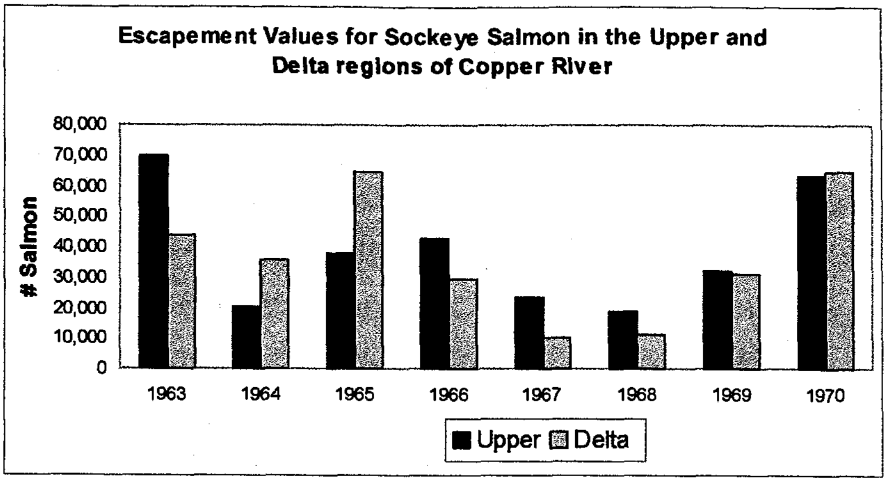

Figure 4.7 Analysis of the escapement data for sockeye shows the upper reaches of Copper River had low spawning numbers in 1964 with a larger return in 1965. There are declines in escapement numbers for both upper and delta portions of the watershed in 1964. In the upper reaches of the watershed the 4 years between 1966-1969 had low returns. On the other hand, the delta portion of the watershed shows weak escapement numbers in 1967 and 1968.

Shellfish

Clam harvests in Cordova Bay consisted of razor clams and was concentrated in Orca Inlet and the Copper River delta. The graph shows the drastic economic decline of the industry in the 1960's due to changing market demand. However, this does not imply that the earthquake of March 27 that caused entire razor clam areas to be lifted about 6.5 feet (Alaska Department of Fish and Game, 1964b) did not have an effect on populations. The coseismic uplift put roughly 25% of the Copper River Delta razor clam beds above the level at which the clams can survive (ibid.). It was also reported that the loss of habitat benefited harvesters, as there were more exposed clam beds. This was reflected in the slightly better commercial harvest in 1964 than in 1963. The 1965 shellfish report commented that the lower than average density of clams on the beaches, as well as the extremely low harvest value, was partially attributable to biological factors (Alaska Department of Fish and Game, 1964b). This loss of habitat resulted in "record low harvests in the 1970's and early 1980s and caused a shift in clam digging effort to the east side of the Copper River delta and Controller Bay area" (Berceli and Brannian, 2000).

Extensive uplift in this area likely led to the harvesting of a greater proportion of the population than normal, possibly contributing to the decline of the population and the fishery. The decline in razor clam harvest in Orca Bay and western Copper River delta was attributable to a change in substrate caused by alteration in the Copper River outflow which severely affected juvenile survival. The 1964 earthquake also caused significant uplift in prime razor clam habitat in Orca Inlet. Currently there are no areas within Prince William Sound that are certified for commercial clam harvest.

There was a reported mortality of Dungeness crab in the Copper River-Bering River delta area due to the earthquake (Alaska Department of Fish and Game, 1965). However, the commercial catch was not affected, indicating no significant mortality compared to pre-1964 levels.

Cook Inlet

Upper Cook Inlet shows little earthquake impact in the catch data (Appendix C3). There is a definite alternating strong/weak run pattern seen in the total salmon catch data (a reflection of the dominate pink and coho fisheries). Pink commercial catch shows a slight decline in the even-year stock with 1966 and 1968 having lower values (2,006 and 2,277 respectively) than the 1964 parent stock (3,232). The odd years are consistently low; indicating it is the weaker of the two stocks. Since this run is small, it is difficult to discern impacts from the earthquake.

Chum salmon catch levels do not indicate any ill effects from the earthquake as the 1964 cohort continues to be strong in the following 1968 run. The 1965 run is a weaker cohort and remains so with no further decline occurring post-1964. Chinook catches are generally lower after 1964 compared to the previous 4 years. Whether or not any decline in the populations is attributable to the earthquake is difficult to discern.

Lower Cook Inlet also shows a decline in pink salmon catch values for the 1964 stock, with a small increase in 1970. With the size of the 1962 parent stock being so large (2,248,341), the size of the 1964 (1,053,417) and following years is surprisingly small ($\leq$ 579,240), although pink stocks are highly variable. The chum catch of 1968 (75,134) was a great deal lower than its 1964 parent stock (323,335). Coho also declines in the 1964 returns in 1970, although it is still an average catch value for this 10-year period. Chinook has variable catch sizes throughout the decade, although 1965 appears to be the lowest year. Sockeye is very low throughout the decade, with the exception of 1968 and 1969 (Appendix C4).

Shellfish

Razor clam harvests in Upper Cook Inlet declined drastically in 1963 for economic reasons (Appendix C5). During the 1960's, clams were primarily used as Dungeness crab bait, but there is an increase in catch levels in the 1970's when there was demand from Washington and Oregon for human consumption. A large decline in density was noticed when the razor clam harvest was renewed. This could be attributed to the loss of clam beds in Cook Inlet due to uplift and/or damage from tsunami waves. The high mortality in the 1960's would be noticed in the 1970's, as that is when the juveniles would have been mature for harvest. The increased mortality of juveniles in 1964, as well as the over harvest that may have occurred in exposed beaches, lead to there being fewer adults in the 1970s (Alaskan Department of Fish and Game, 1965).

Kodiak Island

Catch data for the salmon industry are inconsistent and incomplete; therefore analysis was not possible for this study. Kodiak Island razor clams declined in harvests due to the 1964 earthquake, taking six years for populations to re-establish themselves, albeit at a diminished density (Westward Region Shellfish Management Staff, 2000) (Appendix C5). Clam digging has never become re-established and the fishery has been strictly for the use in the Dungeness crab fishery (ibid.).

Dungeness crab populations declined in 1965 and reached one of lowest numbers for that decade in 1966 (Figure 4.7). This species of crab require approximately two to three years to mature, hence if there was an excess mortality of crab larvae in the spring of 1964 this could explain this dip in population numbers. Tsunami waves would not have caused excess mortality directly, but rather would have carried the planktonic larvae away from suitable habitat (e.g. deeper waters or onto shore). The destruction of estuarine habitats would also decrease the likelihood of larvae settling in suitable habitat.

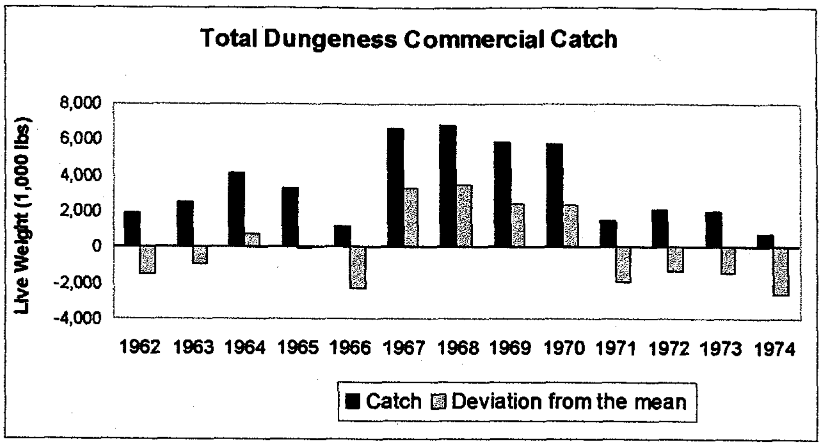

Figure 4.8 Commercial catch rates for 1962 - 1974 from the Kodiak district. Catch values are measured by live weight. The black bars indicate the catch rate and the gray bars are the deviation from the ten year mean. Negative values occur in years where the catch rate was below the mean. Catch rates declined for two years following the earthquake, possibly as a result of the tsunami waves carrying larvae into unsuitable habitat.

SUMMARY

Many of the fish and shellfish populations were affected by the mega-earthquake. Table 4.2 is a summary of the fisheries by region, indicating the qualitative amount of effect this event had on the populations. In many instances catch rates for the year of the earthquake (1964) were lower than average. This might indicate that there were mortalities due to wave action from the tsunami suddenly carrying fish from depth to the surface, resulting in fish bladders being ruptured. Stream mortality of salmon eggs and fry would be reflected in subsequent years. For instance, the pink salmon fry that were in streams at the time of the earthquake would have been from the 1963 parent stock. Therefore, declines in populations were reflected in the 1965 runs. The adult salmon returning to spawn in 1964 would have been faced with habitat changes and negative effects would be evident in later years. In this instance, excess mortality would be due to spawning occurring in marginal habitats. If the habitat did not re-establish itself (resulting in a net loss) then it is possible that the 1965 return would have been unable to spawn successfully. Species such as coho may have experienced difficulties during their seaward migration in 1964 due to changes in local hydrology and habitat. Pink and chum were the salmon species that had evidence of declines in the 10-year period examined that could be attributed to the earthquake.

Table 4.2 This summary table qualitatively shows, by region, the amount of effect the mega-earthquake had on each of the fisheries. Severe effects indicates those species that were reported to have experienced a great deal of habitat loss and/or mortalities and these effects were reflected in the fisheries data either by a substantial decline or by several year. If any effects were report and were minimally reflected in the fisheries data or the effects were only seen for a year or two, then it was considered to be moderate. Effects that were briefly mentioned in reports but not seen in the fisheries data was slight. No detectable change indicates populations that showed no declines in the data and were no significant effects were mentioned in the reports. For some regions, such as Kodiak, there was minimal fisheries data and that is indicated.

	Fishery	Region: P.W.S.	Cordova	U. Cook Inlet	L. Cook Inlet	Kodiak
Salmon	Pink	***	***	**	**	nd
Salmon	Chum	***	***	~	***	nd
Salmon	Chinook	~	~	~	*	nd
Salmon	Coho	***	**	~	*	nd
Salmon	Sockeye	~	~	~	~	nd
	Crab	**	*	*	**	**
	Clams	**	***	*	*	***

*** severe effects
** moderate effects
* slight effects
~ no detectable change
nd no data

If habitats were able to recover and reach a state of stability soon after the earthquake, then stocks would have a high survival rate of their spawned eggs and fry, showing minimal or no evidence of seismically induced mortality. However, for those species that are more sensitive to habitat changes would have shown a decline in population, as evident in the catch and escapement data. For instance, pink and chum species utilise the intertidal zones and river mouths and hence experience and must adapt to the greatest amount of habitat modification. These two species are highly sensitive to habitat changes and are unable to easily overcome barriers and therefore were the most affected by the 1964 mega-earthquake.

Clams also had difficulty recovering from mortalities because of their protracted development to sexual maturity. Populations in areas that had undergone subsidence were able to re-establish themselves, albeit at a lower density. Populations in uplifted areas, however, were unable to recover as they were under intense environmental stress as well as increased predation. There were many areas that suffered burial by tsunami deposition or scouring as the waves exposed clam beds. In areas where there was not complete removal of the intertidal substrate there were partial recoveries of shellfish populations. Recovery typically occurred only in areas where shellfish were still in sufficient numbers to allow for spawning and had suitable sediments on which to settle.

This chapter examines key information to gain an understanding of the physical and biological changes that may occur in northern Cascadia when the next mega-earthquake occurs. With similar oceanographic, geophysical, and biological characteristics it is not unreasonable to assume that similar outcomes will occur here as in Prince William Sound.

Knowing the potential effects this may have on the fisheries the next topic that needs to be addressed is the local awareness among those who rely on the fisheries. Those who are dependent upon the fisheries and live on the coast need to be aware of the potential outcomes of a mega-earthquake, as it may affect not only the local biodiversity but also their livelihoods.

CHAPTER 5

SEISMIC RISK PERCEPTION ON WCVI

INTRODUCTION

As the previous chapters indicate, the tectonic and biological attributes of WCVI are fairly well known. It has also been shown that a mega-earthquake has a great effect on coastal habitats and the organisms. This chapter describes the survey procedure, discusses the responses and compares stakeholder perceptions with "reality" (based upon the Alaskan earthquake of 1964). The surveys were designed to investigate the state of awareness among the managers/biologists who are responsible for running the fisheries, the fishermen and the aquaculturists who exploit these resources. These findings will be useful in the development of contingency plans to prepare stakeholders for the next mega-earthquake.

People in the west coast fishing industry have two main sources of risk. The first are those associated with fishing. There are the risks of being out on the water and potentially being caught in storms or something going wrong with the boat or equipment. There is always the risk of not finding and catching the fish. And even if the fishing is successful, there are risks associated with variations in demand and potentially not getting enough income to pay the bills. These risks are environmental (e.g. climate change) and economic (e.g. market demand) in nature and are numerous due to the lack of knowledge about the state or processes of nature. These risks are then compounded with the continued exploitation of stocks (Francis and Shotton, 1997; Geiger and Gharrett, 1997).

A second type of risk is physical and arises from the geophysical aspects of living along the Cascadia subduction zone. In these cases, the risk of the hazard occurring is substantially less but it is also sudden without warning. The damage to the human-made environment from a mega-earthquake is drastic and is not preventable. The risks of a mega-earthquake to the fisheries' stakeholders may be mitigated; it can be minimised or compounded depending on community knowledge. With knowledge about seismic effects perhaps the negative impacts to the fisheries, and therefore the stakeholders, can be kept to a minimum.

In this context there is an increasing probability of a Cascadia mega-earthquake occurring and, because the WCVI is a populated area with a significant amount of maritime activities and resource wealth there is significant risk of exposure. This chapter aims to assess the stakeholders' knowledge of the risks a mega-earthquake may have on the fisheries, and hence the risks to the stakeholders' wealth and livelihood. This will complete the risk assessment procedure that was outlined in Chapter 1. The previous chapters identified the hazards, estimated the potential of the hazard occurring as well as identified where the greatest risks would be (the habitats and the fisheries). This chapter will examine the social awareness of these risks and discuss their importance.

SURVEYS

Information on stakeholders' knowledge, awareness and understanding of Cascadia earthquakes was gathered by means of a mail-in or electronic survey (see Appendix for complete survey). Managers/biologists, fishers and aquaculturists from the WCVI were asked to participate in a 20-minute survey. Individuals were contacted in June - October of 2002 through E-mail requests, by word of mouth, personal contact at the work place/on the docks, by posters displayed in coastal villages, through newspaper articles as well as by advertisements placed in the local fishing magazines. Individuals were directed to where in town they could pick up a survey as well as being provided with the website should they prefer to complete the online version. Although all the surveys were generally the same, slight variations were made to the open-ended portion of the survey to correspond to each of the aforementioned groups. The survey was broken down into several sections that assessed respondent's knowledge about the size and frequency of a large earthquake, the amount of physical damage that could occur, how this might affect the fish or shellfish populations, and, finally, their preparedness.

Section 1 was the same for everyone and was aimed at defining what was thought of as "the big" earthquake. Through the use of the Modified Mercalli Index (MMI) and a map, participants were asked to describe their vision of "the big" earthquake. Questions were asked such as how long the shaking might last, the spatial extent along the Pacific Northwest that would experience some damage from the earthquake and, most specifically, which areas on Vancouver Island would suffer severe damage. Following these questions, the survey inquired about the historical frequency of big earthquakes in the region. This indicated their perception of when the next big earthquake will occur.

Section 2 was aimed at gaining an understanding of the physical changes that might occur in the area as a consequence of a "big" earthquake. Questions were geared to assess how much uplift and subsidence they thought might occur and how this habitat deformation might be reflected in mortality rates of the fish/shellfish. There were also questions that addressed the extent of tsunami inundation and the potential for subsequent resource mortality.

The final sections were open-ended questions tailored for each of the occupational categories. Managers were asked what effects this type of event might have on the coastal organisms such as salmon and shellfish, and if catch limits would have to be adjusted. Specifically, questions related to the existence of management contingency plans should a large earthquake and tsunami adversely affect certain species. Fishers were also asked about the effects on the biota; they were also asked if they would be willing to lessen their catch limits, following such an event. They too were asked if they had any contingency plans (such as insurance coverage) in the event of a big earthquake. Aquaculturists answered questions concerning what they thought might happen to their stocks and facilities should such a seismic event occur. And again, they too were asked if they had insurance or a back-up plan in such an emergency.

Although there were approximately 40 hits on the website and 100 hard copies of the surveys distributed, the number of respondents was small. Only two aquaculturists (one salmon and one shellfish), four fishers and twelve managers completed questionnaires. There were a couple of reasons for such a low response rate. The most common reason was evidenced by the initial reaction to the survey. Most people were apathetic, showing no concerns regarding the occurrence of large earthquakes or the effects of one and often scoffed at the subject matter. Many fisherman were not very interested in the consequences and had a laid-back perspective with a "take it as it comes" attitude. Some of the aquaculture companies were defensive and hesitant to speak with any outsider, especially a researcher.

The second possible reason for the lack of responses may be due to the time of year the surveys were distributed. During the summer and early fall most of the people involved with the various fisheries are either fishing or out in the field. This is followed by a period of time when biologists and managers are catching up on paperwork, writing reports. Few fishermen are down on the docks, which results in a lack of interest to take the time to answer the survey and difficulty in making more than a few personal contacts. Aquaculturists were difficult to get a hold of, as most facilities are generally located offshore. Regardless of their isolation, they were leery of the enterprise, being very apprehensive of researcher intentions. Most did not want to talk at all and were very quick to end any phone or face-to-face conversation.

SURVEY RESULTS

The majority of respondents thought that the earthquake would shake for 30-60 seconds and would measure IX on the MMI. This MMI category is described as having "damage that is considerable in specially designed structures and well-designed frame structures are thrown out of plumb. Damage would be great in substantial buildings, with partial collapse. Buildings would be shifted off foundations". These views likely underestimate the duration and amount of ground motion that will occur in the next Cascadia earthquake. In 1964 in southern Alaska, shaking lasted 4 minutes (excluding aftershocks)(see chapter 3) (Hansen, 1966) and damage was estimated to be XI or XII on the MMI scale. Only three respondents said that shaking would last >120 seconds.

The next question asked respondents to map the spatial extent of moderate damage. Figure 5.1 shows the percentage of respondents who thought certain areas were to feel the effects of a mega-earthquake on Cascadia. This too can be considered as being underestimated. Many respondents highlighted only the coastal areas, believing that the damaging effects of the earthquake would not extend inland farther than 200 km and would only affect the areas directly east of the subduction zone (areas 18, 19, 21, 22, 24, 25, 27). Focusing on Vancouver Island, many thought the whole island would be moderately affected. Of those respondents that did not highlight the whole island, the Nootka, Clayoquot and Barkley Sounds (areas J, M, P, and S) areas were considered most at risk.

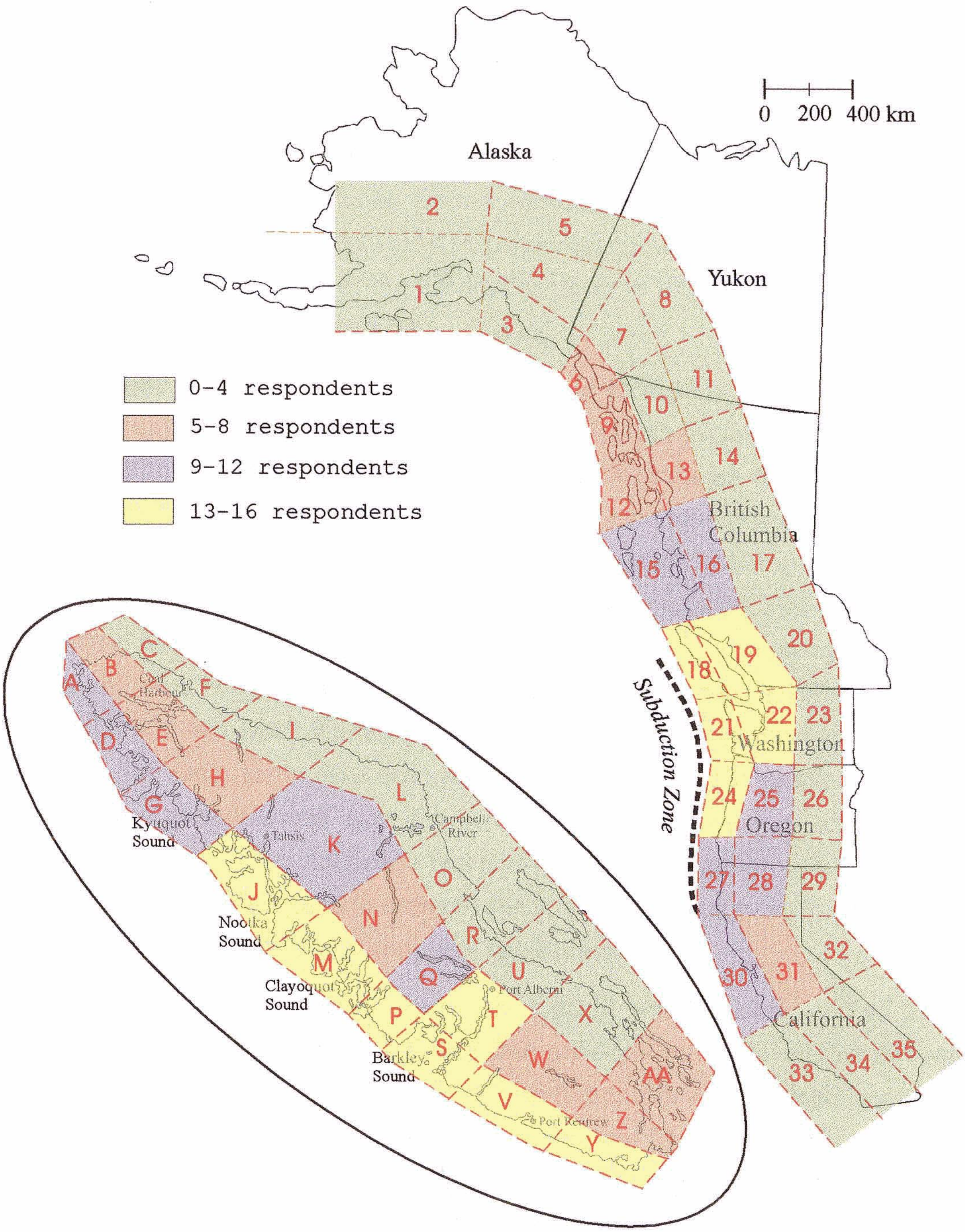

Figure 5.1 Areas within the Pacific Northwest are shaded according to the number of respondents that believe will be moderately affected should the entire Cascadia subduction zone rupture. The inset indicates the areas on Vancouver Island that respondents believe will experience damage.

Comparing this to Alaska, this again underestimates the spatial extent of the damage. In Alaska ground deformation extended as far as 300 km, from the convergent margin. However, if measured from the northeast tip of the fault to the farthest extent, there was land deformation close to 400 km inland. As seen in chapter 4 and Figure 4.1, deformation was not restricted to areas adjacent to the fault. This would imply that ground motion from a Cascadia rupture would cause damage to infrastructure further inland than most respondents believed. As well, it is not possible for areas that are adjacent to the subduction zone to experience moderate to high damage without peripheral areas being affected.

When asked to estimate when the last big earthquake occurred, the answers varied. Four of the eighteen believed the last earthquake occurred less than 50 years ago. These respondents might have underestimated the strength of the earthquake that would occur should the entire Cascadia subduction zone rupture and are referring to a smaller, more recent event (possibly the 1946 Vancouver Island event that was M_w 7.3). Another four said the last large earthquake occurred 300-400 years ago, coinciding with the AD 1700 earthquake. The remaining responses were equally distributed, with two respondents for each of the remaining choices (50-100, 100-200, 200-300, >500 and Don't Know). These last respondents may have simply guessed when the last large earthquake occurred knowing that it occurred over a generation ago. These mixed results regarding when the last earthquake occurred are not surprising since there has not been a recent event. There would be a greater chance of the majority of the population to correctly identifying the latest event if it had occurred within a time period of the past couple of generations.

The next question asked what they thought was the likelihood of a mega-earthquake occurring within given future time periods. Half believed that an event in the next 25 years was a distinct possibility, with five of those respondents saying it was likely or most likely. Six respondents believed it was likely or most likely to occur within the next 50 years, and eight thought it might be possible. There were eight respondents who believed that it is likely or most likely to occur within the next 100 years, while five thought it was possible. Most respondents said it was likely or most likely for such an event to occur in the next 500 years (Table 5.1). This indicates that the majority of respondents realise that a big earthquake can occur in the near future and in as little time as the next 50 years. It is estimated that there is a 9 to 25% (90% confidence interval: 2-57%) likelihood of a great earthquake (M_w >8) occurring at Cascadia within the next 50 years (Stein, *et al.*, 2001).

Table 5.1 Estimated probabilities of a mega-earthquake occurring in various time periods. Most respondents believe it is possible, likely or most likely for such an event to occur within the next 50 years.

Timing of next Earthquake	Probability of Occurance					
	Most Likely	Likely	Possible	Unlikely	Least Likely	Don't Know
less than 25 years	1	4	9	1	1	2
less than 50 years	2	4	8	1	1	0
less than 100 years	4	4	5	1	1	1
less than 500 years	9	4	2	0	0	1

The next question concerned the amount of uplift and subsidence resulting from a mega-earthquake. The majority of respondents thought the extreme amount of uplift and subsidence (4 and >5 m) is unlikely or least likely. There were two that believed 5 m of uplift is possible and four who believed 5 m of subsidence is possible. Only two respondents said that 4 m of uplift is possible, likely or most likely and four believed 4 m of subsidence is possible. There are nine who believed that 3 m of uplift is possible, likely or most likely and ten who believed 3 m of subsidence is at least possible. The majority (twelve respondents) believed that 2 m of uplift is possible, likely or most likely as is 2 m of subsidence. Uplift of 1 meter is believed to be possible, likely or most likely by fourteen respondents, with thirteen believing it is possible, likely or most likely for subsidence of 1 meter to occur. There were only five who believed no land deformation was possible, likely or most likely (Table 5.2). These results are in keeping with the Alaskan experience in that Alaska on average experienced 2 m of land deformation. However, people may be underestimating the maximum amount of vertical deformation that could occur.

Table 5.2 Estimated probabilities of various amounts of land deformations as a result of a mega-earthquake. Most respondents said no vertical change was Unlikely and that 1-3 metres was Possible, Likely or Most Likely.

Land Deformation (meters)	Probability of Occurance					
	Most Likely	**Likely**	**Possible**	**Unlikely**	**Least Likely**	**Don't Know**
uplift >5	0	0	2	4	7	2
uplift 4	0	1	1	8	3	2
uplift 3	1	2	6	5	2	0
uplift 2	2	3	7	2	2	0
uplift 1	4	7	3	0	1	1
0 (no change)	0	2	3	6	1	4
drop 1	7	4	2	1	1	1
drop 2	3	3	6	2	1	1
drop 3	1	1	8	4	1	0
drop 4	1	0	3	7	2	2
drop >5	0	0	4	4	5	2

Fifteen respondents believed deformation of 2 m of uplift could result in either moderate or high mortality among salmon and/or shellfish populations. There are also fifteen respondents who believed 2 m of subsidence could result in either moderate or high mortality among these populations. There are only two who switch their answers between these two questions. The first said there would be minimum effect with 2 m uplift but moderate effects if there were 2 m subsidence. The second person is a representative of an aquaculture company, and said the exact opposite. These responses suggest that participants realise such habitat changes can have an impact on coastal resources. However, they do not necessarily take the extremes, as seriously as perhaps they should. The results indicate that the respondents underestimate the size of the earthquake, the spatial extent of potential deformation, and the risks that heavy habitat deformation may have on the resources.

The survey also attempted to assess what respondents knew about tsunamis. Responses were mixed. The time estimates for the tsunami waves to reach the west coast varied from "less than 30 minutes" to "more than a day" with only one person answering she/he did not know. There were seven that answered it would take less than 30 minutes and five said 30 minutes to an hour. This is a realistic estimation as Alaska experienced its first tsunami wave approximately 20-45 minutes after the earthquake began (Lander, 1996). It is estimated for Cascadia that wave heights of 10-15 m will arrive in 5-45 minutes after the earthquake (Ng, *et al.*, 1990; Myers, 2001).

There were 11 respondents who said there could be >10 m run-up from the tsunami; four said 5-10 and three said <5 m. From the records, in the Gulf of Alaska the tsunami inundated as much as 25 m and as little as a half meter above the mean high-high water line (Lander, 1996). It should be noted that the earthquake and hence the tsunami occurred during low tide; the reported waves could have reached farther inland had it occurred at high tide. The largest tsunami waves were actually a result of locally generated submarine landslide. These tsunami waves arrived minutes after the initial shaking, causing most of the damage.

When asked about the potential damage a tsunami could inflict upon salmon and shellfish populations, five said it could be high, nine said moderate, three said minimum and one person said she/he did not know. However, as seen from Alaska, tsunami waves could do enough destruction as to result in mortality of entire clam beds. Alaska also experienced varying degrees of damage to spawning beds, with some areas experiencing complete mortality of salmon fry. Even BC experienced fish mortality from the Alaskan tsunami. A field report from March 28th, 1964 by the Tahsis region fisheries officer stated there were "{s}everal thousand bottom fish killed at Tahsis Narrows by tidal surge of March 27th-28th" (DFO weekly report - I'm not sure how to reference this). It is also important to note that the Cascadian coastline has previously experienced loss of resources as a result of a mega-earthquake. The inferred abandonment of Native villages in Nootka, Clayoquot and Barkley Sounds following the 1700 AD earthquake may have been due to the possibility that tsunamis damaged salmon and shellfish resources (Hutchinson and McMillan, 1997).

When asked if respondents had previously considered the effects a mega-earthquake and tsunami might have on littoral populations, only two respondents said yes. One was a fisherman; he claimed however, that it was not a large concern for him but rather a theoretical interest or curiosity. It is interesting to note that this person had realistic perceptions regarding the size of a mega-earthquake and the possible land deformation. This fisherman was also the only person to have of a plan of sorts in the event of a large earthquake: to take his boat out to sea at the time of the earthquake. The other was a representative from an aquaculture company that was genuinely concerned about engineering and insurance implications. However, no insurance or plan was in place for this company should a seismic event occur.

Managers/Biologists were asked if harvest levels would remain unchanged after a large earthquake and tsunami; everyone said no. They explained that assessment of the impact would have to occur and then harvest levels should reflect the findings. Five of the twelve managers estimated that shellfish mortality could be extensive due to either uplift causing desiccation or by subsidence due to increased predation. Two managers said that harvesting should be stopped or greatly diminished until/while assessments are undertaken. One manager remarked that in conjunction with the necessary time for a damage assessment to be done, harvest levels would have to be taken into consideration throughout a recovery time. Another manager recognised the difficulties with obtaining a complete "before and after" picture of stocks, especially shellfish. One manager was aware of the secondary hazards such as landslides and logjams that could effectively "wipe out years of population cohorts in salmon/trout wild stocks".

Fishermen were asked if they had contingency plans should harvest levels be changed. They replied saying no, that they would rely on government assistance or their savings if they were unable to fish. This indicates they believe any changes to their allowable catch would be short-term, lasting perhaps one year. Aquaculturists were asked if they have any insurance coverage for this type of hazard and what their emergency plans would be. They were worried about the ability of their facilities to withstand damages, although they had no contingency plans or insurance coverage. One of the aquaculturists believed that floating and submerged rafts would suffer minimal damage if the company used systems of adequate strength. However, they did not indicate if they had conducted any testing of their systems. Because seismic events of this size have not happened in recent history, it is not surprising that this is not a prime concern.

The survey also sought opinions as to when the most and least amount of damage would occur. A recurring answer was that an event in fall and winter would have the greatest potential for damaging effects on salmon populations. The fall season was of concern because that is when adult salmon are typically returning to spawn. Habitat changes would prevent spawning from occurring or would diminish spawning success. On the other hand, winter would be a concern with regard to the survival of eggs and fry. There could be increased mortality of this life stage due to land deformation, flooding or sedimentation.

Early to mid summer were times respondents perceived that there would have the least impact on the stocks. This is the season when there are no fry in the rivers (either migrated down to the ocean or are in fresh water), mature fish are typically out at sea and streams are at their lowest flows so flooding wouldn't have as much of an impact. It was also pointed out that if an earthquake occurs in the summer there would be a greater amount of time for the habitat to settle out and re-establish itself before major spawning runs occur in late fall and early spring.

For shellfish, anytime was considered to be a concern, as land deformation would lead to increased mortality regardless of season. However, three respondents noted that spring/summer would be of greatest concern, as it would disrupt their spawning success and juvenile settlement.

For aquaculture, summer and fall were considered to be the most damaging time as there is a high potential of losses when the seed (shellfish) are still small. For finfish the biggest worry would be when tides are highest, as this would create larger tsunami run-ups. They were more concerned with tsunami waves occurring in conjunction with diurnal high tides and seasonal spring tides, fearing that these would exacerbate wave height and energy.

Respondents consistently underestimated the size/magnitude of the potential earthquake. They understood that some land deformation would occur but not necessarily how much. When respondents reached the opened ended questions they were somewhat better prepared to answer them in that they came to the realisation that changes to the land by a mega-earthquake might have an effect on the biota. Once participants thought about the potential effects, they came to the realisation that harvest levels would have to be addressed, as would aquaculture escapes.

At present, the method of dealing with such an event would be one of reaction, with no precautionary approach indicated through the development of a contingency plan. The stakeholders at present have a crisis management method of dealing with problems that could arise in such a situation. With respect to risk assessment step three, it can be said that the community of WCVI may have the knowledge to imagine the outcomes of a mega-earthquake on the fisheries. However, as of yet, they have largely chosen to ignore it and underestimate the probability of a mega-earthquake even occurring.

Although the survey results, per se, did not call attention to the topography of the coast, it is important to recall the discussion in Chapter Two regarding the unique characteristics of the WCVI fjords, which would likely amplify the effects of the tsunami. As modelled by Ng, et al. (1990) and Whitmore (Whitmore, 1993), tsunami waves produced from a Cascadia earthquake would have run up heights of 5 m and reach shore about 15 minutes after the generative event. These waves will be further amplified to a height of up to 15 m due to the natural resonance of BC fjords (Ng, *et al.*, 1990).

SUMMARY AND DISCUSSION

The survey indicates that although individuals were generally aware of hazard of a mega-earthquake, they underestimated its magnitude. The significance of these results, as well as the lack of completed surveys, is the propensity of individuals or households to ignore hazards that occur infrequently. None of the respondents had fully realised the risks to the fisheries associated with a mega-earthquake. However, when asked, they were able to identify critical or riskier time periods for an earthquake to occur. Looking to the Alaskan experience, it is evident that there was a recovery for most of the affected populations: there are strong fisheries throughout Alaska at present. Why this is, could be due to a number of reasons: strong populations prior to the earthquake or perhaps favourable oceanic and coastal conditions encouraged population recovery.

However it is important to note some of the differences between Alaska and WCVI. First, Alaska had no threat of declining stocks. WCVI on the other hand has a number of salmon stocks at risk of endangerment or which are at critical status. This may mean that BC populations are more vulnerable to disturbances than were the Alaskan populations. Therefore, even though there were no catastrophic population losses experienced in Alaska, it does not guarantee there won't be along the WCVI.

A second important difference is that BC supports an aquaculture industry, whereas Alaska never has. This is a major and growing economy on BC's coast and should not be ignored. Unfortunately, Alaska cannot provide the answers or any insight into what may happen to this infrastructure; however, some outcomes can be presupposed. For instance, knowing the size and strength of the tsunami waves that hit Alaska, perhaps it is not unreasonable to predict that damage will occur to fish pens. As experience has shown that naval ships can be tossed on to land, it would seem reasonable to think the same could occur to fish pens. This leads into certain questions and concerns regarding what could happen to the fish in the pens.

CHAPTER 6

IMPLICATIONS FOR WCVI

INTRODUCTION

Cascadia has experienced great earthquakes measuring M_w >8 every 200-600 years in the late Holocene. Since the last great earthquake (January 26, AD 1700), a great amount of potential energy has accumulated along the plate margin. When the next rupture occurs it will almost certainly be a M_w >8 event. Not only will there be many causalities and wide spread property damage, but disruption of coastal ecosystems will also occur.

Research conducted to date on Cascadia fisheries and Cascadia paleo-earthquakes has not yet considered the linkages between these two components of the natural environment. Fisheries research has focused on environmental and anthropogenic threats not the catastrophic threats, such as mega-earthquakes. Geological literature for the Cascadia subduction zone focused on paleo-earthquakes regarding the magnitude, spatial extent of land changes, and recurrence. This body of research is valuable when looking to the future and predicting the outcomes with respect to direct seismic impacts to humans and man-made infrastructure. This thesis however, focused on the effects the next catastrophic rupture will have on the coastal habitats and biota, which will in turn affect those people who rely on these marine resources.

Cascadia geological research indicates that earthquakes of M_w>9 have affected a great deal of the coastal region, with evidence of the AD 1700 mega-earthquake being found from Vancouver Island down to northern California. The coast is presently being shortened and raised, indicating the tectonic plates of the Cascadia subduction zone are locked and are accumulating strain. The release of this stored strain energy will lead to widespread devastation of the coastal habitats, as documented in the paleo-earthquake studies. When this occurs the altered habitats will result in changes to the corresponding biocommunities.

Habitat change due to catastrophic seismic events should be a concern for BC as many people depend upon the ability to harvest marine resources. Combined, the wild fisheries in this area are currently valued at close to $700 M with aquaculture bringing in over $300 M. With such great economic and intrinsic value placed on

BC's marine resources it is important to be prepared for a future catastrophic seismic event. Therefore, the risk analysis that was completed for the WCVI also included a survey for the stakeholders of this region.

The three main objectives of this study were to determine the physical effects of a mega-earthquake on the coast of WCVI; the biological effects on certain WCVI stocks and; the awareness among WCVI stakeholders of the risks from a mega-earthquake on the marine organisms. This chapter presents a general overview of the physical and biological effect mega-earthquake can have the WCVI. It also discusses some of the concerns and issues for the WCVI that were unable to be extracted from the Alaskan analogy (e.g. aquaculture and stock status). There will also be a review of stakeholder awareness and the issues surrounding management after an earthquake. It will then conclude with some recommendations and implications for the fisheries of WCVI after an earthquake.

ANTICIPATED PHYSICAL EFFECTS

Having examined the subduction zones in the Pacific Ocean with young oceanic plates, and the coastal biocommunities associated with each region, it was evident that Alaska was the most similar to Cascadia. Alaska provides valuable insight into the physical and biological impacts Cascadia will experience from a mega-earthquake. Alaska experienced extensive vertical deformation, occurring over 285,000 km^2 and averaging 4 meters (2 m uplift and 2 m down-dropping). The Cascadia region is geophysically and geomorphically similar to that of Alaska so WCVI can expect vast vertical deformation. Based on estimates from the 1700 Cascadia event, WCVI can expect deformation to range from 0.0-1.6 m (Hughes, *et al.*, 2002).

The amount of deposition and erosion along the coast from tsunami waves is also important to recognise. Tsunami run-up in Alaska reached a maximum of ~10 m above the high-high tide line, although this varied with shoreline morphology. For WCVI, the heads of fjords will be hardest hit. This is because most fjords on WCVI open directly to the ocean with very little protection (i.e. few islands at the mouths). Therefore these fjords act as funnels, concentrating wave energy towards the head. Another issue is the natural resonance of the fjords. Port Alberni experienced damage from the 1964 Alaskan tsunami because the natural resonance of the fjord amplified the waves. Fjords in Nootka and Clayoquot Sounds have similar bathymetry and will also experience this phenomenon (Clayoquot being the most protected of the three).

These physical forces (shaking, vertical deformation, and tsunamis) as a result of the Alaska mega-thrust earthquake caused a great deal of deformation of the coastal habitats. Habitats along WCVI will also experience this habitat degradation. Areas that are either dropped or lifted out of their ideal tidal zone will experience a change in erosion/depositional rates as well as tidal action. There will also be immediate changes in substratum because of the tsunami waves. Places like Long Beach or the Port Alberni, located at the head of a fjord, will likely experience immediate and massive erosion/deposition by tsunami waves crashing on shore.

ANTICIPATED BIOLOGICAL EFFECTS

The 1964 Alaskan analogy offers a great deal of information with respect to vertical deformation and tsunami effects upon the biota. The initial reports noted the decline in algal abundance and mortality in barnacle, salmon (adults, juveniles, fry and eggs) and clam populations (Thorsteinson, 1965; Plafker and Kachadoorian, 1969a; Haven, 1971; Johansen, 1971; Noerenberg, 1971; Thorsteinson, *et al.*, 1971; Hanna, 1971a; Hanna, 1971b). The Alaskan fisheries catch data for the Prince William Sound, Cordova Bay, Cook Inlet and Kodiak districts provide a longer-term perspective on biological changes in the affected areas. Drastic changes to the environment led to changes in the biocommunity and the fish populations. Using catch data as a measure of population size, it was evident that some natural populations were casualties of the earthquake.

Species that utilise the intertidal zones or lower reaches of streams suffered population declines (e.g. Prince William Sound pink salmon) or collapsed (e.g. Cordova Bay clams) after the earthquake. Although there were minimal data to show evidence, it is reasonable to expect that a M_W 9.2 earthquake and large tsunami would also cause increased crab mortality. Given that the WCVI is in the same oceanic region and has the same habitats and species as Alaska, it can be expected that the WCVI populations will also experience declines in the aftermath of a great earthquake.

Finfish experienced increased mortality throughout the Gulf of Alaska, by direct and indirect means. Direct mortalities resulted from fish bladders rupturing as tsunami waves suddenly brought fish to the surface (this was also reported to have occurred in Tahsis Narrows in Nootka Sound). There were great mortalities of salmon egg and fry that were in stream and clam beds from the vertical deformation of habitats. Uplifted areas raised spawning streams and clam beds out of the water, resulting in desiccation from exposure. Subsidence increased water depth causing spawning and clam beds to be flooded. Clam beds would also have been exposed to increased predation in the lower intertidal zones. Additionally, mortalities resulted from scouring by the force of the waves or burial by sediment. Many clam beds, salmon eggs and fry were simply washed away or buried.

Indirectly, fin and shellfish were affected by a loss of habitat or decreased access to habitats. Intertidal spawning areas were either uplifted out of use or down-dropped into subtidal zones, leaving either less habitat for the returning adults to utilise, less ideal habitat for spawning and juvenile rearing, or greater barricades to bypass in order to reach spawning areas. Clams had to recolonize displaced tidal zones, and these juveniles took several years to reach harvestable size. The tidal zone in which the clams would have to move into may not have had the desired substrate, leading to less successful recruitment. These effects were seen in the fisheries catch data, which means there is a direct impact on the people who rely on these marine resources.

Those salmon species, such as pink, chum and certain coho populations, that are highly dependent on coastal habitats (e.g. eelgrass beds, intertidal zones or river mouths) had continuing lower escapement numbers each year that followed the earthquake. The 1964 cohort would have had fewer adults successfully return and spawn, explaining why there were declines in the population of the cohorts following the earthquake. With high mortality of the fry spawn in 1963 during their first spring, when they are still in the gravel (emerging fry), also resulted in declines in catch rates. These cohorts would have been subject to a number of disturbances, such as shaking, drought, flood, seawater intrusion, scouring and/or burial, at a vital time of their growth cycle.

Those salmon species (e.g. sockeye, coho, and chinook) that do not utilise the intertidal and lower stream reaches for spawning would be less affected. These disturbances would only affect these species when they migrated downstream in the spring to saltwater, utilising the estuaries and intertidal zones. Their survival there would again be determined by the disturbed, shifted or lack of habitat. Those areas that experienced large vertical deformation may not have re-established by the time the juveniles arrived. This, combined with continued fishing stress, might have led to stocks being very low with poor recruitment through to the 1970's.

At present there is no commercial clam harvest in Prince William Sound. In 1964 the Copper River Delta had a bumper razor clam harvest. Unfortunately it was also the last. Due to exposure of large expanses of clam beds, harvesters were easily able to harvest the clams that were previously unattainable. The uncontrolled harvesting resulted in a collapse of the population. The following year, there was an extremely small harvest. Numerous beaches were reported to have very low density of clams. This, in conjunction with the increased natural morality due to the seismic hazards occurring in the spring, had a detrimental effect.

Clams, being broadcast spawners, have variable and poor recruitment. The Alaska clams experienced difficulties with recovery because the coseismic mortality occurred prior to spawning season (June to September). This led to there being fewer adults available for spawning in 1964, resulting in the demise of entire populations. Unfortunately, the areas that had the greatest clam harvest (Copper River and Orca Bay) also experienced the greatest vertical deformation.

Very little information is available on crab populations in Alaska following the earthquake, with only Kodiak Island having a decline in catch rates. This could be because of the time of year that the earthquake occurred. Since the earthquake occurred in the spring, prior to breeding season, the crabs were likely still in their offshore habitat. Should the earthquake have occurred between May and August, there likely would have been a greater rate of mortality as this is when the crabs breed in the inshore waters and juveniles are found in tidal and estuarine waters.

EXPECTATIONS FOR WCVI

Coastal areas of Cascadia would likely experience vertical deformation equivalent to that of Alaska and the AD1700 Cascadia events during the next great earthquake. It can be assumed that the biological effects would be equally severe. Although the coseismic effects in Alaska were substantial, they were not devastating. There was no collapse of the salmon and crab fisheries. Alaska continues to have a strong salmon fishing economy, and no stocks are currently labelled as "extinct", "at risk", "endangered", or of "special concern".

For WCVI, areas that should be of greatest concern are those in which there are declining fish populations. Along this coast there are 1200 stocks comprised of the 6 salmon species. Of these 445 are considered to be at high risk and 168 that are of moderate/special concern, according to the Nuu-chah-nulth Tribal Council (NTC) (Hall, *et al.*, 1998). The declining performance of wild fish populations is largely a result of the over-exploitation of these stocks. This situation has been exacerbated by the loss of breeding and rearing habitat as a result of the combined effects of logging in coastal watersheds, urban development, and pollution. Having fisheries that are presently at risk, of special concern or declining in numbers leaves them in great danger when a catastrophic event such as the AD 1700 mega-earthquake recurs.

BC's spring chinooks are healthy, although these stocks spawn in the upper reaches and tributaries of large river systems. They remain in freshwater for at least one year as juveniles. Hence they are larger and stronger when they reach the sea then their "fall" counterparts. The fall chinook juvenile goes to sea in the spring after hatching, spending only a few weeks in freshwater. They migrate to estuarine rearing habitats and tend to complete their ocean life relatively close to their natal streams. These stocks have an extremely high exploitation rate that is estimated at 80% of the potential spawners (Pacific Fisheries Resource Conservation Council, 1999). Over the past 20 years declines have been as much as 90% and these stocks are said to be in "very deep trouble" (ibid.).

Chum spawn in the lower reaches of BC streams. As a result, chum is particularly sensitive to large-scale habitat damage. However they are highly invasive and can quickly take advantage of new spawning opportunities which, may lead to an easier recovery/adaptation to the deformed habitat. Juveniles head out to sea in the spring following hatching. They, just like chinook, rear in estuaries before they head out to sea. Chums have highly variable returns within and between stocks. Some stocks appear to be stable whereas other appears to have declined over the past 50 years. The NTC classified the WCVI chum stocks as: 20.9% at high risk, 3.6% moderate to special concern, 0.4% extinct, 62.6% still strong and 12.5% unknown (Hall, *et al.*, 1998).

Coho, like chum, can be aggressive colonisers when favourable habitat is created or restored. They spawn in small streams, even tiny tributaries that are less than 1 m wide and 10-20 cm deep. After spending one year in freshwater they head out to sea, spending two years in waters near their natal streams. Coho have suffered severe declines since the mid 1980's. The NTC report that there are 39.2% stocks at high risk, 16.1% at moderate or special concern, none are extinct, 27.5% are in a good state and 17.2% are unknown. Under current marine survival conditions, there are some stocks that can sustain no exploitation rate whatsoever. "Many coho stocks will probably never be able to withstand the harvest rates, and habitat changes..." (Pacific Fisheries Resource Conservation Council, 1999). Knowing this, the status of coho populations should be of great concern after a mega-earthquake.

Like chum, pink salmon spawn mainly in lower reaches of coastal rivers, with juveniles heading out to sea soon after hatching. Unlike chum and chinook, pinks do not rely on estuaries. On the contrary they immediately migrate north, along the shoreline to their Alaska feeding grounds. Pinks, like chinook and chum, can also be highly invasive aggressively colonising new habitat opportunities. On the WCVI, only the even-year pinks have been seen in any numbers since the 1950s. NTC reports 75.5% stocks being at high risk, 7.4% are of moderate/special concern, 1.1% extinct with 10.1% being strong and 5.9% are unknown. They will be vulnerable to the tsunami waves and habitat changes.

Studies on Northern pink salmon show that populations respond with an effect called "depensation", where at very low spawning abundance, there can be severe depression in juvenile survival rates, apparently due to most fry being eaten by predators. "Such depensatory effects can hinder or delay recolonisation after a natural disaster or over-fishing, and also cause extinctions after even relatively short periods of over-fishing" (Pacific Fisheries Resource Conservation Council, 1999). Knowing this, a mega-earthquake could be the event that pushes populations to extinction. However, knowing that pink salmon can recover, there is hope that stocks can recover from such an event and the consequential population declines. In either case, close attention will have to be paid to these stocks.

Sockeye spend up to 2 years in freshwater and reach a healthy size prior to migrating out to sea. Hence they have a relatively high ocean survival rate. Those that rear in less productive lakes (i.e. coastal lakes on VI) go to sea when they are much smaller, lowering their marine survival rates. Most of the larger sockeye stocks have previously recovered from over-fishing and disasters (e.g. Hell's Gate). In some instances sockeye have recolonised spawning areas that were barren of fish as much as 80 years ago (Pacific Fisheries Resource Conservation Council, 1999). At present, with almost 39% of the WCVI stocks being of high concern and another 14.5% classified as special concern (Hall, *et al.*, 1998), precautions will have to be taken following a Cascadia rupture.

To know the effects, both physical and biological, a mega-earthquake could have on WCVI is important. This is especially true for WCVI specifically, as opposed to Alaska, because of the status of many of the species. The stakeholders are the most important people who need and should have this knowledge. There also needs to be a realisation of the risks associated with continued harvesting proceeding a mega-earthquake. Many of the salmon stocks along the WCVI most likely would not survive if during the initial period after the mega-earthquake (the recovery years) they were fished with the same intensity as they are prior. However, with awareness there is substantially greater probability of stakeholders to react in a sound and responsible manner; one which is beneficial for the maintenance of stocks and the sustainability of the fisheries.

PERCEPTION OF THE RISKS

It is often assumed that the individuals have relatively complete knowledge of the occurrence and consequences of local hazards (White, 1994). From this study it is evident that people engaged in the coastal economy on WCVI underestimate the magnitude of the hazard. It is also apparent that prior to this study it was not a consideration. This is interesting because how people perceive a hazard depends on the information available to the individual, their personal experience and the physical nature of the event as well as the perceived economic gain/losses (ibid.). The unrealistic perception among those who participated in this survey was not surprising considering no one had previously experienced a mega-earthquake.

The respondents' lack of awareness is reflected in their lack of preparedness. Patterns of response to natural hazards are a function of the hazard's frequency, magnitude, suddenness of onset and the ecological setting (Kates, 1994). It was not surprising to have no respondents with a contingency plan, in large part because mega-earthquakes occur infrequently. In consequence, stakeholders have very little knowledge regarding the hazard itself or its effects upon the resources from which they obtain their livelihood. According to Kates (1994), however, there should be some response pattern (plan of action) as the hazard cannot be predicted, has a quick onset and has an intrinsic tie to the physical and biological setting in which they live.

The discrepancy between theory and reality, in this situation, was revealed by the attitudes of the various stakeholders. There was a divide in attitudes between the managers and the fishers after completing the surveys. The managers were concerned about the issues raised by the survey, whereas the fishers remained largely indifferent. Variation in perception of a specific natural hazard (expectation of future occurrence and of personal vulnerability) can be accounted for by a combination of three factors. Firstly, by the way in which characteristics of the natural event are perceived, secondly, by the nature of personal encounters with the hazard and thirdly by individual personality (Kates, 1994).

In this study, the natural event is perceived by fishers as something that they cannot control and therefore is not a concern. The personality of the fishers can be generalised as being relaxed and laid-back, and only a few people have memories of the 1964 Alaskan event. They work in a field that is unpredictable and highly variable and have adjusted to sudden changes in fortune (i.e. years with poor runs).

Managers and scientists, on the other hand, considered that they could control what happens in the earthquake's aftermath. They were better able than the fishers to assess the physical and biological after effects. This could be due in part to their academic training and the fact that they are in positions that require them to foresee and solve problems.

It is difficult to make statements regarding aquaculturists, as there were few who were willing to partake in discussions or the survey. However, one manager of a salmon aquaculture plant was interested to learn more about this hazard and was concerned about any potential impacts upon the company. After the survey, he perceived a mega-earthquake to be a threat even though he had never experienced one. The shellfish aquaculturist showed a different attitude. This person did not perceived a mega-earthquake as a major threat, believing that the floats and rafts would be fine if strong enough lines were used.

Of the many possible characteristics of natural events, the perception of magnitude, duration, frequency and temporal spacing of the natural event appears to be most significant. For personal experience it is the frequency, intensity and how recent such an experience is that appears most critical when individuals generate their interpretations and expectations of a hazard (Kates, 1994). With hazards that have a minimum probability of occurring, people are less likely to make any adjustments for the hazard (Kates, 1994; Mileti, 1994). This explains why mega-earthquakes were never before thought about and why there are no contingency plans amongst any of the stakeholders.

The increased emergency preparedness, or the capacity of a social system to respond to disaster, refers to adjustment policies that reduce or redistribute the cost of anguish of recovery after a disaster. Adjustments that enhance the emergency preparedness for this particular hazard would include insurance, savings and warning systems. There is little that can be done as a means of reducing the amount of the losses prior to the occurrence of a mega-earthquake. In this situation, reduction of losses will be entirely up to post-earthquake management. Disasters are averted or lessened by adaptation and implementation of policies to mitigate risk and negative effects of environmental extremes (Mileti, 1994).

Earthquakes can't be prevented, they can't (as of yet) be predicted, and their magnitude, frequency and spatial extent can't be controlled. Changing our use of the environment won't affect the earthquake in any way either, although it might affect the amount of damage. Therefore, the most common adjustment to such a hazard is to bear the losses when they occur. However, post-emergency planning can help control or minimise the losses. It is important to know the potential negative effects and be able to act in a manner that will not exacerbate the loss of species.

RECOMMENDATIONS AND IMPLICATIONS

With a-priori knowledge of the effects a mega-earthquake will have on WCVI resources, it is easier to develop post-earthquake contingency plans. For management this will entail developing a survey method that will complete reports similar to what the U.S. Geological Survey produced. This would involve taking inventory of where, what type and the amount of habitat change that occurred. Then a compilation of this data with the stock status reports would have to be done to determine which, if any, species that are classified as at risk, of high or special concern would be directly impacted. It is evident that certain species will be of greater concern than others. Chum and pink are highly adaptable but they use the intertidal and estuarine waters which will experience the greatest amount of damage. Coho would also be of concern, as will the shellfish. Crab will be impacted if the earthquake occurs during the breeding season or if their habitat is greatly altered. By combining this information it will give management the information necessary to plan the annual allowable catch rates, keeping in mind which stocks could not sustain a harvest. This pre-cautionary approach to post-earthquake fisheries management would help maintain stocks.

Fishers should be prepared to experience cuts in their fishing allowances. These may be extensive (entire species through several districts) or relatively constrained (specific populations or cohorts) and may last one year or several years and for certain cohorts (i.e. the odd year cohort of pink salmon may not be able to support a fishery for 3 runs). Whole beaches may also be closed for several years to clam and crab harvesters. This will allow the remaining adults to spawn, recolonize the area and mature. These concessions will help ensure that nature is given every opportunity to recover without the added pressure of harvesting.

The main concern for aquaculturists should be that their facilities will likely be damaged from the tsunami. Their main problem will then be the fish that are released as a consequence of pens being damaged and moved. All facilities have a contingency plan for escaped finfish, however it does not deal with escapes of this magnitude nor do they have insurance for these instances. One aspect that will help is that aquaculture site selection requirements usually require calm, protected waters, so it is possible that they may not experience the full force of the tsunami. On the other hand, many of the aquaculture sites lie inside the fjords, where tsunami waves will be compounded. This is something that would require more extensive research. Present net technology is such that it could not withstand a tsunami; escapees and equipment loss are virtually certain.

SUMMARY

This research demonstrated that mega-earthquakes have an impact upon coastal biocommunities, which are then reflected in the local fisheries and the stakeholders that rely on them. There is very little awareness among the stakeholders, although this was expected considering the infrequency of this hazard. However, because of this lack of knowledge, the risks to the fisheries are greater. It is also greater along WCVI because of declining stock and the threat of continual anthropogenic and environmental impacts. The research was completed with the desire to reduce these risks to the fisheries by raising the awareness of stakeholders who will then partake in the creation of contingency plans.

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APPENDIX A: ETHICS APPROVAL

SIMON FRASER UNIVERSITY

OFFICE OF RESEARCH ETHICS

BURNABY, BRITISH COLUMBIA
CANADA V5A 1S6
Telephone: 604-291-4370
FAX: 604-291-4860

April 9, 2002

Ms. Deirdre Dobson
Graduate Student
Department of Geography
Simon Fraser University

Dear Ms. Dobson:

Re: Risk Associated with Large Cascadia Subduction Earthquakes On Coastal Fisheries Along Western Vancouver Island, B.C.

I am pleased to inform you that the above referenced Request for Ethical Approval of Research has been approved on behalf of the Research Ethics Board. This approval is in effect for twenty-four months from the above date. Any changes in the procedures affecting interaction with human subjects should be reported to the Research Ethics Board. Significant changes will require the submission of a revised Request for Ethical Approval of Research. This approval is in effect only while you are a registered SFU student.

Best wishes for success in this research.

Sincerely,

Dr. Hal Weinberg, Director
Office of Research Ethics

c: I. Hutchinson, Supervisor

/bjr

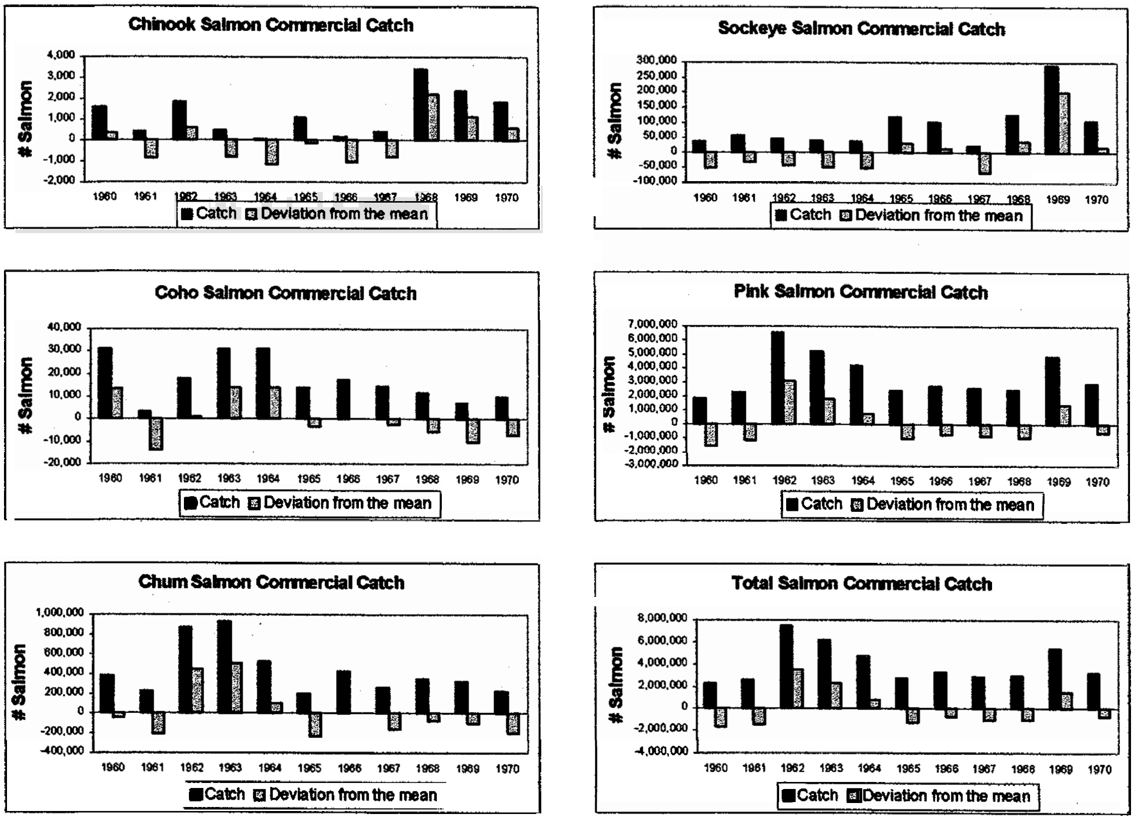
APPENDIX B:

PDO AND RECRUITMENT R^2 VALUES

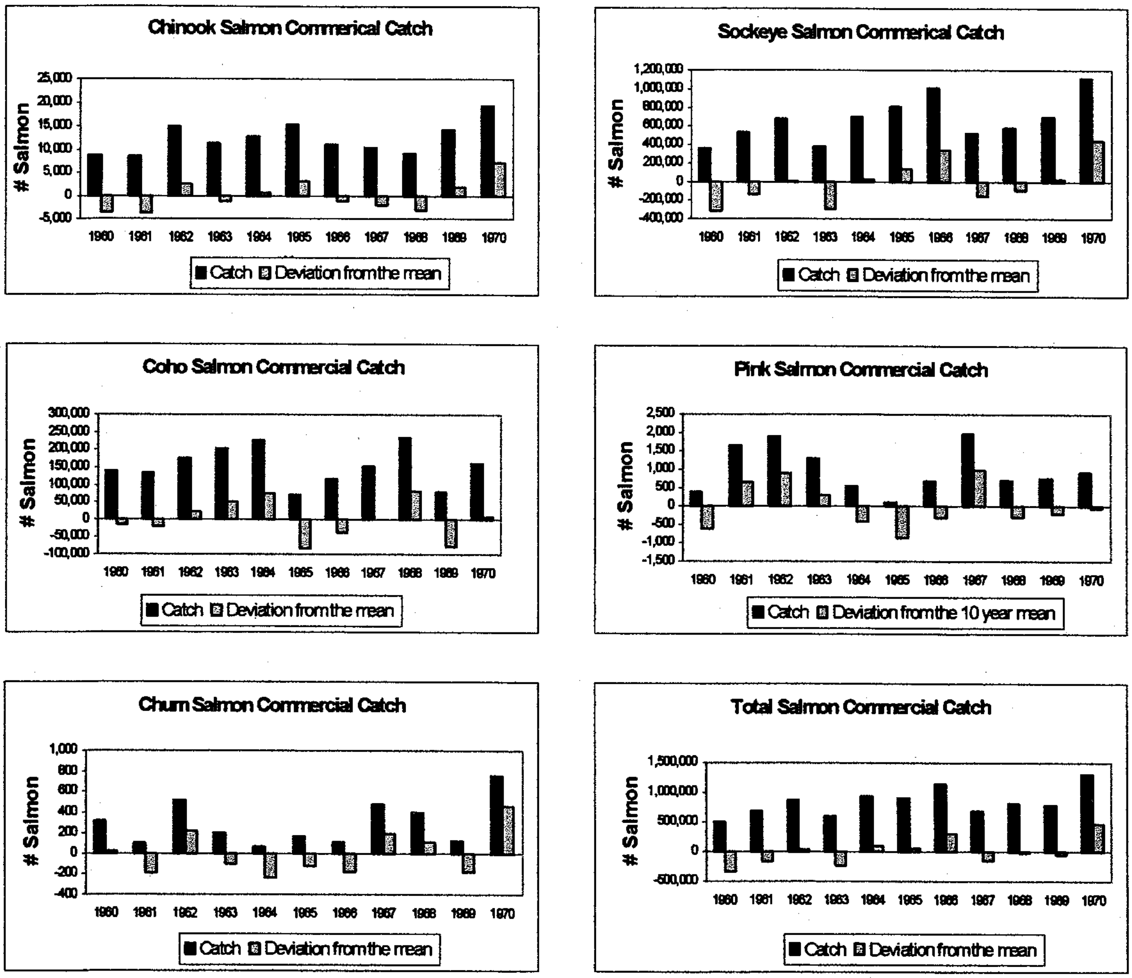
A regression analysis was run on the salmon recruitment data and the Pacific Decadal Oscillation Index. These R-squared values indicate that there is no correlation between the two data sets for the years of 1940-1970.

Fishery	Region				
	P.W.S.	Cordova	U. Cook Inlet	L. Cook Inlet	Kodiak
Pink	0.039	0.020	0.092	0.190	no data
Chum	0.000	0.062	0.012	0.001	no data
Sockeye	0.005	0.003	0.073	0.025	no data
Chinook	0.009	0.010	0.026	0.000	no data
Coho	0.001	0.000	0.013	0.081	no data

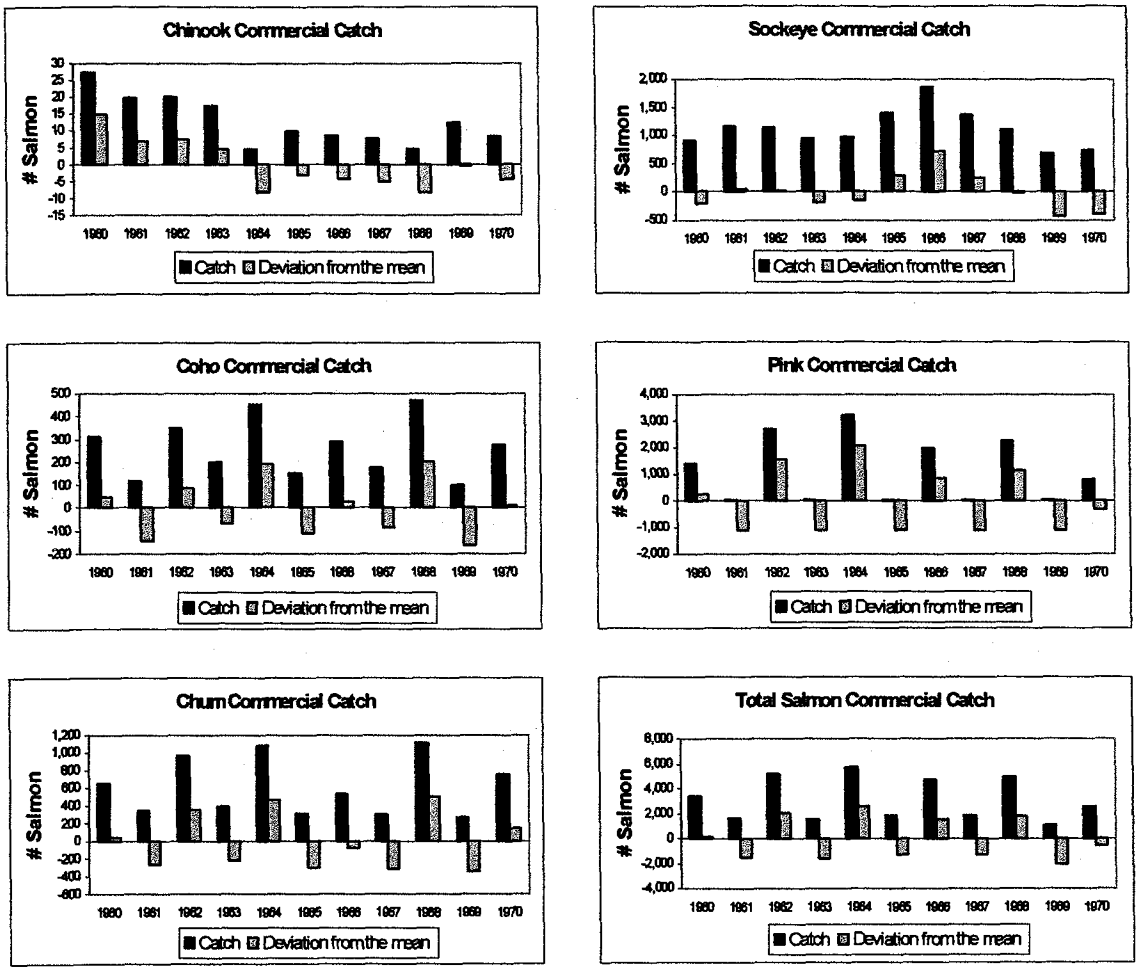
APPENDIX C: FISHERIES CATCH DATA



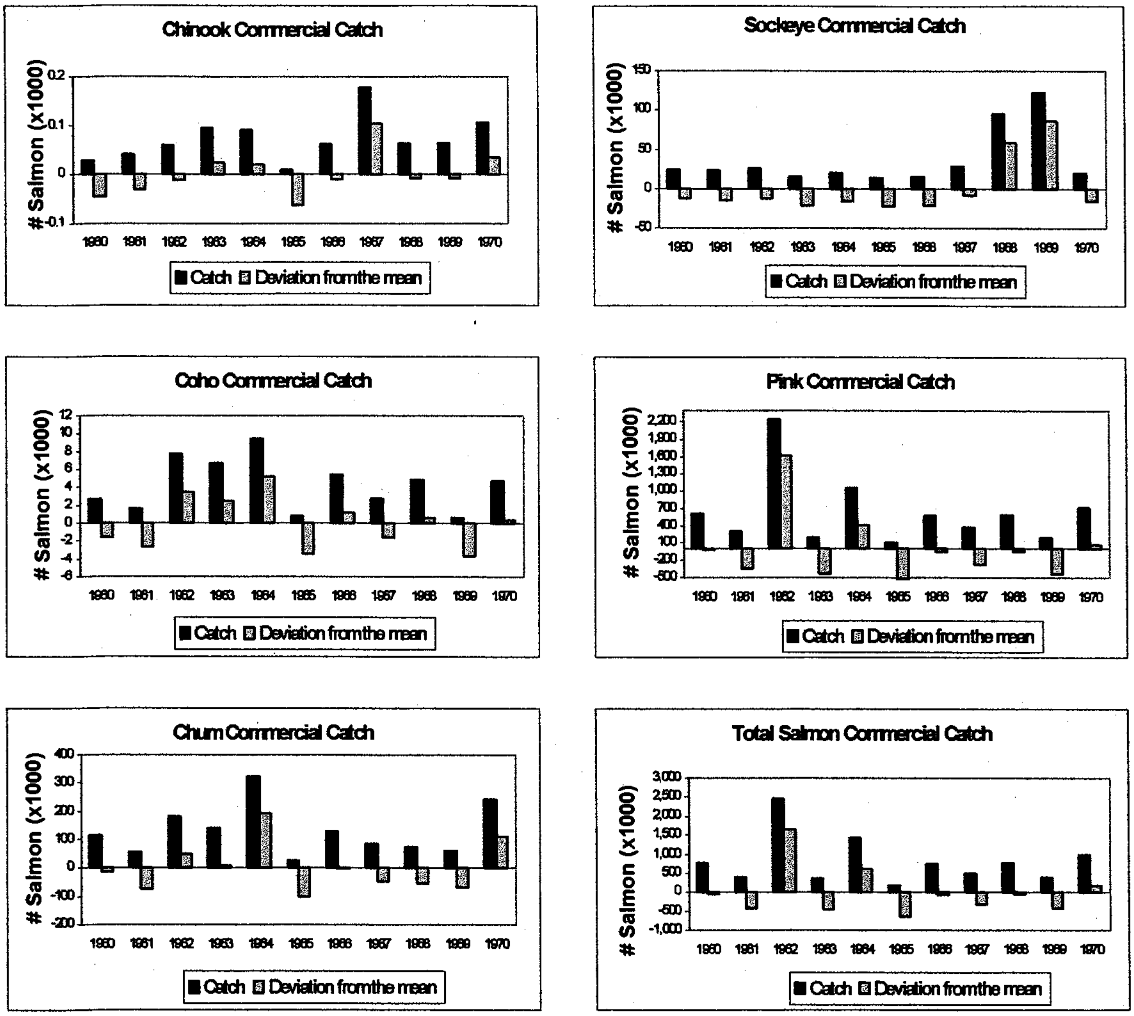
C1 Catch rates for Prince William Sound District. Catch values are in thousands of salmon per year. The difference from the ten year average is noted in the gray bars where negative numbers indicate a lower than average catch. Pink, chum and coho show delines in recruitment levels following the 1964 earthquake. Chinook and sockeye have poor recruitment levels throughout the decade with no discernible declines after the earthquake.



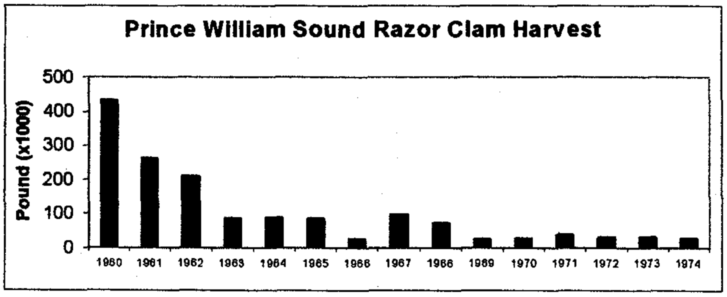
C2 Catch rates for Copper River District. Catch values are in number of salmon per year. The difference from the ten year average is noted in the grey bar where negative numbers indicate a lower than average catch. Pink, chum and coho all exhibit declines in recruitment levels following the 1964 earthquake. Chinook and sockeye however, appear to have stable runs throughout this 10-year period.

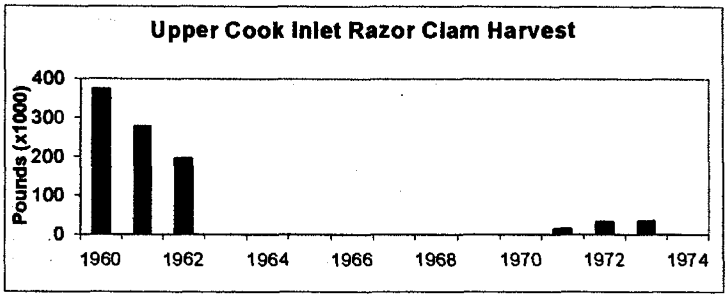


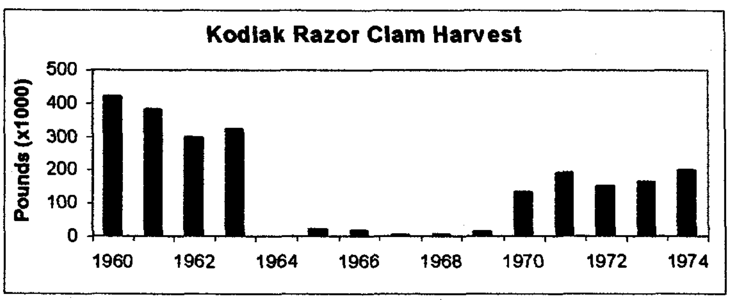
C3 Catch rates for Upper Cook Inlet District. Catch values are in thousands of salmon per year. The difference from the ten year average is noted in the grey bar where negative numbers indicate a lower than average catch. Over all, this region's catch data shows little impact from the 1964 earthquake. Pink salmon shows a slight decline in the even-year stocks, however this stock is consistantly small and it is therefore difficult to attribute declines to the earthquake.



C4 Catch rates for Lower Cook Inlet District. Catch values are in thousands of salmon per year. The difference from the ten year average is noted in the grey bar where negative numbers indicate a lower than average catch. This region shows a decline in pink salmon catch values for the 1964 stock, although pink salmon have a great deal of natural variation. Chum and coho also show declines following the 1964 earthquake. Chinook and sockeye have declines in certain years following the earthquake, however it is difficult to attribute it solely to the occurrance of the earthquake.







C5. Clam harvest levels within the Prince William Sound, Upper Cook Inlet and Kodiak Districts. In the Prince William Sound and Cook Inlet districts, the post - 1964 catches were only a fraction of the levels reported for years prior to the earthquake. This was reported in fishery reports as a reflection of market demands rather than of a population decline. Clam harvest levels within the Kodiak district also dropped dramatically in 1964. There was a minor population recovery six years later. However, a commercial clam harvest has never ben able to re-establish itself and harvest clams are solely used as bait.

APPENDIX D: SURVEY EXAMPLE

Like California, BC is susceptible to earthquakes. There is a good deal of research concerning earthquakes being done in the fields of geology, engineering, and emergency planning however, there is very little in the field of fisheries management. The purpose of this study is to assess the effects a large earthquake could potentially have on local fisheries and aquaculture facilities. The purpose of this survey is to seek to understand people's awareness of earthquakes and the potential damage that could ensue, should an earthquake occur. Specifically, I am interested in those involved with the fishing industry along the west coast of Vancouver Island.

The first questions are aimed at understanding your perception of what is commonly referred to as "The Big One". Following this, the research questions address physical changes to the environment and how this may affect the fish, shellfish and aquaculture facilities. Other research questions address how a large earthquake and tsunami may affect the people dependent upon such resources.

Throughout this survey, the questions are all in reference to a very large earthquake. For your reference, the last substantial earthquake felt by most people in the Lower Mainland and Vancouver Island, occurred at 10:54 PST on February 28th, 2001 and measured magnitude 6.8 with shaking lasting 20-60 seconds.

These questions are aimed at gaining an understanding of how big of an earthquake you think will happen when "The next Big One" occurs.

1) There is a lot of publicity surrounding when the next "Big" will occur and just how big is "Big". One way people who experience earthquakes describe the size of the earthquake is by how long the shaking lasts. If you were to experience an earthquake equal in size to what the public refer to as "The next "Big" earthquake, how long do you think the shaking will last? This is a way for you to describe how big you think the next "Big" earthquake will be.

< 15 seconds

15-30 seconds

30-60 seconds

60-90 seconds

90-120 seconds

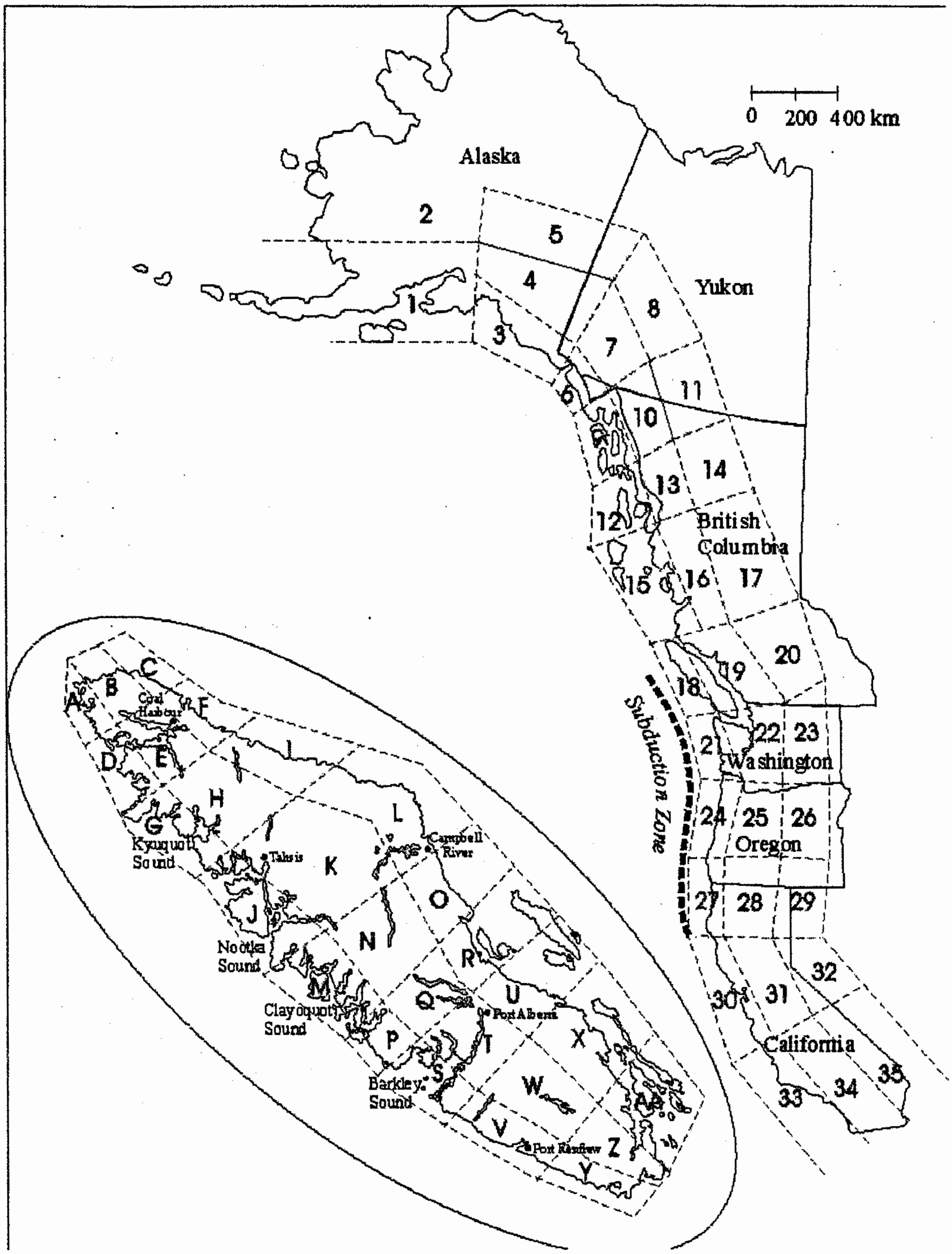
>120 seconds

Don't know

2) Another way people measure earthquakes is by the Modified Mercalli Scale, which expresses the intensity of the earthquake's effects in a given locality. Given the following table, what you think the intensity of the earthquake will be should a "Big" earthquake occur?

MM Intensity	**Description of Intensity Level**	
I	Not felt except by a very few under especially favourable circumstances.	
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.	
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration 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. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.	
VII	Damage negligible in building 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. Noticed by persons driving motor cars.	
VIII	Damage slight in specially designed structures; considerable 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 distorted. Objects thrown into the air.	

3) Assume an earthquake equal in size and intensity to the one you just described occurs off the coast of Vancouver Island. If the entire subduction zone indicated on the map ruptures, how large of an area do you think would be at least moderately affected? Indicate your answer by shading in the areas on the map provided that you think would experience some damage due to shaking by the earthquake.



The follow questions are aimed at gaining an understanding of how often you think such large earthquakes occur along the coast of BC.

4) When do you think the last big earthquake, such as the one you described, occurred off the west coast of Vancouver Island?

within the past 50 years

between 50 and 100 years ago

between 100 and 200 years ago

between 200 and 300 years ago

between 300 and 400 years ago

between 400 and 500 years ago

more than 500 years ago

Don't know

5) For each of the following future time periods, indicate how likely (or unlikely) you think it is that an earthquake, equivalent in size to your previous description will occur:

	Most likely	Likely	Possi-bly	Unlikel y	Least Likely	Don't Know
Within next 25 years						
Within next 50 years						
Within next 100 years						
Within next 500 years						
Never						

The following questions are aimed at understanding how much physical and biological change or damage you think may occur as a result of a large earthquake.

6) With large earthquakes there is commonly uplift and/or down-dropping of the land along the coast. Should an earthquake equivalent in size to your description occur, what do you think could happen with respect to land level changes along the coast?

	Most likely	Likely	Possibly	Unlikely	Least Likely	Don't Know
uplift > 5 meters						
uplift 4 meters						
uplift 3 meters						
uplift 2 meters						
uplift 1 meters						
0 meters (no change)						
drop 1 meter						
drop 2 meter						
drop 3 meter						
drop 4 meter						
drop > 5 meter						

7) Assuming that on average 2 meters of uplift were to occur in your area, how extensive do you think the mortality (direct or indirect) would be within the salmon or shellfish population?

None; there will be no mortalities as a result of 2 m uplift

Minimal; there may be little mortality but nothing to be concerned about

Moderate; there will be some mortality that may affect population numbers (size)

High; there will be a high mortality rate, possibly total regional mortality

Don't Know

8) Assuming that on average 2 meters of down-dropping were to occur in your area, how extensive do you think the mortality (direct or indirect) would be within the salmon or shellfish population?

None; there will be no mortalities as a result of 2 m drop-dropping

Minimal; there may be little mortality but nothing to be concerned about

Moderate; there will be some mortality that may affect population numbers (size)

High; there will be a high mortality rate, possibly total regional mortality

Don't Know

9) Large offshore earthquakes create large tsunamis (tidal waves). Assuming an earthquake, equivalent in size to the one you described as a "Big" earthquake, occurs 100 kilometres off the coast of Vancouver Island, how long do you think it will it take for the tsunami wave to reach your area?

Immediately

Less than 30 mins

30 mins to 1 hour

1 to 2 hours

2 to 6 hours

6 to 12 hours

12 to 24 hours

More than a day

Don't know

10) Tsunami waves, created by a large earthquake, can reach great heights and reach far distances inland. Since heights are more difficult to judge, how far inland do you think the tsunami wave may reach in your area? Measurements are typically taken from the high-high tide line.

Not passed the high-high tide line (zero meters inland)

Less than 5 meters

5-10 meters inland

Greater than 10 meters inland

Don't know

11) What do you think the extent of the damage would be in the aftermath of the tsunami?

None; there will be no mortalities and/or destruction of habitat

Minimal; there may be little mortality and/or destruction of habitat but nothing tobe concerned about

Moderate; there will be some mortality and/or destruction of habitat that may affect harvests/production

High; there will be a high mortality rate and/or destruction of habitat, possibly total regional mortality and/or loss of habitat

Don't Know

12) Have you previously considered the effects that a large earthquake or tsunami might have on the salmon or shellfish populations?

Yes _____ No _____

This section is asking questions regarding how much preparation or forethought there is regarding large earthquakes and tsunamis.

13) Have you, in your work position, considered any precautions/preventative measures or have some sort of a contingency plan with respect to harvest levels should such an event occur?

Yes _____ No _____

If "Yes" please explain what these precautions are. If "No" are there plans to instate precautions?

14) Do you think harvest levels should remain unchanged after an earthquake or tsunami?

Yes _____ No _____

Please explain:

____

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____

15) If such an event were to occur, what time of year do you think would cause the most amount of damage to the salmon or shellfish population? Please explain why and the type of damage you would expect.

____

____

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____

16) If such an event were to occur, what time of year do you think would cause the least amount of damage to the salmon or shellfish population? Please explain why.

This portion of the survey has personal questions in order to find out some background information for a better understanding of your perspectives.

17) What is your occupation / position and where on the along the coast do you work?

18) How many years of experience do you have in this field of work?

19) What age group do you fit into?

< 20

21-30

31-40

41-50

51-60

60 +

20) What information can I supply to you at the conclusion of this study?

____

____

____

____

Thank you for taking the time to complete this survey.

Please submit by mail, in the attached envelope, to:

Deirdre Dobson
Geography Department
Simon Fraser University
8888 University Dr.
Burnaby, BC
V5A 1S6