An Overview of the Volcano-Tectonic Hazards of Portland, Oregon, and An Assessment of Emergency Preparedness

by

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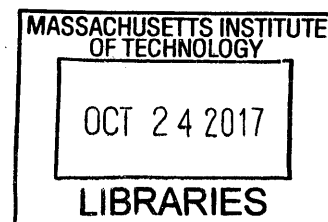
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ABSTRACT

Portland, Oregon, lies within an active tectonic margin, which puts the city at risk to hazards from earthquakes and volcanic eruptions. The young Juan de Fuca microplate is subducting under North America, introducing not only arc magmatism into the overlying plate, but also interplate and intraplate seismicity related to the subduction zone. Large crustal earthquakes are also probable in Portland because of the oblique strike-slip Portland Hills Fault zone. These hazards create risk to Portland residents and infrastructure because of pre-existing vulnerabilities. Much of Portland's downtown area, including the government and business districts, is at risk of ground shaking infrastructure damage, liquefaction and landslides due to earthquakes. Additionally, the city is within 110 km of three active Cascadia stratovolcanoes, two of which pose hazards from tephra and lahars. Though the city is under the umbrella of four emergency response plans—city, county, state and federal—there are critical gaps in mitigation strategies, emergency exercises and community education and outreach. Portland cannot prevent earthquakes or volcanic eruptions, but the city can reduce its vulnerability to these hazards.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

BEOP:	Basic Emergency Operations Plan
CSZ:	Cascadia Subduction Zone
DOGAMI:	Oregon Department of Geology and Mineral Industries
ECC:	Emergency Coordination Center
ETS:	Episodic Tremor and Slip
FEMA:	Federal Emergency Management Agency
FHWA:	Federal Highway Administration
GIS:	Geographic Information Systems
GPS:	Global Positioning System
ICS:	Incident Command System
LUPM:	Land Use Portfolio Model
M_L:	Richter magnitude
M_W:	Moment magnitude
MMI:	Modified Mercalli Intensity
NIMS:	National Incident Management System
NRF:	National Response Framework
OEM:	Oregon Emergency Management
PAR:	Pressure and Release Model
PBOT:	Portland Bureau of Transportation
PGA:	Peak Ground Acceleration
PNSN:	Pacific Northwest Seismic Network
POEM:	Portland Office of Emergency Management
UNDP:	United Nations Development Programme
USGS:	United States Geological Survey
WGSC:	Western Geologic Science Center

I. INTRODUCTION

This study examines the risks to the City of Portland, Oregon, that arise from the subduction of the Juan de Fuca microplate beneath the North American plate. In addition to outlining and assessing the impact of volcano-tectonic hazards, this paper analyzes the emergency management and response systems for Portland in order to determine the preparedness of Portland to mitigate and respond to seismic and volcanic hazards. After an assessment of risk and a discussion of emergency preparedness, this study concludes with several recommendations to improve the resiliency of Portland to geologic disasters.
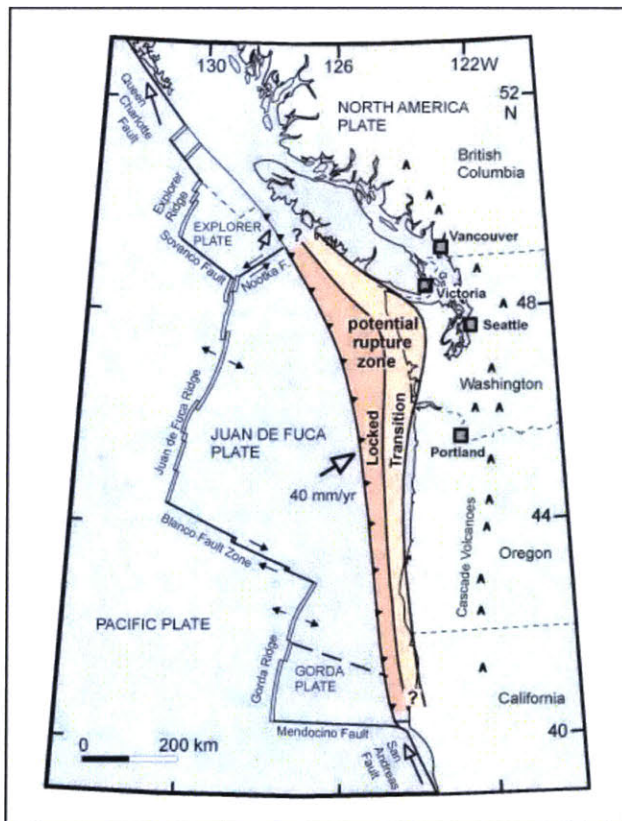
Figure 1. Cascadia Subduction Zone. This map, taken from *Geological Survey of Canada* [2008], depicts the regional tectonic setting for the Pacific Northwest, identifying the Juan de Fuca subduction zone, transverse plate boundaries, and volcanoes (indicated by [^]).

The tectonic activity in the Pacific Northwest is primarily defined by subduction and transform motion offshore, which causes compression in the west-northwest and extension in the east [*Bird*, 2002; *Blakely*, 1995; *Wells*, 1990; *Beeson et al.*, 1985; *Magill et al.*, 1982]. The Cascadia Subduction Zone (Figure 1) runs approximately 500 km along the coast of British Columbia, Washington, and Oregon, more than 200 km west of the Portland-Vancouver basin [*Blakely*, 1995]. Geologists and geophysicists have estimated that significant damage to Portland could result due to earthquakes along the subduction zone: the Oregon Department

of Geology and Mineral Industries (DOGAMI) approximates that a large event on the Cascadia Subduction Zone could lead to 5,000 casualties and over $30 billion in infrastructure damage [*Oregon Dept. of Geo. and Min. Indus.*, 2010]. Geologists also estimate that the Cascade volcano chain, which runs generally N-S to the east of Portland, could cause millions in damage from a single event at one of the three active volcanoes within 70 miles[1] of the city [*Scott et al.*, 1997].

The recent earthquakes in Japan make studies of Portland's seismic hazards especially poignant. The magnitude 9.0 Tohoku earthquake occurred at the subduction zone boundary between the Pacific and North American plates on March 11, 2011, approximately 130 km east of Honshu [*U.S. Geological Survey*, 2011]. The Japanese National Police Agency has confirmed 18,414 deaths and casualties, as well as 14,734 missing persons from the earthquake and resulting tsunami [2011], and the Japanese government estimates total damages at $309 billion, making the Tohoku earthquake the most destructive natural disaster in history [*Hosaka*, 2011]. Despite some differences in subduction zone characteristics, scientists have predicted similar events along the Cascadia Subduction Zone [*Heaton and Hartzell*, 1987], estimating that a magnitude 8.5 or greater earthquake and accompanying tsunami could occur within the next 200 years [*Atwater*, 1987; *Pokarney*, 1996].

By all accounts, Japan is better prepared for earthquakes and tsunami than any other country in the world [*Foster*, 2011], including the United States [*Schmid*, 2011]. Geologists with the U.S. Geological Survey, DOGAMI, Portland State University, University of Washington, Humboldt State University, Boise State University, and Cal Tech, among others, have been studying the seismic and volcanic activity in the Pacific Northwest for decades, with special focus on recurrence intervals, possible destruction, and secondary hazards. Many scientists have

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[1] The U.S. Geological Survey defines Mount Hood, Mount St. Helens, and Mount Adams as active volcanoes.

attempted to inform emergency response policy, publishing volumes on hazards and emergency preparedness specifically for use in cities like Portland [e.g. *Atwater*, 1987; *Heaton and Hartzell*, 1987; *Madin*, 1989; *Scott et al.*, 1997; *Rogers et al.*, 1998; *Wang*, 1998a; *Wang*, 1998b; *Wang*, 1999; *Wang and Clark*, 1999; *Zoback*, 2006]. Ultimately, all sources come to the same conclusion: the City of Portland is unprepared for a major geologic disaster. Though Portland falls under the cover of several types of emergency management systems in addition to its own, including county, state and federal plans, the city lacks an organized assessment of volcano-tectonic risks or a comprehensive policy to prepare for, respond to, and recover from geologic hazards. The scientific community continuously calls upon the city to exercise "more due diligence," as communities from New Zealand to Chile suffer from events similar to those facing Portland [Yeats in *Rojas-Burke*, 2011].

Following this introduction is an overview of how to define and determine risk and its components. Chapter 3 describes the geologic and tectonic history of Portland, Oregon, with discussion of climate patterns that exacerbate hazards in the area. Chapter 3 also discusses the demographics of Portland, including populations that are most susceptible to natural disasters. Chapter 4 details each of the emergency management structures governing Portland response systems, while Chapters 5 and 6 feature the specific seismic and volcanic risks to of Portland, respectively. This study concludes in Chapter 7 with an evaluation of the susceptibility of Portland, the city's preparedness and recommendations for emergency response communities in the Portland area.

II. METHODS OF RISK ANALYSIS

The primary focus of this study is to evaluate the risk of a natural disaster occurring due to volcanic and seismic activity in the Portland area by first assessing the geologic hazards and then determining Portland's vulnerability by examining populations at risk and their emergency preparedness. This working definition of risk is taken from the USGS Western Geographic Science Center (WGSC), which defines risk as the intersection between hazards and vulnerability of a system (Figure 2) [*Wood, 2011*]. Though the exact definition and evaluation of risk is, in and of itself, a focus of research and debate, this definition or some close variation (*e.g.* in which exposure is a separate component) is commonly used in the natural disaster literature to evaluate risks to populations [*Wisner et al.*, 2004; *Birkmann*, 2006b; *Coburn et al.*, 1994; *Peduzzi*, 2006]. Hazards are "extreme natural event[s] or process[es]," such as floods or hurricanes [*Wisner et al.*, 2004]. Though Portland is subject to many natural hazards, as briefly covered in the Introduction, this study will only evaluate geologic hazards resultant from seismic or volcanic activity. Evaluating hazards, as with evaluating risk, is an academic field unto itself, and we will only scratch the surface in order to comprehensively evaluate the major hazards facing Portland residents. And though evaluating the purely geologic hazards is a necessary component of addressing risk, we cannot have a discussion
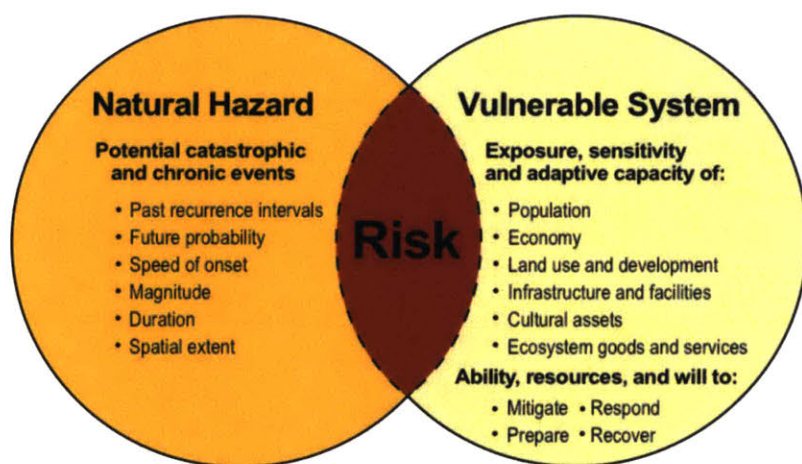
Figure 2. Risk Assessment. Taken from *Wood* [2011], this Venn diagram shows risk as the intersection between system vulnerability and naturally occurring hazards.

about natural hazards without also addressing societal vulnerability. As stated in *Wisner et al.*, "There is a danger in treating disasters as something peculiar, as events that deserve their own special focus. It is to risk separating 'natural' disasters from the social frameworks that influence how hazards affect people, thereby putting too much emphasis on the natural hazards themselves, and not nearly enough on the surrounding social environment" [2004]. In the most simplistic sense, this study analyzes risk from the perspective that "hazards only become disasters when people's lives and livelihoods are swept away" [Kofi Annan in *Birkmann*, 2006b].

There are numerous ways to measure and model risk, from the simplistic, conceptual approach shown in Figure 2 to more complicated algorithms using Census data, land surveys, and GIS mapping tools. The highest-level assessment would include counting all persons who have been impacted by a particular disaster and dividing that by the number exposed to the hazard [*Coburn et al.*, 1994]. *Wisner et al.* discuss two more comprehensive risk models, the general Pressure and Release model and the expanded Access model [2004], while FEMA distributes HAZUS-MH and the WGSC utilizes the Land Use Portfolio model. Though this study will not measure the risk to Portland from first principles or raw data using any of these models in particular, it is important to understand the conceptual framework for what determines risk, the mechanisms for creating (and reducing) risk, and the factors to consider when trying to quantify something so dynamic and indefinite. Risk can be quantified by loss of human life, loss of property, damage to infrastructure, increased insecurity of a population, damage to the natural environment, or any other number of ways. Thus, we will examine these models for common themes and identify the parameters most essential to the discussion and analysis of hazard and vulnerability in later chapters.

The Pressure and Release model (Figure 3) "resembles a nutcracker, with increasing pressure on people arising from either side—from their vulnerability and from the impact (and severity) of the hazard for those people" [*Wisner et al.*, 2004]. The set up implies that vulnerability develops through the interaction of access to resources and dynamic political, social environmental and economic systems that can exacerbate or create vulnerability (such as a recession or increased urbanization). Hazards, which are changes or impulses to climate or geologic systems, can increase the pressure on the population. Thus, the risk of a natural disaster is the combined "pressure" of hazards and vulnerability. The release model shows that risk can be reduced by decreasing vulnerability or the impact of hazards, though *Wisner et al.* argue that reducing risk by changing the relevant systems really only addresses vulnerability, rather than hazards (as shown in Figure 3, taken from *Alexander et al.* [2006]). The PAR model, though general and non-algebraic, builds upon the Venn diagram in Figure 2 by introducing the concept of "root causes" interacting with systems. The Access model, also discussed by *Wisner et al.*, expands upon this framework by introducing differential vulnerability within a community and iterative assessments of risk throughout the natural disaster.

The Access model is a processed oriented and iterative complement to the PAR model, focusing on the relative impacts of factors on group vulnerability and the influence hazards might have on increasing vulnerability itself. The foundation of the Access model lies in evolving and internally varying systems that lead to evolving risk. The model incorporates evaluation of hazards and "unsafe conditions" that lead to a disaster, and then evaluate the response to that disaster. The cycle iterates until the community has returned to some specified baseline [*Wisner et al.*, 2004]. This represents two major differences from the PAR model. Firstly, a natural disaster can differentially impact specific groups based on the type of hazard:

Analysis of Risk: Pressure Model

Vulnerability Progression →

Risk   Hazards

Root Causes

Low Access:
•Power
•Structures
•Resources

Systems:
*Political
*Economic

Dynamic Pressures

Lack of:
•Training
• Institutions
• Skills
• Investment
• Markets

Forces:
•Population ⇑
•Urbanization
•Degradation
• ⇓Soils

Unsafe Conditions

Fragile physical environment

Fragile local economy:
• Risky livelihoods
• Vulnerable inputs
• Low incomes

Risk =
Hazard *
Vulnerability

(R = H * V)

Drought

Pests

Winds

Flood

Analysis of Risk: Release Model

← Safety Progression

Risk Reduction   Reduce Hazard Impacts

Address Root Causes

Improved Access:
•Power
•Resources

Reduce Pressures

Develop:
•Training
• Institutions
• Skills
• Investment
• Markets

Stabilize/ Improve:
•Population
•Urbanization
•Degradation

Improve Conditions

Protected Environment:
•Safe, hazard-resistant
•Hazard prepared

Strong local economy:
• Diversified & strong livelihoods
* Risk Sharing
• Increased incomes

• Restricted damage

• Food, Income, Livelihood Security

•Appropriate infrastructure & methods to reduce impacts

•Improve coping capacity

Source: (Modified from Blaikie et al., 1994)

Figure 3. The Pressure and Release Model. Taken from *Alexander et al.* [2006], this figure details the pressure and release components of the PAR model. The pressure component demonstrates the two pressures on communities (vulnerability and hazards) that interact to create risk for natural disasters. The release component implies that reducing risk generally involves removing vulnerability pressure through improving and building political, social, economic and environmental systems.

for example, a heat wave might negatively impact the elderly or those with outdoor employment more so than any other group, despite the fact that access to resources within those groups might be the same as the population at large. Secondly, once a natural disaster occurs, the Access model cycles through the iteration again, reassessing vulnerability and hazards through time. For instance, if a severe flood occurs, it may wipe out the crops of specific farmers in one area, but not others. Thus, the flood not only differentially impacts the community, but it also creates more vulnerability by decreasing the access to food, which is necessary for recovery. Though useful in

evaluating natural disasters in real time or after the fact, the Access model is not necessarily the best method for quantitatively determining risk before an event, because the variability in risk over time is difficult to predict without introducing contrived data into a model. Alternatives to the PAR and Access framework are FEMA's HAZUS-MH and the Land Use Portfolio model, which focus less on theoretical process and more on expected outcomes.

HAZUS-MH ("Hazards U.S." multiple-hazard version [*Dinitz*, 2008]) is statistical software developed and distributed by FEMA that utilizes geographic information systems data to model potential losses from earthquakes, floods and hurricanes. It geographically illustrates physical damage, economic loss, and social impacts (such as displaced households) to help users determine which areas are high-risk [*FEMA*, 2011]. This is the primary software used by government and academics to determine risk, although WGSC at USGS developed their own model.

Similar to HAZUS-MH, the Land Use Portfolio model (LUPM), which was developed by WGSC, utilizes geologic, economic, statistical, hydrological, and geographical data along with specific inputs of investment in risk-reduction [*Dinitz*, 2008]. The LUPM allows policy makers to estimate the distribution of risk to determine the most cost-effective mitigation measures (utilizing equations derived from Modern Portfolio Theory [*Dinitz*, 2008]). The data are analyzed using GIS, because determining risk is an "inherently spatial problem…. Data inputs include the probability of the hazard event, the planning time horizon, the assets at risk (e.g. tax parcels), the spatial probabilities of damage, the dollar value and/or vulnerability of each asset, and the cost and effectiveness of the risk-reduction measures being considered" [*Dinitz*, 2011]. Once all inputs and parameters have been identified, "the LUPM performs the calculations and generates a report summarizing the scenario parameters and model results" [*Dinitz*, 2008]. This type of

analysis allows users to gain more insight than regional-scale assessments but is more cost-effective than site-specific studies [*Taketa et al.*, 2010]. The LUPM is ideal for policy makers on a budget and preferable to HAZUS-MH because it can account for uncertainty in likelihood of event occurrence as well as relative effectiveness of risk-reduction options [*Dinitz*, 2008]. However, LUPM ignores many of the interactions central to the PAR and Access models and requires inputs specifying the dimensions of the hazard and acceptable losses. This study will discuss quantitative findings within a more conceptual framework to truly determine who is at risk, which hazards are most likely to become disasters, and what the city of Portland can do to improve its emergency preparedness and response.

DETERMINING HAZARD

In order to estimate and understand risk to an area, we need to determine the probability of an event occurring and the nature, location, and intensity of hazards resulting from that geologic event. This section will discuss how these parameters are determined and communicated by researchers, and what specific inputs are necessary to derive the characteristics of events and their corresponding hazards.

The severity of natural hazards can be related either through event parameters or site parameters [*Coburn et al.*, 1994]. Event parameters give the magnitude of the event (*e.g.* earthquake magnitude), whereas site parameters quantify the effect the hazards would have at a specific location (*e.g.* peak ground acceleration). For this study, we will primarily utilize site parameters to determine the risk to Portland residents. There are two methods of determining site parameters: deterministic and probabilistic [*Krinitzsky*, 1995; *Romeo and Prestininzi*, 2000]. Deterministic analyses quantify hazards for a given event magnitude at a specified distance from

the site, whereas probabilistic analyses (more common) give the probability of exceedance of specific hazards within a certain recurrence interval. For example, a deterministic analysis would read, "The earthquake hazard for the site is a peak ground acceleration of 0.35g resulting from an earthquake of magnitude 6.0 on the Balcones Fault at a distance of 12 miles from the site" [*FEMA*, 2006]. A probabilistic analysis would read, "The earthquake hazard for the site is a peak ground acceleration of 0.28g with a 2 percent probability of being exceeded in a 50-year period" [*FEMA*, 2006]. Both utilize similar data inputs, but are useful for different purposes. The former gives a non-time-specific reference point of the worst-case scenario for the purposes of designing buildings or facilities (for earthquakes, this is called the maximum credible earthquake, MCE), while the latter estimates the probability of exceedance over a specified time interval. The deterministic model does not take into account the probability of the worst-case scenario occurring (the return period or recurrence interval), nor the influence of multiple faults.

Large, severe events, by definition, are the most damaging, most worrisome, and least frequent, consequently making it difficult to predict a return period. Human records are fairly recent and do not offer enough data to accurately predict hazards that occur on timescales of hundreds, thousands, or millions of years (such as earthquakes or large volcanic eruptions). Some major events can be detected with paleoseismology or geologic field studies, but the continuous evolution of the earth's surface and our limited technologies do not allow for comprehensive insight into prehistoric events. Researchers have been able to conclude, however, that recurrence is inversely related with severity [*Coburn et al.*, 1994]. The recurrence interval for an event is typically given by:

$$T = \frac{n+1}{m}$$

where T is the period of return (in years), n is the number of years on record, and m is the ranking of the event within that time period [Bell, 1999]. Thus, the recurrence interval for the largest flood within a 200-year period would be approximately 201 years. When discussing hazards, the recurrence interval is often used to relate the severity of the event as well as a geospatial indicator of risk (*e.g.* flood inundation maps are typically shown with 100-year and 200-year flood contours).

In addition to determining the recurrence interval, researchers need to utilize other environmental data to determine the nature and severity of hazards that could result from an event of a given magnitude. Several types of studies and their uses in determining hazard severity, nature and risk are listed in Table 1.

Table 1. Survey Data for Hazard Mapping

Type of Study	Hazard Information
Paleoseismic	Recurrence interval, magnitude
Seismic	Fault location, magma chamber location and size, previous displacement
Lidar	Slope stability, drainage basins, flood plains, valleys (for lahars, lava flows, flood waters), surface features associated with volcanoes or faults
Hydrological	Sediment saturation
Geologic mapping	Past events (volcanic eruptions, flood deposits, tsunami evidence, fault plane), sediment vs. bedrock, previous fault displacement
Gravity anomalies	Tectonic plate interactions
Land cover	Slope stability, runoff rates
GPS	Fault creep, slope creep, relative plate motion

DETERMINING VULNERABILITY

The literature includes dozens of definitions for vulnerability, as well as a multitude of relevant indicators and measurement techniques [*Birkmann*, 2006b]. *Wood* [2011] generally describes system vulnerability as the ability, will and resources available to a population to

mitigate, prepare, respond and recover from natural hazards (Figure 2). *Wisner et al.* similarly describe vulnerability as "the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard.... It involves a combination of factors that determine the degree to which someone's life, livelihood, property and other assets are put at risk by a discrete and identifiable event (or series or 'cascade' of such events) in nature and in society" [2004]. *Cutter et al.* define vulnerability simply as "the potential for loss" [2003]. These definitions highlight two distinct types of measures that are essential to assessment of vulnerability: social and environmental. In *Birkmann* [2006b], Cannon et al. include the following as components of social vulnerability: initial well-being, livelihood and resilience, self-protection, social protection, social and political networks and institutions. *Cutter et al.* include more concrete measures of age, gender, race, socioeconomic status, homelessness, and "populations that lack the normal social safety nets necessary in disaster recovery," such as medical services, education, employment, access to lifeline infrastructure,[2] and tenure status [2003]. Environmental measures include the built environment as well as the robustness of the natural landscape and ecosystem [*Cutter et al.*, 2003; *Birkmann*, 2006b] and can be assessed by looking at land use and land cover [*Wood*, 2007], in addition to other factors like slope instability and building stability. Ultimately, vulnerability is an "estimation of the wider environment and social circumstances... [that enable] people and communities to cope with the impacts of hazardous events" [*Birkmann*, 2006b]. In order to quantify vulnerability, we need to determine what specific variables represent vulnerable populations.

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[2] This terminology is used throughout emergency response literature. *Cutter et al.* define "lifelines" as sewers, bridges, water, communications, and transportation infrastructure [2003].

There are many indicators researchers can use in risk models to comprehensively represent social and environmental vulnerability. As stated in *Cutter et al.*: "There is a general consensus within the social science community about some of the major factors that influence... vulnerability.... Disagreements arise in the *selection of specific variables*[3] to represent these broader concepts" [2003]. Indicators are variables that operationalize susceptibility, coping capacity, and resilience of a system to an event or hazard [*Birkmann*, 2006a]. Above all, indicators need to be chosen with goals and a specific framework in mind, rather than at random or based on what seems most "logical." There is neither a standard set of indicators, nor agreement within the vulnerability assessment community as to which indicators are most or least useful [*Birkmann*, 2006a]. At the human level, poverty is understood to be a consistently positive contributor to vulnerability because it implies reduced access to resources for preparation, response and recovery, but there is not a standard metric for poverty [*Wisner et al.*, 2004; *Birkmann*, 2006b; *Cutter et al.*, 2003]. From an environmental perspective, urbanization is also critical to vulnerability: the classification of masonry buildings is one typical measure [*Coburn et al.*, 1994].

In an effort to standardize indicators, *Cutter et al.* collected data on more than 250 variables for over 3,141 U.S. counties, narrowed that to 42 independent measures, and produced 11 factors that explained 76.4 percent of variance (Table 2) [2003]. In Chapter 3, we will examine specific measures that highlight particular populations at risk. But to quantify vulnerability, we must look at the interactions and combinations of indicators and hazards to quantify vulnerability, and subsequently risk.

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[3] Italics added for emphasis.

Table 2. Dimension of Social Vulnerability, after *Cutter et al.* [2003]

		Dimensions of Social Vulnerability		
Factor	Name	Percent Variation Explained	Dominant Variable	Correlation
1	Personal wealth	12.4	Per capita income	+0.87
2	Age	11.9	Median age	−0.90
3	Density of the built environment	11.2	No. commercial establishments/mi^2	+0.98
4	Single-sector economic dependence	8.6	% employed in extractive industries	+0.80
5	Housing stock and tenancy	7.0	% housing units that are mobile homes	−0.75
6	Race—African American	6.9	% African American	+0.80
7	Ethnicity—Hispanic	4.2	% Hispanic	+0.89
8	Ethnicity—Native American	4.1	% Native American	+0.75
9	Race—Asian	3.9	% Asian	+0.71
10	Occupation	3.2	% employed in service occupations	+0.76
11	Infrastructure dependence	2.9	% employed in transportation, communication, and public utilities	+0.77

There are many models and functions to determine vulnerability as a component of risk, but there is no consistent assessment method used across the board [*Cutter et al.*, 2003; *Birkmann*, 2006b]. Using their 11 metrics identified in Table 2, *Cutter et al.* develop a Social Vulnerability Index (SoVI) to compare vulnerability to environmental hazards across localities and time. The SoVI, just one of numerous indices for vulnerability, is an additive metric that gives equal weight to each of the 11 factors, because the authors had no "defensible method for assigning weights" [2003]. Though this might be useful for comparing social vulnerability between localities, the metric itself doesn't tell us how or why certain parameters impact vulnerability, or which indicators are most important for specific hazards. Additionally, the authors found no correlation between SoVI and Presidential natural disaster declarations [*Cutter et al.*, 2003]. Other approaches, including HAZUS and LUPM, use vulnerability functions that

relate the magnitude of hazard to a Mean Damage Rate (MDR) for a given vulnerability indicator. Figure 4, developed by *RiskScape* [2011], is an example of a vulnerability function for building types subject to shaking hazards during an earthquake event. The equations that generate these types of plots are incorporated into most major risk analysis software. RiskScape, the private company that developed the model for Figure 4, has also developed numerous other vulnerability functions for use in their own risk assessment software. Table 3 enumerates the variety in vulnerability functions for different event and hazard types.

Building damage Example
Earthquake
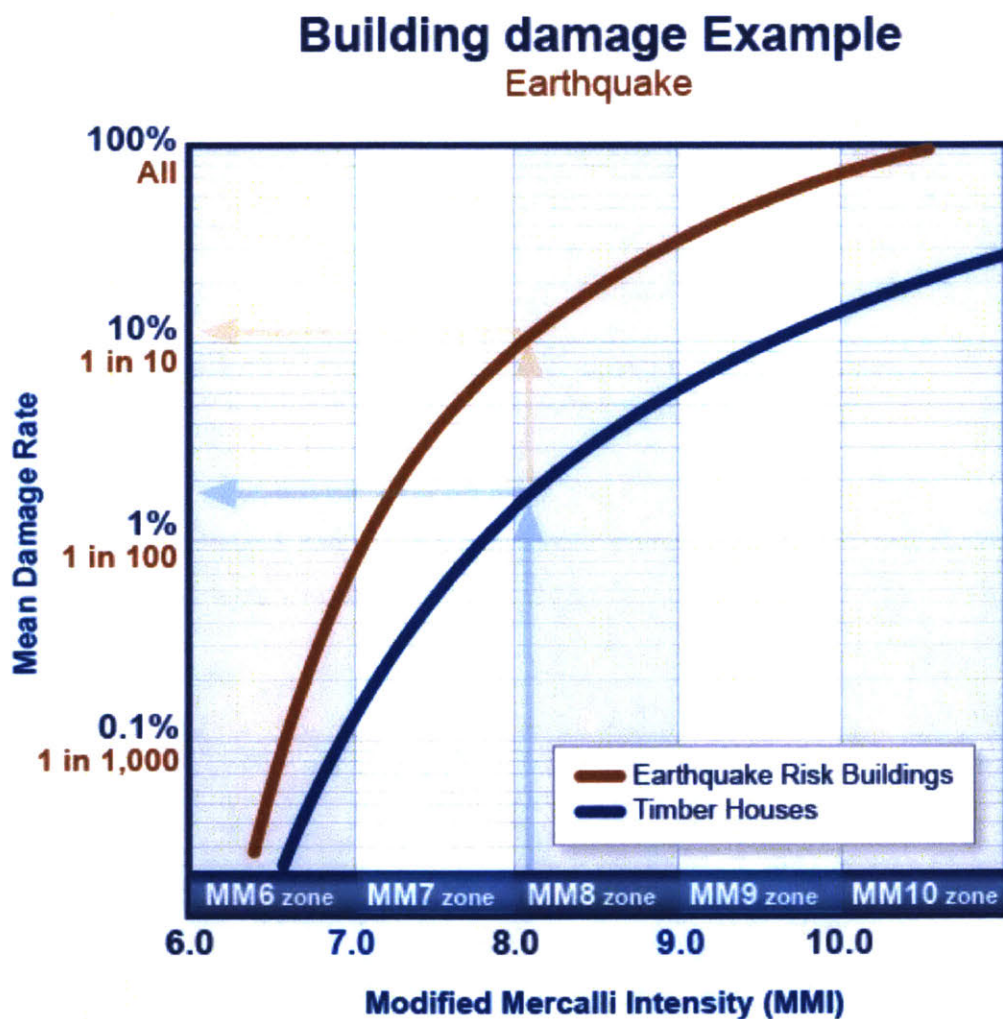
Figure 4. Building Damage Example, after *RiskScape* [2011]. The graph show the expected damage or Mean Damage Rate for two different types of buildings, "risk buildings" (such as unreinforced masonry buildings), and "timber houses," for a range of earthquake shaking intensities. This is an example of a vulnerability function.

Table 3. Vulnerability Functions Developed by RiskScape.

Developed Fragility functions

Impacts		Earthquakes	Volcanic ash	Floods	Tsunami	Wind
Direct impacts						
	Buildings	●	●	●	●	●
	Content	●	●	●	●	●
	Vehicles	●		●	●	
	Roads		●	●		
	Water supply netwk	●	●	●		
	Sewage netwk	●	●	●		
	Stormwater netwk	●	●	●		
	Telecommunications					
	Power netwk	●		●		
	Agricultural		●			
Indirect impacts						
	Displacement	●		●		
	Business disruption			●	●	
	Loss of revenue			●		
	Traffic disruption					
	Injuries	●		●	●	●
	Fatalities	●		●	●	●
Social vulnerability						
	Deprevation index	●	●	●	●	●

● implemented

The City of Portland, Oregon, lies at the confluence of the Willamette and Columbia Rivers on the Oregon and Washington State border in the Pacific Northwest (Figure 5). The city is in Multnomah County, but the metropolitan area also includes portions of six other counties. As defined by the U.S. Census Bureau, the Portland metropolitan area encompasses the larger cities of Beaverton, Gresham, and Hillsboro in Oregon, and Vancouver, Washington [2010b], which lies on the northern bank of the Columbia River. The Census Bureau estimated the population of the metropolitan area at 2.24 million in 2009 [2010b], placing it in the top 30 metropolitan areas in the country. The tourist, downtown, and old town areas lie on the western bank of the Willamette River at the base of the Portland Hills (labeled "Forest Park" in Figure 6).
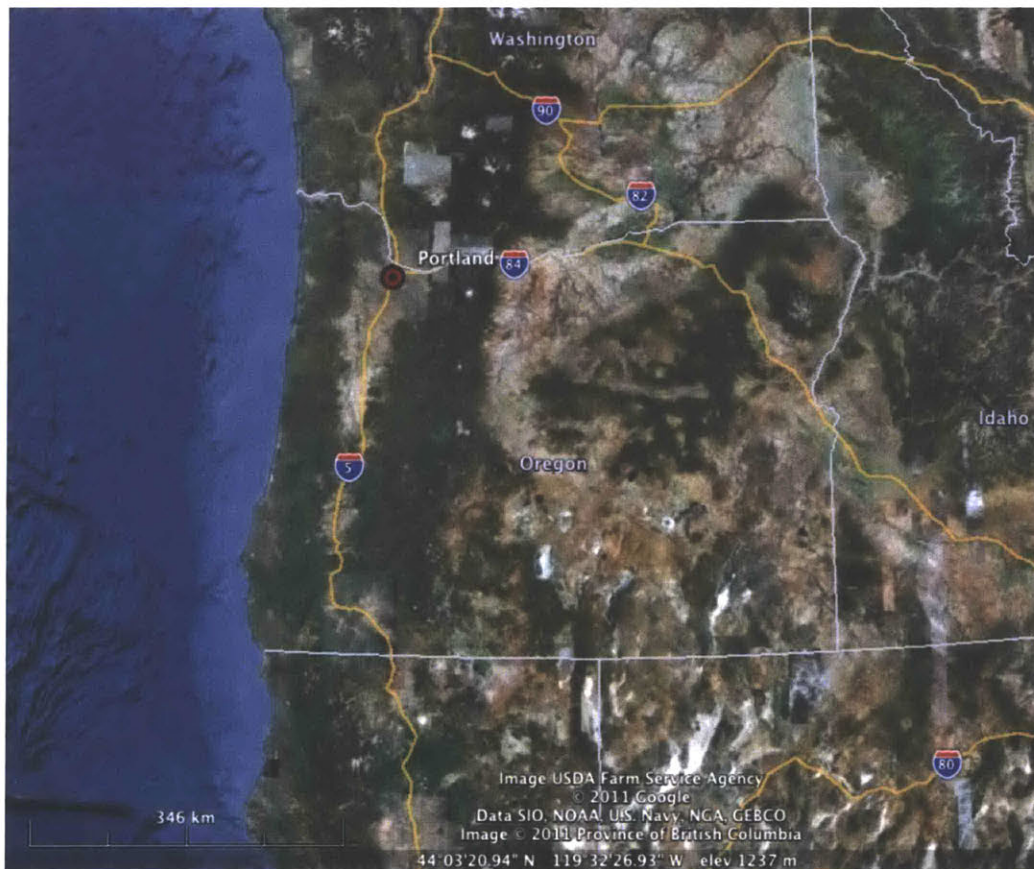
Figure 5. Map of Pacific Northwest. Satellite imagery from Google Earth, showing the location of Portland on the Oregon-Washington border within the Willamette Valley.
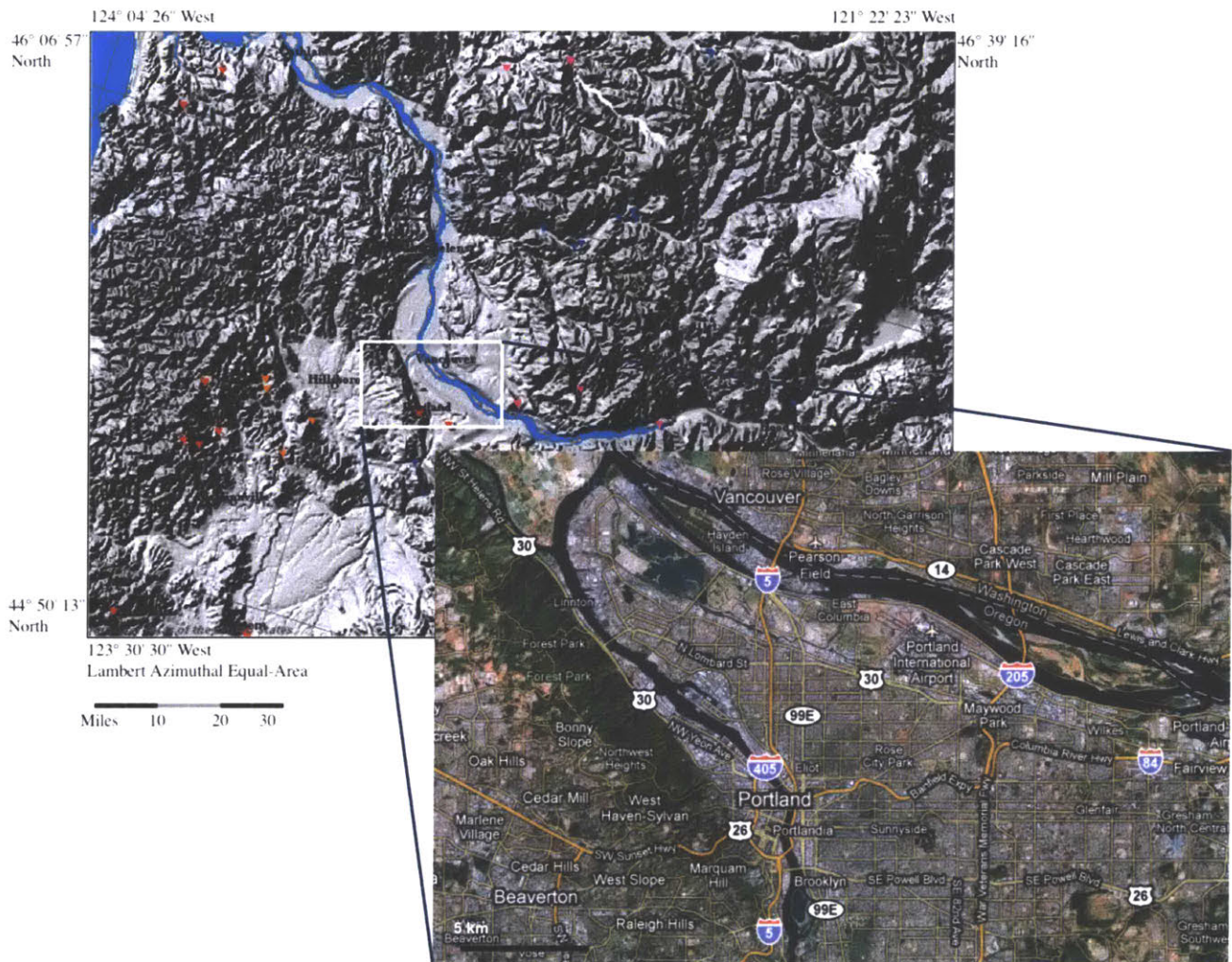
Figure 6. Portland Relief and City Map. Relief images of the Willamette River Valley from National Atlas and satellite imagery from Google Earth give a closer view of the city's local topography and layout. Red, orange, and pink triangles denote a dam.

A more detailed neighborhood map is available in Appendix A. The Portland International Airport (PDX) lies within the city limits on the south bank of the Columbia River, just a few miles downstream of several dams. The Portland wastewater treatment facility is also within the city, west of Interstate 5 at the confluence of the two rivers.

REGIONAL TECTONICS AND GEOLOGIC HISTORY

The geology, topography, volcanic and seismic activity in western Oregon are a consequence of the continuously evolving and active plate boundaries just off the Pacific

coastline. A series of extensional and convergent episodes throughout the Phanerozoic Eon led to the development of the Cordilleran orogen, which comprises most of the western half of the United States [*Burchfiel et al.*, 1992]. Oregon lies in the western accretionary zone of the orogeny, which is comprised of tectonically accreted exotic terranes and numerous volcanics (accreted, plutonic, and extrusive) [*Burchfiel and Crosby*, 2005]. To the east of the accretionary zone are deformed passive margin sediments overlying Precambrian basement (Figure 7).

Between 650-600 Ma, North America experienced extensive rifting off what is today the western margin of the continent. This rifting created a passive margin with a flexural hingeline that trends through Nevada, which subsided rapidly, allowing for extensive non-marine (terrigenous and deltaic) sedimentation [*Burchfiel et al.*, 1992; *Burchfiel and Crosby*, 2005]. From the Cambrian to the Late Devonian, sedimentation at the margin shifted to shallow marine deposits as subsidence decreased with cooling of the extended crust. At the same time, volcanic arcs were forming in the PaleoPacific Ocean. By the End Devonian (355 Ma) the margin switched from passive to active, as subduction of the western North American thin crust underneath the PaleoPacific (east-dipping) thrust the passive margin sediments onto the continent, creating the Antler Orogeny (Figure 8). The Robert's Mountain thrust on the eastern edge of the orogeny loaded the North American crust to create the Antler foredeep basin [*Burchfiel et al.*, 1992]. This foredeep filled with erosional material from the Antler Orogeny, indicating that the west was topographically high (the beginning of mountain building) until around ~350 Ma, when new sedimentation began on top of the orogenic belt [*Burchfiel and Crosby*, 2005]. This processes of thrusting basin sediments and then eroding them greatly extended the western margin and continued through the Late Permian, driven by the collision of volcanic island arcs with the margin [*Burchfiel et al.*, 1992]. In this period, (Late Paleozoic) a

large left lateral transform fault developed along the south-southwestern margin of North America, removing previously accreted terranes (Figure 8).

By the Triassic, the western margin had switched from west-dipping subduction of North America to east-dipping subduction underneath North America, resulting in accreted oceanic crust, arc magmatism, and evolving fold and thrust belts to the east [*Burchfiel and Crosby*, 2005]. Between 165-130 Ma, several large batholiths and plutons intruded these accreted terranes in eastern and southwestern Oregon, resulting in the first rocks to originate in Oregon (which did not exist prior to accretion) [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. Following

these intrusions and through the Late Cretaceous, marine deltaic and terrestrial sediments were deposited from NE to SW Oregon, indicating that this was the edge of the margin [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. During the mid- to Late Cretaceous, the Franciscan subduction complex was accreted, deformed and metamorphosed to the continental margin in modern California and southwest Oregon [*Burchfiel et al.*, 1992]. Arc magmatism from the subducting slab halted abruptly during the end Mesozoic, as the subducting

Figure 7. Western U.S. Cordillera, after *Burchfiel et al.* [1992]. This diagram shows that Oregon is entirely accreted material that occurred due to the convergence of the PaleoPacific Ocean and the North American plate, beginning in the early Paleozoic.

Farallon plate (PaleoPacific) began to shallow out, resulting first in the western, thin-skinned Sevier fold and thrust belt, and then in the eastern Cordilleran Laramide orogeny within the stable craton [*Burchfiel et al.*, 1992]. The uplift of the Laramide orogeny was followed by eastern migration of magmatism and rapidly increasing convergence of the two plates. Between 62 and 49 Ma, "basalts [island arcs]
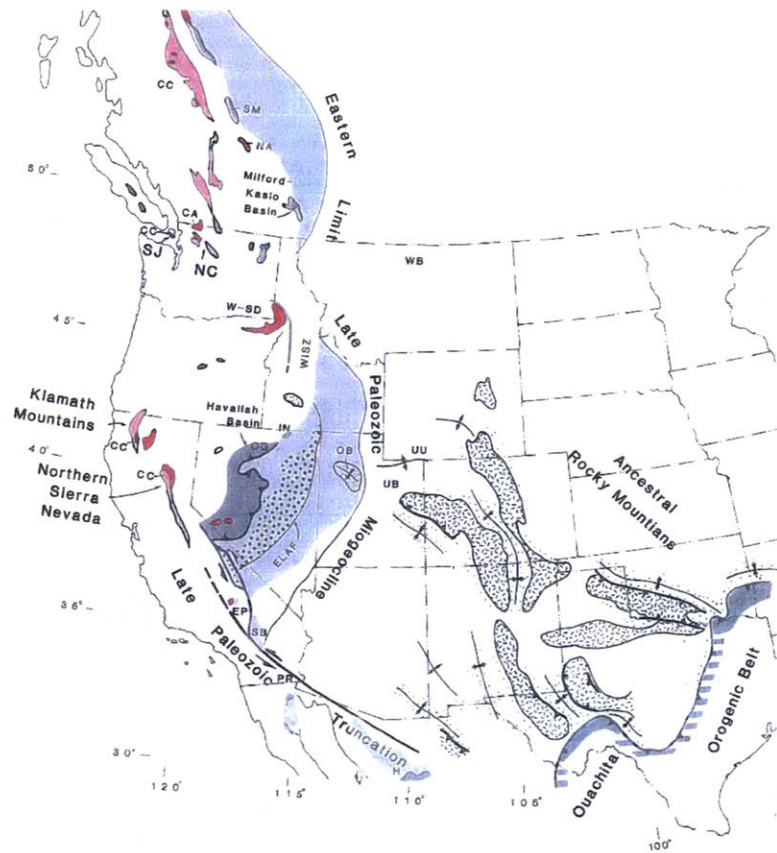
Figure 8. Late Paleozoic to Early Mesozoic Evolution of the Cordillera, after *Burchfiel et al.* [1992]. Accretion of the Havallah Basin onto the Antler orogeny, with truncation of the southern margin. At this time, the majority of modern Oregon had not accreted.

accumulated in coastal Oregon (Roseburg and Siletz River volcanics), Washington (Crescent Formation), and southern Vancouver Island (Metchosin Formation) to form the basement of the Coast Ranges" [*Burchfiel et al.*, 1992]. The Siletz island arc terrane was the last accretion to Oregon's coast, occurring around 60 Ma [*Oregon Dept. of Geo. and Min. Indus.*, 2009].

The Eocene through Miocene Epochs are characterized by heavy volcanism and sedimentary deformation associated with the subduction zone, building up most of the rocks in Oregon. Arc magmatism from the subducting Farallon plate began again in Oregon in the Early Eocene (~52 Ma), marking the beginning of broad magmatism across most of the eastern two thirds of the state. During this period, sedimentary sequences of shale and sandstone accumulated on the Pacific shoreline and then were uplifted, folded and faulted due to the

subduction offshore [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. After the Farallon plate subducted completely under North America around 38 Ma, the relative motion between the Pacific and North American plates resulted in a transform fault (Figure 9) [*Burchfiel and Crosby*, 2005]. The remaining fragments of the Farallon are the Cocos plate to the south and the Juan de Fuca plate, which is currently being subducted under North America off the coast of Oregon, Washington, and British Columbia.

Another episode of regional extension, the Basin and Range Province, began in the Cordillera during the Early Miocene. The Basin and Range province stretches across relatively high relief through modern Oregon, California, Nevada, Idaho, Utah, Arizona, New Mexico, and Mexico. Though the mechanism for this extension is debated, *Magill et al.* [1982], *Wernicke et al.* [1989], *Wells* [1990], *Bird* [2002], and *Burchfiel and Crosby* [2005] suggest that the oblique subduction of the Farallon and subsequent micro plates has translated in some places (such as California along the San Andreas fault) to transform faulting and clockwise rotation in the Pacific Northwest, the interplay of which
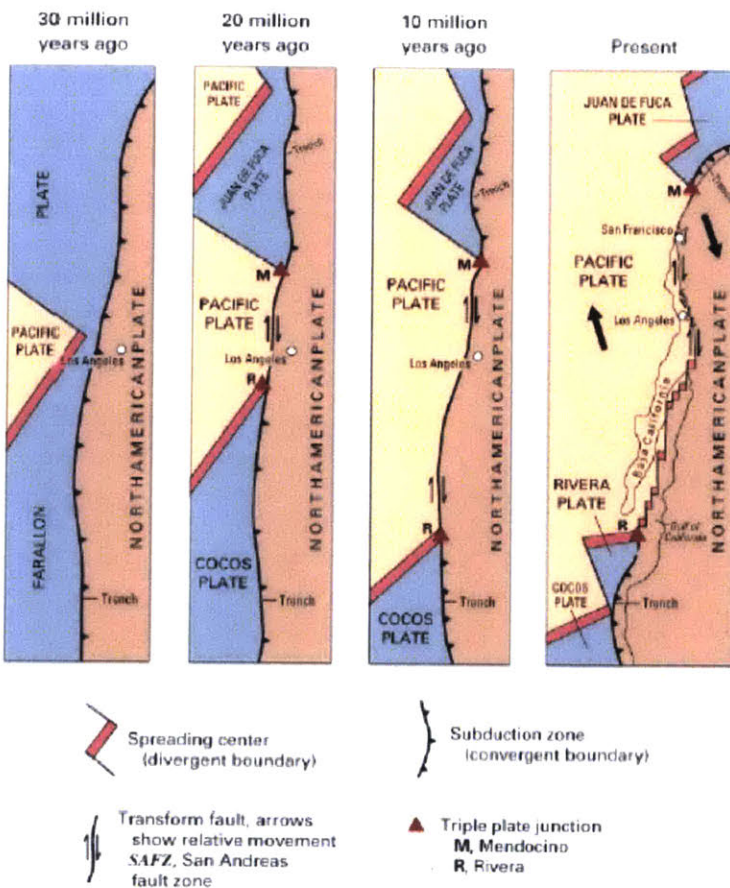
Figure 9. Subduction of Farallon Plate, after *Kelley* [2008]. Depicts the progression of the Farallon subduction beneath the North American plate, resulting in the evolution of transform boundaries and two micro plates, the Cocos and Juan de Fuca.

could account for extension. Additional theories suggest that the extension is from the gravitational collapse of the over-thickened crust [*Gans and Miller*, 1993] or rollback of the Farallon plate. It is likely that this motion is the interplay of many different geologic processes.

In the Late Miocene, over 175,000 cubic kilometers of basalt was erupted in northeastern Oregon, southeastern Washington, and western Idaho. This event, now known as the Columbia River flood basalts, originally covered half the state of Oregon, reaching as far west as the coast line and as far south as the modern California border [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. Explanations for this intense magmatism—one of the largest flows on earth—vary, but studies conducted in *Hooper et al.* conclude that the source of the flows was likely a mantle plume (or hot spot) [2007].

Oregon has experienced ongoing magmatism since the Columbia River flood basalts. As North America continued to move west (relative to modern directions) due to the spreading of the Mid-Atlantic Ridge, the hotspot underneath the continent remained stationary, leaving a trail of volcanoes in its wake (similar to the Hawaiian Island chain). Oregon geologists claim, in the Middle Miocene to Pliocene, the heat from the plume caused crustal rifting in the southeastern part of the state, creating numerous cinder cones and large calderas as well as several extension features. The Rattlesnake Tuff, erupted around 7 Ma, covered one fifth of the state in rhyolitic ash. These features are part of the Basin and Range Province, though it is unclear if these volcanic events were caused by heating the crust or one of the other mechanisms mentioned previously [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. Around this same time, much of Oregon was covered by inland waters that deposited a variety of sedimentary sequences in some of the basins caused by the extension, as well as in the early Willamette River valley.

Much of the most recent magmatism in Oregon is in the Cascade Range. Figure 10 shows the extent of the basaltic flows and andesitic eruptions over the past 6 million years. Some of the larger volcanoes, such as Mount Mazama (now known popularly as Crater Lake), have erupted more than 200 cubic kilometers of material, covering 8 states and 3 Canadian provinces [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. Approximately 3 Ma, young volcanoes in central and southeastern Oregon began erupting large volumes of basalt, creating the Oregon High Desert. The most recent volcanism in Portland is the Boring Lava Field, which is Plio-Pleistocene in age. There are over 20 eruptive centers in the field, but the vents have been inactive for about 300,000 years [*Cascade Volcano Observatory*, 2007].
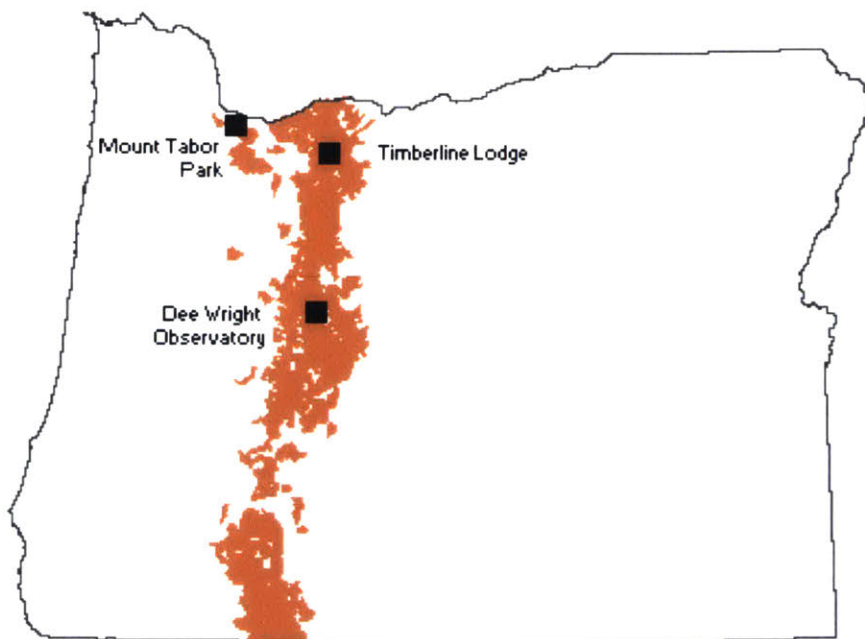
Figure 10. High Cascade Volcanism. The map, taken from *Oregon Department of Geology and Mineral Industries* [2009], shows the extent of Cenozoic volcanism in the Cascade Range in Oregon. This volcanism is the result of flux melting from the subducting Juan de Fuca slab. More about subduction volcanism in Chapter 6.

REGIONAL GEOLOGY

The tectonic history of Oregon has led to the development of a complex landscape of mountain ranges, volcanoes, river valleys and extensional features. Now that the geologic stage has been set, we move to a brief discussion of Late Tertiary activity in the Portland area.

Portland lies within an active margin of tectonic activity, bordered by two mountain ranges that define the limits of the Willamette Valley. The Willamette Valley is located between the Coast Range and the Cascade Range in western Oregon (Figure 11). This valley is filled with fluvial deposits from the last 2 million years, as well as glacial and flood deposits from the end of the last ice age (seen in Figure 12 as the Missoula flood deposits) [*Oregon Dept. of Geo. and Min. Indus.*, 2009]. The stratigraphy in the Portland Basin itself is a result of the deposition of Willamette and Columbia River deposits, volcanic debris, flood deposits, lava flows, and recent crustal tectonics. *Pratt et al.* [2001] found vertical displacements in these formations to suggest recent faulting in the shallow crust, which will be explained more in depth in Chapter 5.
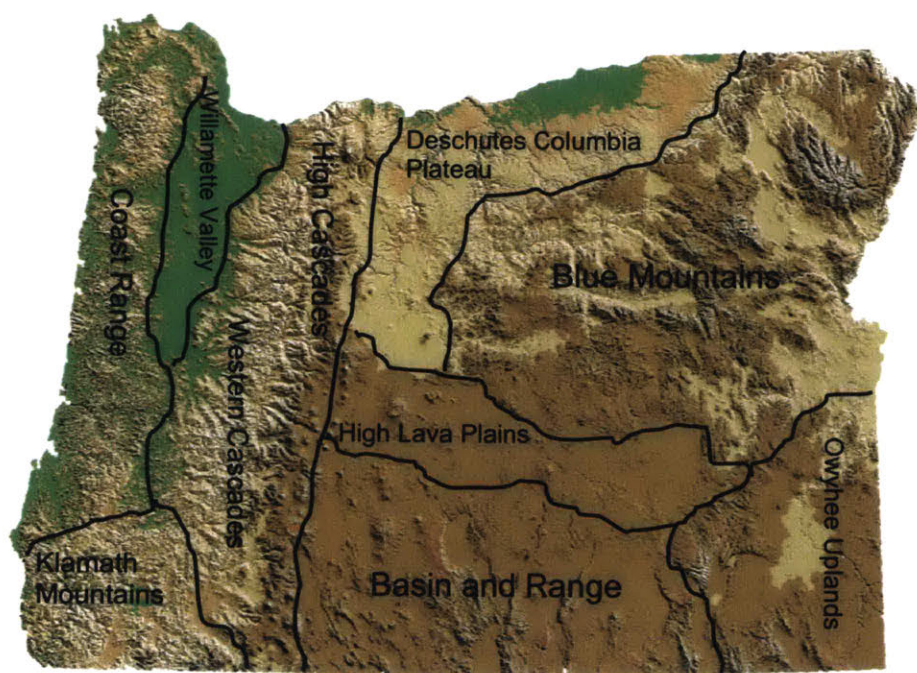
Figure 11. Geologic Provinces in Oregon. DEM image developed by the USGS and available in the public domain. Modified to include boundaries between mountain ranges and other geologic provinces. Portland lies on the northern edge of the Willamette River valley.

REGIONAL CLIMATE

To better understand the risk of seismic and volcanic events, we will give a brief introduction to Portland's climate and an extended overview of the main climactic hazard facing Portland: flooding. This overview will give some context for the non-tectonic hazards facing
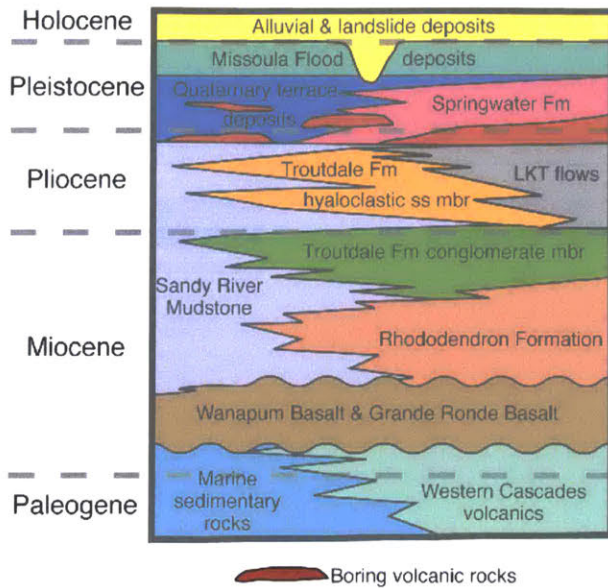
**Figure 12. Portland Basin Stratigraphy, after *Evarts et al.*
[2009]**. Schematic of upper ~400m of stratigraphy underlying
Portland. Post-glaciation flood deposits and Boring Lava
flows represented.

Portland, while also providing information on the factors that can complicate or exacerbate hazards from earthquakes and volcanoes.

Oregon's climate varies greatly across the state, from the western temperate rainforests to the high deserts of the eastern lava plains. The variations in climate are most visible from the precipitation map (Figure 13). The city of Portland has a generally mild climate, with average high temperatures ranging from 46.1°F in January to 81°F in July [*Trimble*, 1963]. More than three-fourths of the annual precipitation falls during the 6-month period from October through March, and there are long frost-free growing seasons [*Trimble*, 1963].

The map in Figure 13 clearly shows the rain shadow effect of the Coast Range: there is a stark contrast between the rainfall in the west coast rainforests and more mild precipitation in the Willamette Valley. The rain shadow created by the Cascade Range is also visible. Rain shadows are created when the moist Pacific Ocean air is carried eastward by the prevailing winds. As the air rises up the side of the Coast Range, it cools adiabatically and releases its moisture. One the air reaches the ridgeline, it is much drier and warmer, creating a more stable climate within the valley. The valley also receives the annual snowmelt from the western flanks of the Cascades, which collects in the Willamette River before it joins the Columbia River in downtown Portland. This basin topography and heavy precipitation patterns result in several floods per season in the

Portland area. In the past 30 years, Portland has suffered more than $200 million in flood-related damages, and the Multnomah County dike system protects more than $20 billion worth of property, including the Portland International Airport [*POEM*, 2010]. Flooding can also cause private property damage, render roads and bridges unusable, cause debris flows, and damage agricultural crops. We will give an overview of the types of flooding that occur and the hazards Portland faces in light of these floods.
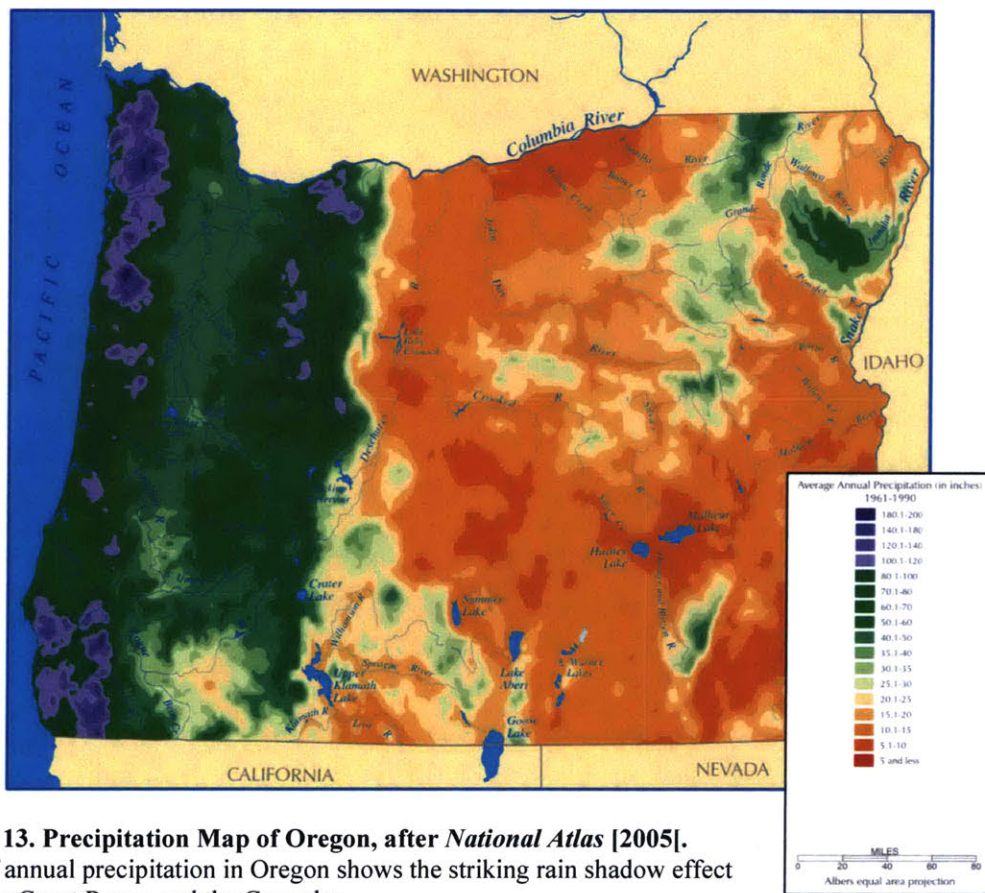
Figure 13. Precipitation Map of Oregon, after *National Atlas* [2005[.
Map of annual precipitation in Oregon shows the striking rain shadow effect from the Coast Range and the Cascades.

Floods occur when the influx of water exceeds the carrying capacity of the river. In the Portland area, both riverine and flash floods can be attributed to either urbanization of the area or to dam and dike failures [*Oregon Emergency Management*, 2010b]. Extreme changes in precipitation patterns can also contribute to flooding. Urbanization is a primary cause of flooding

in areas that would otherwise naturally mitigate heavy rain fall or snowmelt flow. When land is developed and paved, and storm drains are installed as direct arteries into the rivers, water flows much more quickly into the river than it otherwise would. Natural systems slow and extend the return rate of water into rivers by filtering it through sediments, natural aquifers, and vegetation buffers along the rivers [*POEM*, 2010]. Portland has also built over 31 miles of levees (or dikes) to protect the property built up along the banks of both the Willamette and Columbia Rivers [*POEM*, 2010]. This type of development only further exacerbates the problems created by paving and adding storm drains. Rivers have natural flood plains that become filled with water during high flow periods. These floods are also opportunities for the rivers to deposit sediment onto the banks of the river [*POEM*, 2010]. By developing right up to the riverbanks and building levees, Portland has placed properties in the natural flood plain of the river and also created a sediment problem. If the river cannot naturally deposit its sediment on the riverbanks, the sediment will eventually settle out of the flow and onto the riverbed. Over time, the riverbed will thicken and the height of the river will rise, forcing the city to either build higher levees or dredge the river in order to protect Portland from even more floods. But even reinforced, higher levees are not infallible.

Levees and dams are susceptible to breaches due to bad weather or an earthquake, creating an additional hazard from either tectonic or climatic events. Over the last 100 years, over 50 manmade dams have failed throughout Oregon [*Oregon Emergency Management*, 2010b]. Portland is at particular risk of dam failure because it lies on two rivers that have a significant number of dams built upstream. Figure 14 is a map generated by the U.S. Army Corps of Engineers depicting Oregon dams with high hazard potential. It shows at least 6 dams along the Columbia River upstream of Portland with a high risk. There are several other dams on

smaller rivers in the foothills and mountains surrounding the Portland area that, if breached, would drain into the Portland Basin.
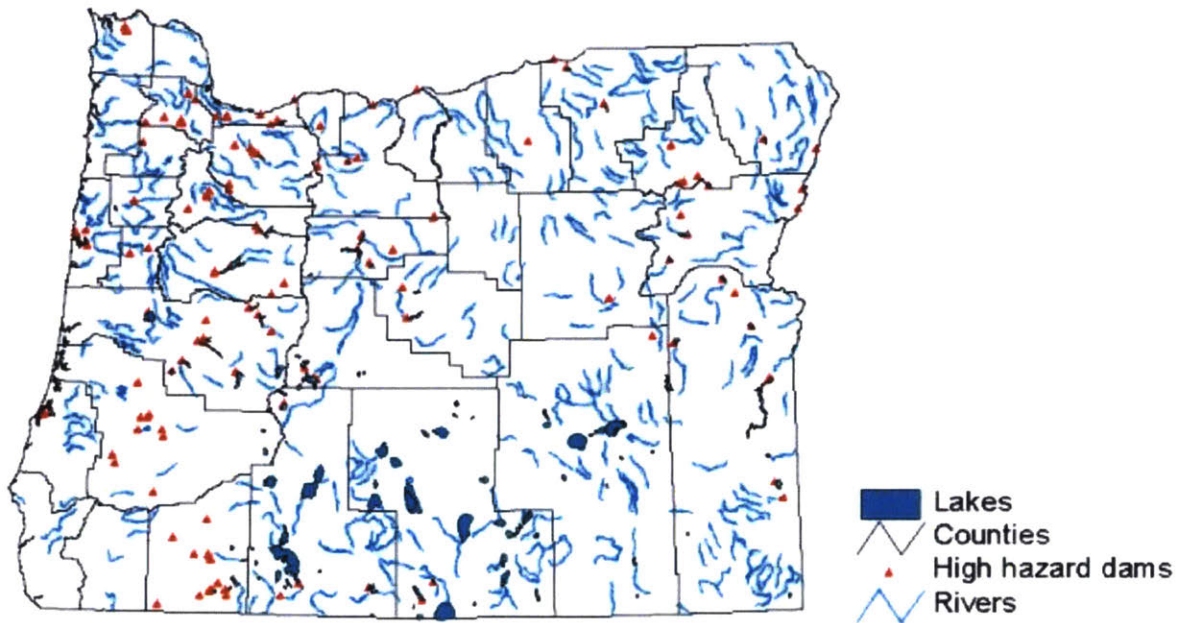
Figure 14. High Hazard Dams in Oregon, after *Oregon Emergency Management* [2010b]. High hazard dams, or dams with a high probability of rupturing and releasing large volumes of water, are denoted with red triangles.

In addition to urbanization and river control, there are other factors that increase the risk of climatically induced hazards in Portland. Urbanization has resulted in deforestation on many of the steep slopes in Portland, creating the opportunity for sediment mobilization after a storm in the form of landslides or debris flows. These mass wasting events can block transportation routes and cause significant property damages. The high density of agricultural land also presents the potential for large loses.

The final climatic consideration related to flooding is the impact of climate change on monthly and annual river flow. Pacific Northwest rivers rely on the current pattern of rainfall in the winter months at low elevations and snowmelt in the summer months (see Figure 15). If climate change predictions for Oregon are accurate, the 6-degree temperature increase by 2080 could mean that Portland experiences significant flooding during winter months (due to more

precipitation falling as rain), and droughts during the summer months (due to loss of snowmelt) [*POEM*, 2010]. The city has already seen some of these effects in recent years: in December 2008, the city "experienced three major snowstorms that produced historically significant snowfall amounts," and in the following July, a heat wave broke several records for the area [*POEM*, 2010].

To better understand the entirety of the risk facing Portland from natural disasters, it is critical to integrate an understanding of flooding and climate change hazards. Though this study does not analyze climate or hydrology models in depth, this basic understanding of riverine processes will be applied to the discussion of seismic and volcanic hazards.
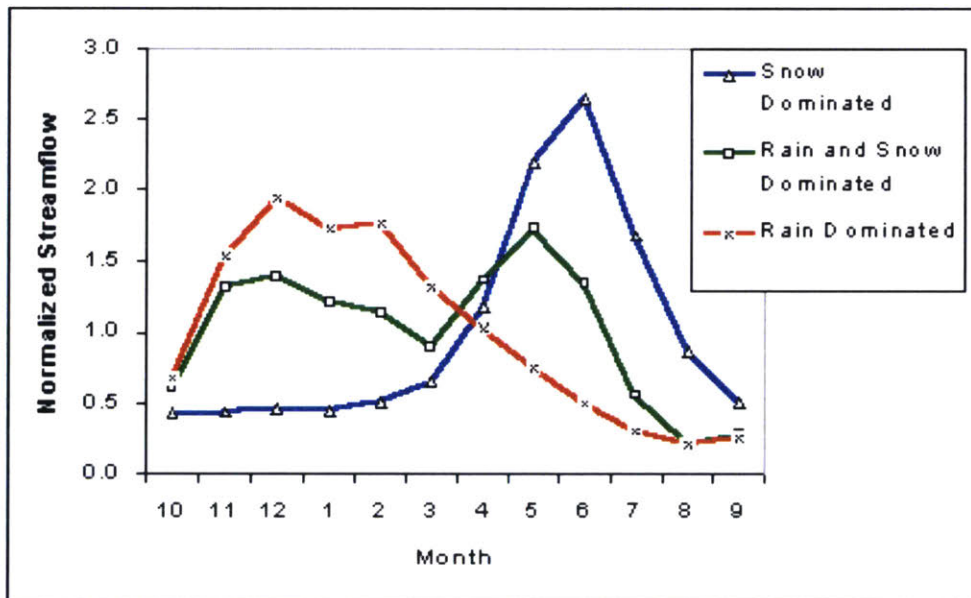
Figure 15. Seasonal River Flow by Precipitation in Oregon. After *Climate Impacts Group.* If more precipitation converts to rain fall instead of snow melt, the red curve will peak in the winter months (indicating flooding), while the blue and green curves lower substantially, indicating drought during the summer and spring months.

VULNERABLE POPULATIONS

As discussed in Chapter 2 on methods, risk is generally defined as the intersection between a natural hazard and system vulnerability (Figure 2). When looking at natural disasters, risk is determined by the probability and intensity of certain hazards (such as liquefaction, or landslides), with consideration given to the people who will be impacted by these events. In this

section, we identify which specific socio-economic populations in Portland are most vulnerable in the event of a disaster. Though most of the literature on vulnerability assesses large populations at the sub-national level, we are looking to define specific characteristics of *individuals* that might make them more susceptible to natural hazards, in order to better inform Portland emergency management outreach and educational efforts. Later chapters will discuss relative geographic or environmental vulnerability of the city as a whole on a hazard-by-hazard basis. The populations discussed here are likely to be the *most at risk* within their communities, given any hazard or event, because they are least able to prepare or recover from any natural disaster.

B.H. Morrow, quoted in *Elliott and Pais* [2006], argues that "'defense in depth'—the economic security, political and social influence, and personal power of the professional classes" is "especially crucial in times of crisis." As discussed in Chapter 2, vulnerability to a hazard is defined by an individual or group's ability to prepare, respond and recover to a natural disaster. The literature identifies several quantifiable factors that are correlated with an individual or household's ability to address natural disasters: wealth, age, race and ethnicity, physical health, housing tenancy, occupation, and insurance (housing and health being the most obvious) [*Cutter et al.*, 2003; *Schneiderbauer and Ehrlich*, 2006]. *Cutter et al.* finds that access to wealth is the most dominant factor in explaining the variance in vulnerability across U.S. counties: "lack of wealth is a primary contributor to social vulnerability as fewer individual and community resources for recovery are available, thereby making the community less resilient to the hazard impacts" [2003]. Oregon Housing and Community Services found that populations in poverty tend to have less access to utilities, healthcare, employment opportunities, and affordable and permanent housing [2004], each of which influence vulnerability. Data from Census surveys

over the past decade reveal these factors to be interrelated. To explain these relationships, we have developed a framework of vulnerability for Portland.

If we accept that access to health insurance, employment, permanent residences, and home (or disaster) insurance are necessary factors to preparing for and recovering from a natural disaster, then the first logical step is to determine what factors lead to increased or decreased access to these resources. We have developed a model for understanding these relationships based on an analysis of socio-economic data for the city of Portland and the state of Oregon, which will be presented in detail in the coming paragraphs. We can separate theses traditional indicators of vulnerability into two categories: root causes and resource outcomes. Figure 16 depicts the contributory relationship between the causes (race, education, and poverty) and outcomes (employment, health insurance, housing tenancy and disaster insurance). The data suggest several relationships: (1) race influences income and educational attainment; (2) race influences access to health insurance, employment, and permanent residences; (3) educational attainment influences future earnings; (4) educational attainment influences employment opportunities; (5) employment status influences income (and perhaps vice versa); (6) poverty influences access to health insurance and permanent housing; and (7) housing tenancy influences access to disaster insurance. Each of these relationships is intuitive to some degree, though we cannot say with certainty that the following observations illustrate causal rather than correlative relationships. The following paragraphs present data to better explain the relationships outlined in Figure 16.
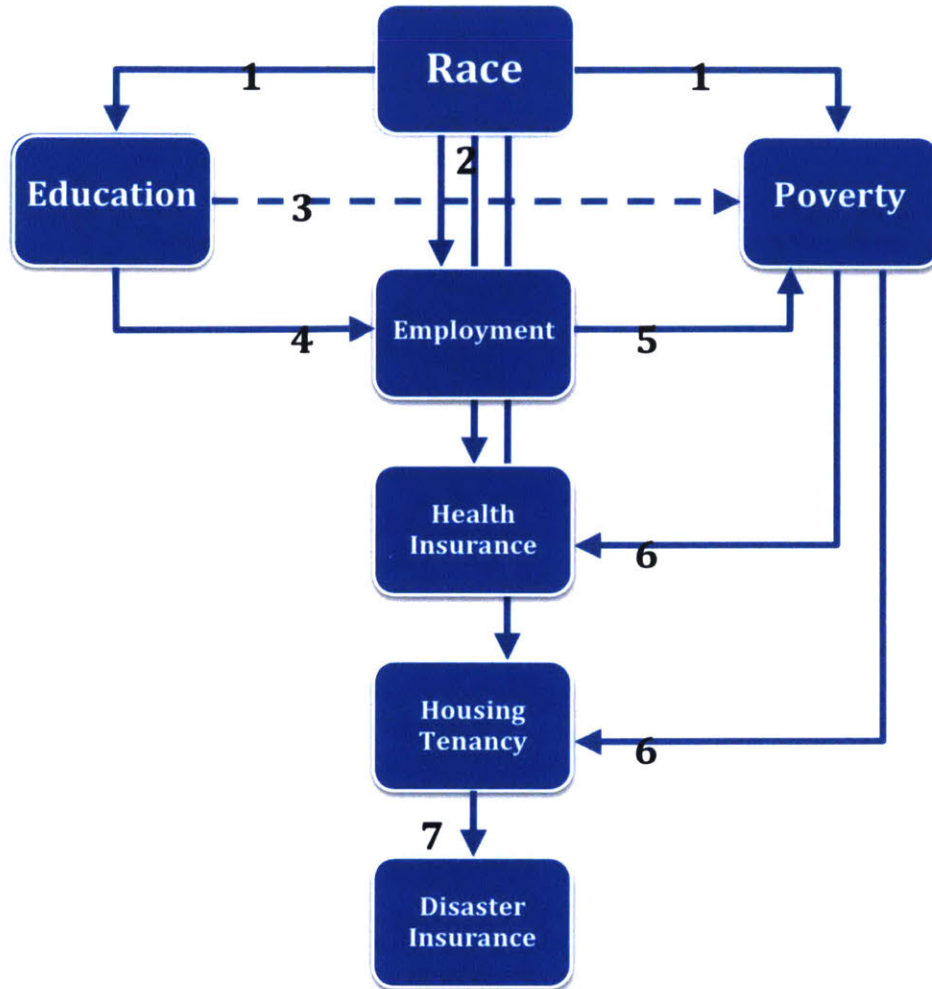
Figure 16. Vulnerability Framework. This conceptual framework demonstrates the relationships between root causes of vulnerability—race, education, and poverty—and the outcomes of factors that make populations less capable of preparing for, responding to, and recovering from natural disasters.

Educational attainment, or the highest level of education achieved by the population 25-years and older, is an important consideration for determining vulnerability to natural hazards. In Portland, the single best predictor of educational attainment is race, and educational attainment is strongly correlated with other important vulnerability indicators, such as income (poverty status) and employment opportunities. Figures 17 presents the breakdown of educational attainment for

Asian and Hispanic residents in Portland.[4] Hispanic residents are the least likely to have received a high school diploma (57% probability) or college degree (34% probability) [*U.S. Census Bureau*, 2009a]. Over 90% of the White population in Portland has attained at minimum a high school diploma, and over 69% of the Asian population has received a Bachelor's degree at minimum. These enormous disparities by race/ethnicity in education level indicate differential vulnerability based on race, since we also find that race and educational attainment are correlated with poverty in Portland.

Education of Asian Population in Portland

- Less than high school diploma
- High school graduate, GED, or alternative
- Some college or associate's degree
- Bachelor's degree or higher
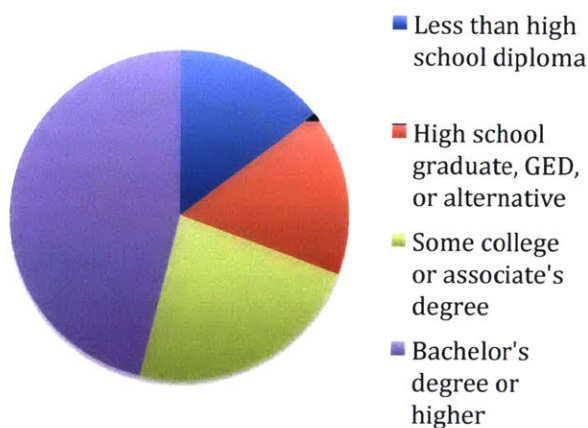
Education of Hispanic Population in Portland

- Less than high school diploma
- High school graduate, GED, or alternative
- Some college or associate's degree
- Bachelor's degree or higher
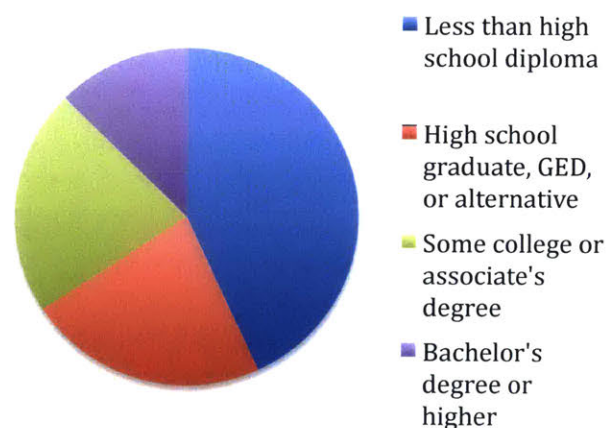
Figure 17. Educational Attainment by Race in Portland. The major disparities in educational achievement by race are most clearly highlighted when we compare the Asian and Hispanic populations of Portland.

Poverty levels in Portland were below the national and state averages in 1999 [*U.S. Census Bureau*, 2000b] and also below the national and state averages between 2005-2009 [*U.S. Census Bureau*, 2009a]. Despite this, the populations below the poverty line are still vulnerable

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[4] Several socio-economic figures were generated from Census data for this analysis. Many are not featured in the text here but can be found in Appendix A.

to natural hazards. Poverty rates for 1999, reported by race, indicate that Black and Hispanic residents have disproportionally high vulnerability within Portland, compared to their White and Asian counterparts (Figure 18) [*U.S. Census Bureau*, 2009b]. There is also evidence that lower educational attainment leads to greater poverty in Portland (Figure 19), which could in part explain the correlation between race and poverty: higher education levels are correlated with an enhanced ability to obtain employment (Figure 20).
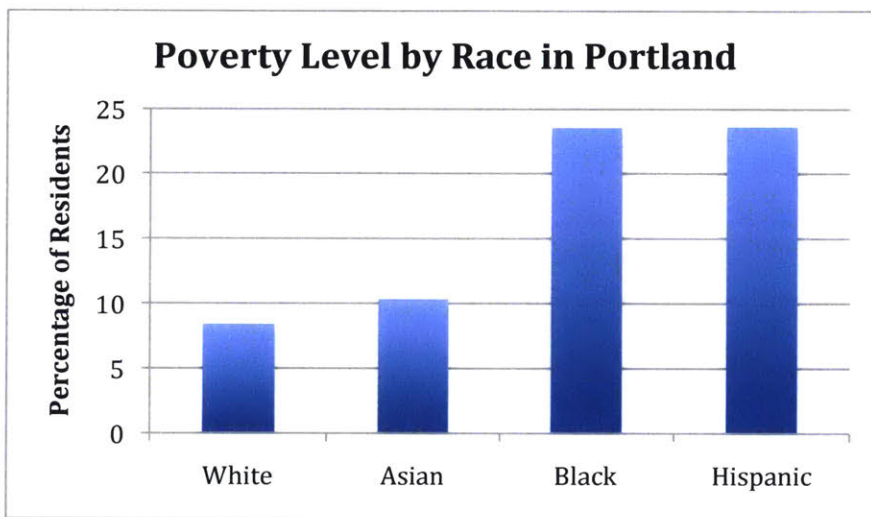
Figure 18. Poverty Level by Race in Portland. Statistics from the 2000 Census [2000b] highlight the disparity in income between the majority (White residents) and minority races. These numbers suggest that certain populations would be more at risk in the event of a natural hazard.
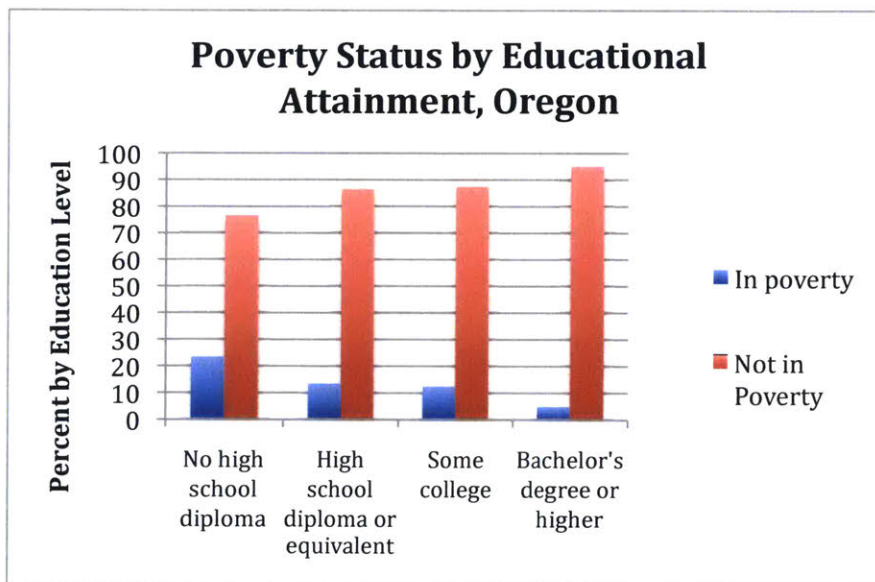
Figure 19. Poverty Status by Educational Attainment, Oregon. Statistics from the Current Population Survey [*U.S. Census Bureau*, 2010a] show a clear relationship between educational achievement and earnings (or poverty status). Based on previous information on race and educational attainment, we can infer that these factors are interrelated.

Employment by Educational Attainment, Oregon
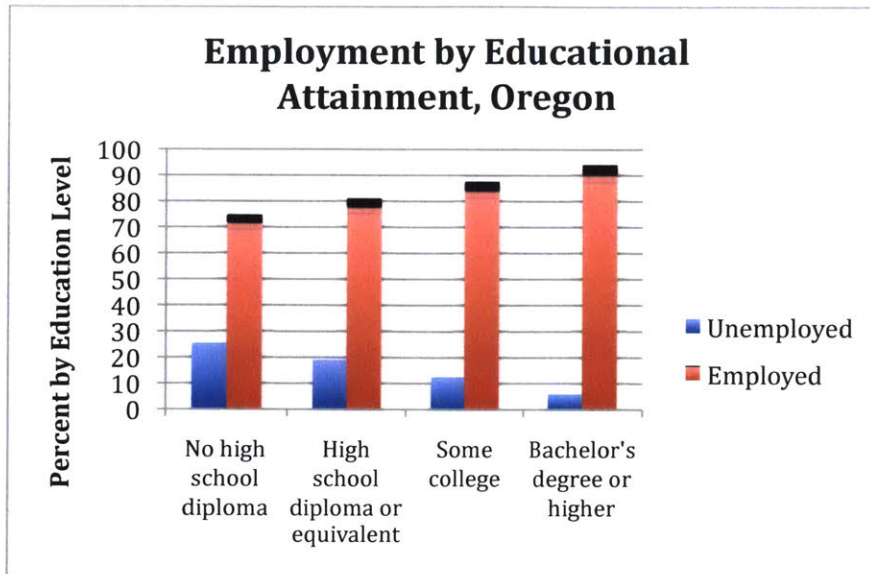
Figure 20. Employment by Educational Attainment, Oregon. Statistics from the Current Population Survey [*U.S. Census Bureau*, 2010a] show a relationship between education and ability to obtain employment in Oregon. These data are for individuals over the age of 15 in the labor force.

Portland's current unemployment rate, estimated by the U.S. Bureau of Labor Statistics at 10%, is slightly above the national average [2011]. In Portland, the unemployment rates vary widely based on race. Data from the American Community Survey [*U.S. Census Bureau*, 2009a] reveal that, for the labor force aged 16 to 64 years, unemployment rates for Black workers (at 14.4%) are 1.94 times higher than White workers, 2.28 times higher than Asian workers, and 1.6 times higher than Hispanic workers. This suggests that, because employment is a key factor to maintaining stability after a disaster, recovery rates in Portland would vary widely by race. Surveys conducted after the 2005 Hurricane Katrina disaster in New Orleans revealed that "the 'average' black worker in New Orleans is actually closer to seven times more likely to have lost his or her job than the 'average' white worker [as a result of the storm]" [*Elliot and Pais*, 2006]. Similar circumstance could befall Black residents in Portland.

Access to medical care is crucial to preparation for a natural disaster, as well as recovery from it. Nationally, the elderly are the most likely to have healthcare because of Medicare and Medicaid programs, and the poorest people are the least likely to have health coverage [*U.S. Census Bureau*, 2009b]. In Oregon, access to health insurance is related to both poverty and race

[*U.S. Census Bureau*, 2010a]. Figure 21 breaks down each racial/ethnic group by those who are insured and those who are not: Black and Hispanic populations are markedly less insured than White and Asian populations in Oregon, suggesting that physical health prior to and after a natural disaster might be a larger issue for these groups.
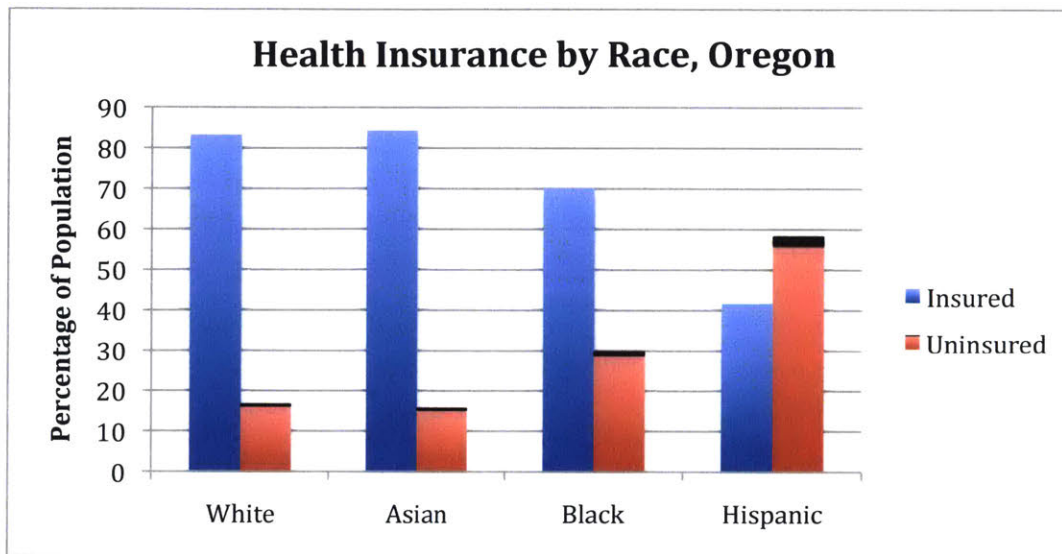
Figure 21. Health Insurance by Race in Oregon. Data from the 2010 Current Population Survey [*U.S. Census Bureau*, 2010a] show wide variation in insurance coverage between White and Asian populations and Black and Hispanic populations, adding another level of disparity to natural disaster vulnerability.

The final factor to consider is access to disaster insurance, which is strongly dependent on housing tenancy. Earthquake, flood, and disaster insurance are not required in Oregon, nor are they part of standard homeowners or renters insurance policies [*Martinis*, 2010; *Insurance Information Institute*, 2010a]. Additionally, Federal disaster relief only covers events of a severe magnitude, and this type of assistance may be in the form of federal loans rather than direct aid [*Martinis*, 2011]. If an individual cannot afford flood, earthquake, or disaster insurance, he or she cannot benefit from risk transfer, a system that shifts "damage to private real property to the insurance industry" [*Freeman*, 1999]. Thus, individuals without disaster insurance may have much more difficulty recovering than others with similar assets who have insurance. This leads us to ask the question, who has disaster insurance?

Nationally, there is a very large disparity in disaster insurance enrollment between homeowners and renters: "A 2006 Insurance Research Council poll found that 96 percent of homeowners had homeowners insurance while 43 percent of renters had renters insurance" [*Insurance Information Institute*, 2010b]. This statistic suggests that the buy-in for disaster insurance is, at most (and likely less), 43% among renters. In Portland, homeownership varies by income and widely by race/ethnicity. In 2000, the average income of a renter was lower than the average income of an owner, with 39.4% of all renters making less than $25,000 annually, compared to 13% of owners [*U.S. Census Bureau*, 2000b]. Additionally, White and Asian residents were more likely to own their homes than not, while Black and Asian populations were more likely to rent by 17% and 38%, respectively (Figure 22). Though homeowners may have more assets (and thus more to lose in the event of a disaster), those without insurance are likely to lose a higher percentage of their assets in a disaster.
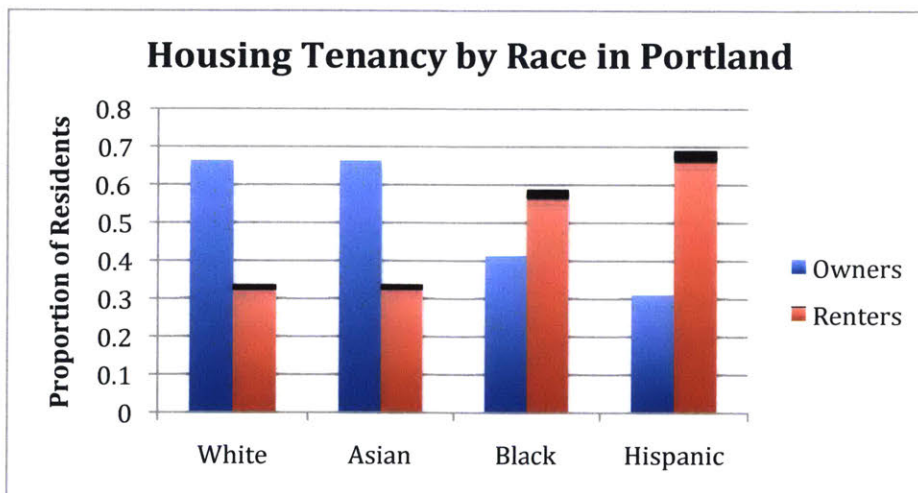
Figure 22. Housing Tenancy by Race in Portland. Data from the 2000 Census [2000a] expose the contrast in home ownership between White and Asian populations and Black and Hispanic populations. Because renters are less likely to purchase renters insurance (and thereby disaster insurance), rental populations are likely to be at greater risk of losing their possessions without

Though the population of Portland is predominantly White (77.9%) [*U.S. Census Bureau*, 2009c], preliminary results from the 2010 Census indicate that Hispanic and other minority population are growing far faster than the White population in Oregon. Given that Black and

Hispanic residents in Portland are more likely to be impoverished and unemployed, less likely to have access to health and disaster insurance, and more likely to be highly vulnerable to natural disasters, it will be critical for members of the Portland Office of Emergency Management, as well as county and state emergency functions, to reach out to these populations.

Emergency operations plans are designed to allow a regional authority to respond to any emergency of any magnitude, be it a natural disaster, train wreck or terrorist threat. Plans are written to be scalable and to utilize existing authorities, such as the police, in the response. Emergency response plans for any level of government are developed in accordance with FEMA's National Incident Management System (NIMS) and the National Response Framework (NRF). NIMS incorporates the Incident Command System (ICS) to set up and organize response agencies on site, while the NRF describes the roles and response mechanisms of governmental and nongovernmental partners. Noncompliance with these systems disqualifies authorities from receiving federal grants and funding for emergency response.

The City of Portland falls under the cover of several types of emergency management systems in addition to its own, including county, state and federal plans for natural hazard response and recovery. As the authority becomes broader, the plans become less specific to the area and residents of the city. Local authorities are the first responders for any event, but emergencies of large areal impact (such as a hurricane) or high-cost damages (such as a large earthquake) will often attract the aid and coordination of higher authorities. The series of tornadoes that ravaged the South in April 2011 brought in federal aid from FEMA in addition to the state, county and city offices that responded first [*FEMA Public Affairs*, 2011]. Portland recognizes that "a large-scale event will exceed the emergency response capabilities of the City of Portland and the state. Additional resources will be required from other states and/or the Federal Government" [*Portland Office of Emergency Management*, 2011]. This chapter will review the structure of the city, county, state and federal emergency response systems. Specific emergency plans for seismic and volcanic hazards will be discussed in Chapters 5 and 6, and the

Discussion (Chapter 7) includes an assessment of the efficacy of each emergency management system.

CITY OF PORTLAND

The Portland Office of Emergency Management (POEM) is responsible for effectively coordinating emergency preparedness, response and recovery efforts in order to protect lives, property, and the environment in the event of any emergency, disaster, or disruption to continuity of operations. POEM was created in 2003 in order to coordinate the city bureaus and agencies under the central leadership of the Mayor during emergencies [*Griffin-Valade et al.*, 2010]. The Office is intended to provide planning documents, hazards research, training exercises for response personnel, and educational outreach to the community, in addition to managing the city's Emergency Coordination Center during a crisis. They are also responsible for activating emergency warning systems [*Griffin-Valade et al.*, 2010].

The creation and maintenance of the city's emergency response plan is charged to POEM. The umbrella plan, known as the Comprehensive Emergency Management Plan (CEMP), has multiple components and is the responsibility of POEM (Figure 23) [*Griffin-Valade*, 2011]. The CEMP is designed to address all specific hazards as well as the non-hazard-specific citywide response framework. The Basic Emergency Operations Plan (BEOP), the core of the CEMP, was most recently updated in February 2011, though it is still in its draft phase. The two most recent drafts of the plan (2006 and 2011) do not contain the Functional Annexes or Hazard appendices, though POEM released a separate Natural Hazard Mitigation Plan in 2010, which discusses eight natural hazards and 102 action items to mitigate risk [*Portland Office of Emergency Management*, 2010]. The Portland Plan, a 25-year initiative of the Portland Bureau of

Planning and Sustainability to improve the city, has produced several maps of city resources, demographics, and hazards. These maps have been used by POEM in both the BEOP and the Natural Hazard Mitigation Plan.

The BEOP is designed using the National Incident Management System (NIMS) framework, which allows POEM to coordinate and utilize existing Portland bureaus and offices during an emergency. The plan assigns bureaus the responsibility of leading the response or maintaining specific disaster plans for certain hazards. In the case of an earthquake hazard, the Portland Bureau of Transportation (PBOT), police department and fire department would lead the response, and during volcanic hazard, PBOT is the lead. In emergencies impacting large areas or requiring multi-bureau coordination, the Emergency Coordination Center, staffed by POEM, would become activated. When not responding to an emergency, POEM and the various bureaus are charged with developing plans, training responders, holding simulation exercises, and establishing communication systems and response facilities. The Disaster Policy Council (DPC), comprised of representatives from several city bureaus, "advises the mayor on public policy decisions necessary in an emergency event" [*Portland Office of Emergency Management*, 2011]. POEM is responsible for producing and maintaining DPC meeting records, including the agendas, minutes, exhibits and attendance [*Griffin-Valade*, 2011].

The Natural Hazard Mitigation Plan, released in early 2010, provides hazard profiles for earthquakes, severe weather, floods, landslides, erosion, wildland urban interface fires, invasive plant species, and volcanic activity. The plan also approximates potential damages based on vulnerable population and hazard occurrence estimates. POEM is likely using this plan to fulfill the Hazard Specific Appendices and Natural Hazard Mitigation—Risk Reduction Strategy components of the CEMP (Figure 23).

Comprehensive Emergency Management Plan

Basic Emergency Operations Plan	Draft report February 2011

Functional Annexes
 	
    A. Coordination, Direction and Control
    B. Communications
    C. Notification and Warning
    D. Emergency Public Information
    E. Population Protection
    F. Mass Care/Emergency Assistance
    G. Health and Medical
    H. Resource Management
    I.   Public Works
    J.   Fire
    K. Law Enforcement
	Sub-Plans do not exist

Hazard Specific Appendices
 	
    1. Chemical, Biological, Radiological, Nuclear and Explosive
        a. Hazardous Materials
        b. Terrorism
    2. Earthquake
    3. Severe Weather
        a. Snow and Ice
        b. Severe Weather Warming Center
    4. Flood
    5. Wildland Urban Interface Fire
    6. Landslide
    7. Volcanic Activity
	Sub-Plans do not exist

Natural Hazard Mitigation – Risk Reduction Strategy 1. Hazard Vulnerability Assessment	Natural Hazards Mitigation Plan February 2010

Recovery
 	
    1. Damage Assessment
    2. Debris Management
    3. Continuity of Operations
	Responsibility of the bureaus

Figure 23. Components of the Comprehensive Emergency Management Plan. The maroon text to the right denotes the current status of each of these components of the Portland CEMP. Information taken from *Portland Office of Emergency Management* [2011].

MULTNOMAH COUNTY

The Multnomah County Office of Emergency Management is currently revising their emergency response and recovery plans to comply with federal guidelines. Consequently, none

of the plans are publicly available, though the plans are filed with the state office of emergency management [J. Lewis, Oregon Emergency Management, personal communication, May 2011]. As of this writing, a copy of the county plan was not available for review.

STATE OF OREGON

Statewide emergency is coordinated and facilitated by the Oregon Emergency Management (OEM) Office, which is in the Oregon Military Department. OEM is the state equivalent of POEM: the office coordinates and supports the Governor's Emergency Coordination Center (ECC); develops and conducts local and state training exercises; maintains the Oregon Emergency Plan (Figure 24); runs the Geologic Hazards Program for earthquake, tsunami, and volcano hazards; and oversees the Oregon Emergency Response System (OERS). The Geologic Hazards Program works closely with the Oregon Department of Geology and Mineral Industries (DOGAMI) in addition to other government and community hazard groups. DOGAMI geologists have prepared numerous scientific reports about the hazards from earthquakes, tsunami and volcanoes in Oregon. OERS, which is activated during a disaster to coordinate and manage state resources, is the point of contact for all cities, counties, and public agencies when there is any emergency that requires state support. The OERS Council is comprised of representatives from all of the relevant state agencies and functions similarly to the Portland Disaster Policy Council.
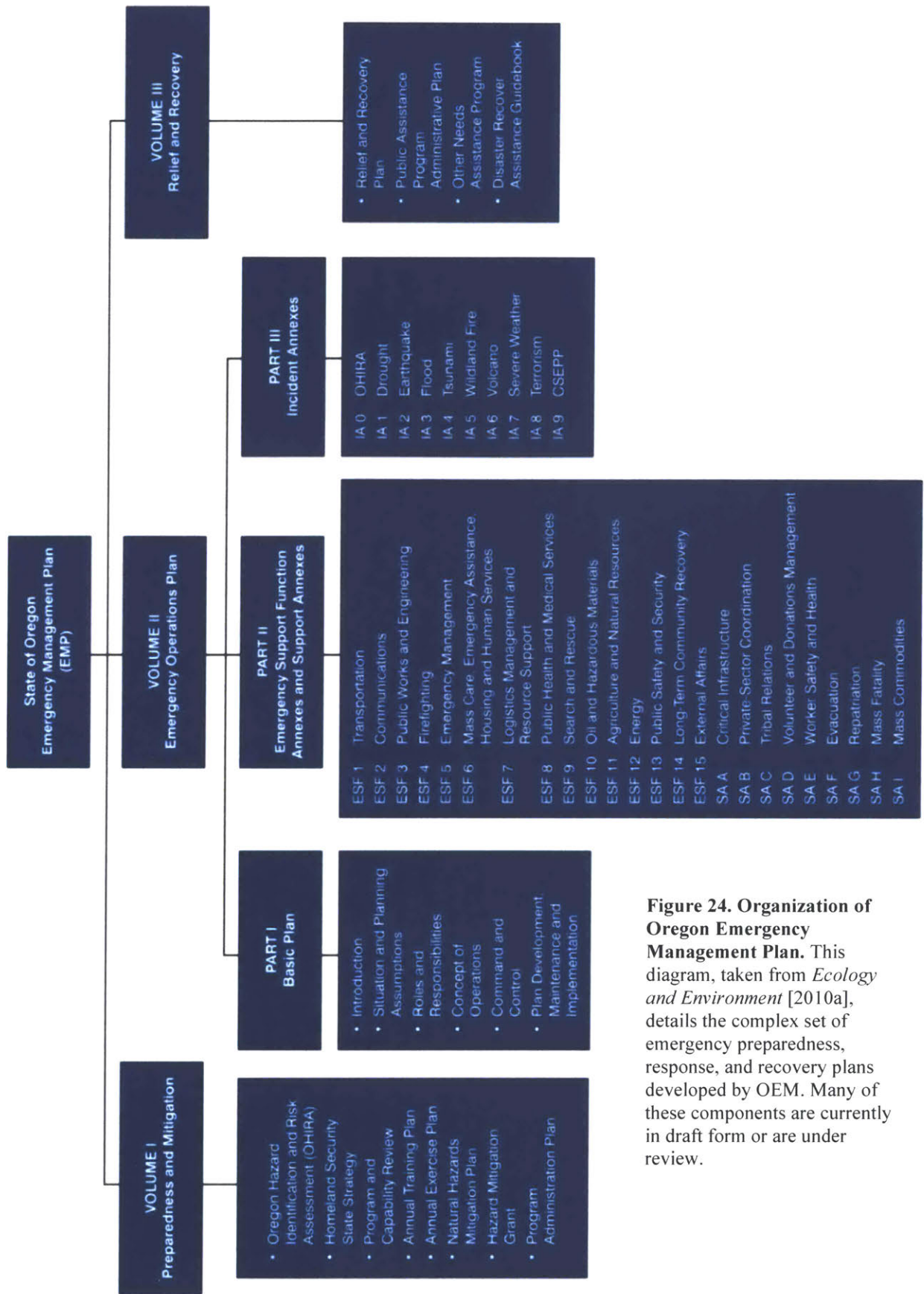
Oregon has its own Emergency Management Plan (EMP), which contains three volumes in accordance with federal natural disaster frameworks (e.g. NIMS and the NRF) (Figure 24). Volumes I and III are currently under review by OEM and are not available for analysis [J. Lewis, Oregon Emergency Management, personal communication, May 2011]. Volume II is the

Emergency Operations Plan (EOP), containing the Basic Plan as well as Emergency Support Function (ESF) Annexes, Support Annexes, and Incident Annexes. The EOP was last updated in September 2010. ESF Annexes "establish fundamental disaster roles and responsibilities... during a State or Presidentially declared disaster," and state offices are assigned roles under 15 specific support functions [*Ecology and Environment*, 2010b]. The Support Annexes detail roles that are not covered in the ESF, and the Incident Annexes detail the response framework and activities during specific incidents (such as earthquakes or floods). The EOP conforms to the National Response Framework model established by FEMA.

FEDERAL

The federal government provides support to emergency responses in two ways: information and data support for mitigation, and response support during an event. The U.S. Geological Survey and the National Weather Service are the primary federal sources for data, and the Federal Emergency Management Agency (FEMA) is the primary federal response organization.

The U.S. Geological Survey within the Department of the Interior provides information on seismic and volcanic activity in the region. USGS has several observation stations, including the Cascades Volcano Observatory, that provide real-time data and comprehensive overviews of the geologic hazards nearby. The USGS also supports the Pacific Northwest Seismic Network (PNSN), which operates out of the University of Washington. PNSN also provides data and preparedness information on earthquakes and geologic hazards in the region.

Figure 24. Organization of Oregon Emergency Management Plan. This diagram, taken from *Ecology and Environment* [2010a], details the complex set of emergency preparedness, response, and recovery plans developed by OEM. Many of these components are currently in draft form or are under review.

State of Oregon Emergency Management Plan (EMP)

VOLUME III Relief and Recovery
- Relief and Recovery Plan
- Public Assistance Program Administrative Plan
- Other Needs Assistance Program
- Disaster Recover Assistance Guidebook

VOLUME II Emergency Operations Plan

PART III Incident Annexes
- IA 0 OHIRA
- IA 1 Drought
- IA 2 Earthquake
- IA 3 Flood
- IA 4 Tsunami
- IA 5 Wildland Fire
- IA 6 Volcano
- IA 7 Severe Weather
- IA 8 Terrorism
- IA 9 CSEPP

PART II Emergency Support Function Annexes and Support Annexes
- ESF 1 Transportation
- ESF 2 Communications
- ESF 3 Public Works and Engineering
- ESF 4 Firefighting
- ESF 5 Emergency Management
- ESF 6 Mass Care Emergency Assistance Housing and Human Services
- ESF 7 Logistics Management and Resource Support
- ESF 8 Public Health and Medical Services
- ESF 9 Search and Rescue
- ESF 10 Oil and Hazardous Materials
- ESF 11 Agriculture and Natural Resources
- ESF 12 Energy
- ESF 13 Public Safety and Security
- ESF 14 Long-Term Community Recovery
- ESF 15 External Affairs
- SA A Critical Infrastructure
- SA B Private-Sector Coordination
- SA C Tribal Relations
- SA D Volunteer and Donations Management
- SA E Worker Safety and Health
- SA F Evacuation
- SA G Repatriation
- SA H Mass Fatality
- SA I Mass Commodities

PART I Basic Plan
- Introduction
- Situation and Planning Assumptions
- Roles and Responsibilities
- Concept of Operations
- Command and Control
- Plan Development Maintenance and Implementation

VOLUME I Preparedness and Mitigation
- Oregon Hazard Identification and Risk Assessment (OHIRA)
- Homeland Security State Strategy
- Program and Capability Review
- Annual Training Plan
- Annual Exercise Plan
- Natural Hazards Mitigation Plan
- Hazard Mitigation Grant Program
- Program Administration Plan

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The National Weather Service is a part of the National Oceanic and Atmospheric Administration, which falls under the Department of Commerce. NWS issues weather warnings, advisories and outlooks for Portland and the Pacific Northwest, as well as historic information on past events. The Forecast Office updates the online weather map in real time and includes gale and flood warnings.

FEMA is within the Department of Homeland Security. FEMA is designed to support local response efforts in preparing for, mitigating, responding to and recovering from natural disasters. The agency developed the National Response Framework (NRF), which organizes response into a series of subject annexes (such as energy, transportation, public affairs, etc.). Within the NRF, FEMA utilizes a system called NIMS, the National Incident Management System, as well as the Incident Command System (ICS). All state, county, and city emergency response systems follow this structure. In addition to providing an operating framework, FEMA can supply regional governments with crew, machinery, and other resources during a major disaster.

V. EARTHQUAKES

In the Natural Hazard Mitigation Plan, POEM identifies earthquakes as the greatest hazard to the

City of Portland. At the most general level, an earthquake is the release of stress, through plate

movement, that accumulates either within a tectonic plate or between plates. In the Pacific

Northwest, plate stress is the result of spreading forces at the divergent margin between the

Pacific and Juan de Fuca plates, subduction forces at the convergent margin between the Juan de

Fuca and North American plates, and the oblique interactions between plates and these margins.

Using magnetic lineation data, geologists have calculated that the spreading ridge is adding

approximately 3 cm of oceanic lithosphere to the Juan de Fuca plate per year, while the Cascadia

Subduction Zone (CSZ) is converging by 3.5-4.5 cm/yr [*Heaton and Hartzell*, 1987]. However,

these rates do not necessarily mean that the plates are sliding freely at a constant rate. Based on

thermal models and heat flow observations, the CSZ is considered to be locked at the trench to a

depth of about 15 km beneath the continental slope [*Wang et al.*, 2003; *Dragert et al.*, 2004],

meaning that stresses build up over time along the strike of the trench and release in episodic

slip, which can produce large earthquakes (this is also called the stick-slip model). This is the

location where we would expect to generate very large (M_W 8-9) subduction zone earthquakes.

This locked zone transitions into an episodic tremor and slip (ETS) zone, which has only recently

been studied [*Rogers and Dragert*, 2003; *Dragert et al.*, 2004]. ETS events, which accommodate

slow slip rates between the overlying plate and the subducting slab, are mostly aseismic shear

slip, producing only low-frequency tremors. But ETS may increase or decrease stresses in other

zones along the plate, perhaps triggering a large interplate earthquake or contributing to the large

intraplate earthquakes observed in the same region [*Roberts and Dragert*, 2003; *Schwartz and*

Rokosky, 2007]. Intraplate earthquakes occur within the subducting slab in a region termed the

Wadati-Benioff Zone at a depth of 40-70 km in Cascadia [*Wong*, 2005]. Beyond the ETS zone is the free slip or plastic zone, in which the subducting slab is expected to descend freely without accumulating stress, and thus without producing earthquakes. The depth of this zone varies along strike [*Dragert et al.*, 2003; *Wong*, 2005], but generally begins near 45-70 km in Cascadia. Figure 25 details the different slip regimes of the CSZ, identifying the locked zone, transition zone, ETS zone and the plastic (or free slip) zone.
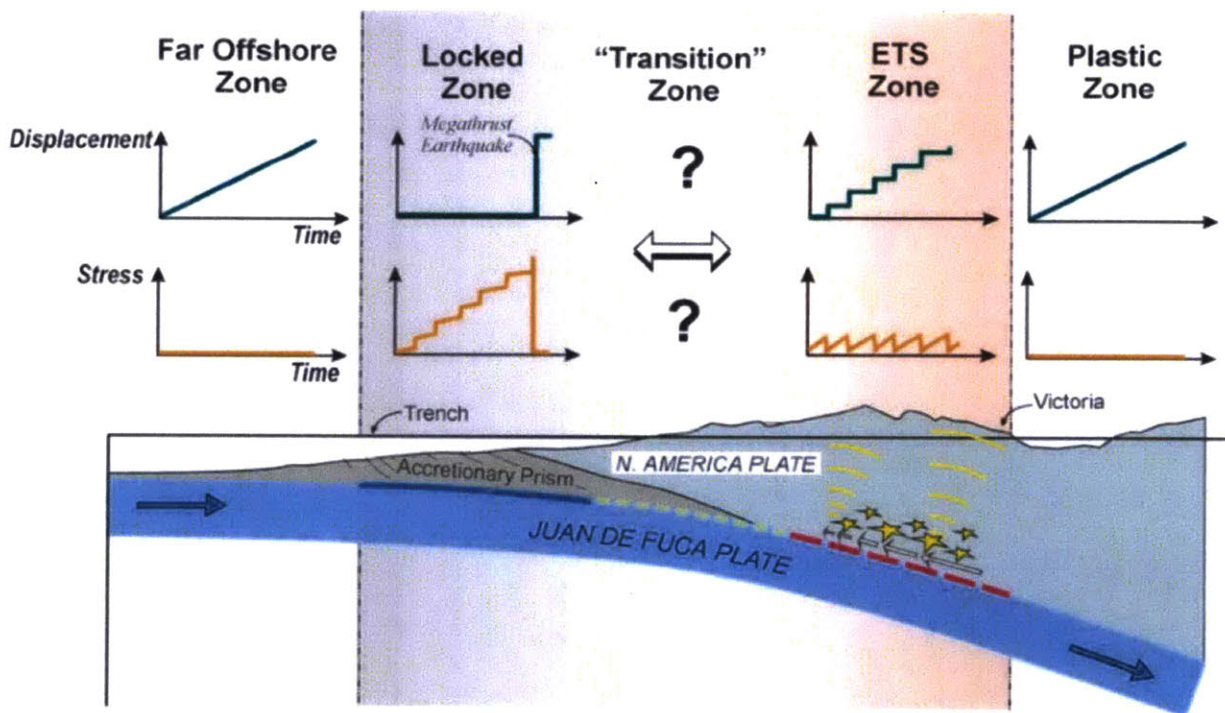

Figure 25. Episodic Slip Along the Cascadia Subduction Zone, after *Dragert et al.* [2004]. Distribution of slip deficit (in which displacement is not concurrent with convergence) along the Cascadia Subduction Zone near Victoria, Canada. Displacement and stress graphs are intended to be schematic and are not quantitative. Interplate earthquakes or "megathrusts" are expected to occur in the locked zone, while intraplate or Wadati-Benioff Zone earthquakes are expected to occur at depth. Crustal quakes can occur at nearly any longitude in the overlying plate.

There is also significant shallow faulting in the crust of the overlying North American plate. Though the exact cause of these stress fractures are not well constrained due to a short record of historical seismicity, very little data on deformation rates and poor exposures [*Wells et al.*, 1998], several theories link these crustal features to the oblique nature of the subduction and

strike-slip margins along the Pacific coast [*Magill et al.,* 1982; *Wells,* 1990; *Wells et al.,* 1998; *Bird,* 2002]. The stresses from the active margin, potentially in conjunction with other forces, such as Basin and Range extension, have created strike-slip and extensional features throughout Oregon, with several crustal faults trending through downtown Portland.

An evaluation of all recorded moderate-sized earthquakes in Portland revealed that the city is the most active seismic area in Oregon. Based on these records, *Bott and Wong* [1993] estimate that events M_L 5.5 and larger will occur every 100-150 years, and events M_L 6 and larger will occur every 300-350 years.

Each type of earthquake previously mentioned—Cascadia Subduction Zone earthquakes, Wadati-Benioff earthquakes, and crustal strike-slip earthquakes (Figure 26)—can produce two different hazards: tsunami and ground shaking. These hazards can lead to other secondary hazards, such as building collapse or landslides. This chapter will discuss the mechanisms, history and probability or occurrence for each of the three types of earthquakes, as well as the risks to Portland from the interaction between seismic hazards and infrastructure and environmental vulnerability.
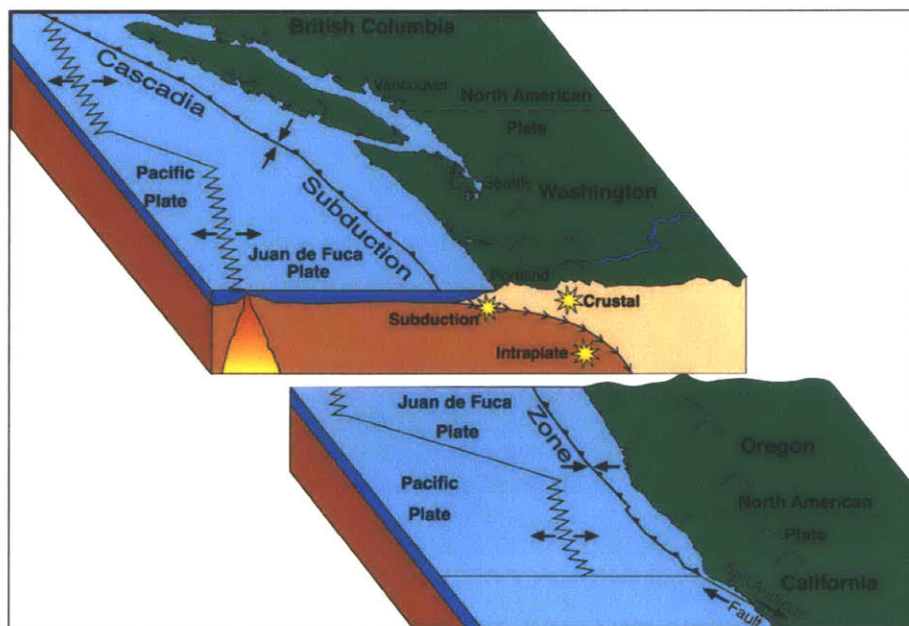
Figure 26. Three Types of Earthquakes in the Pacific Northwest. This schematic, taken from *Barnett et al.* [2009], marks the approximate location and relationship between the three major types of seismicity in the Pacific Northwest.

As stated previously, earthquakes occur at the contact between the subducting plate and the overlying plate along the locked zone, which extends to approximately 15 km beneath the North American plate [*Wang et al.*, 2003]. Though the Juan de Fuca and North American plates are converging at approximately 4 cm/yr, the plates are not sliding passed each other at 4 cm/yr; instead, the plates remain in place as stress accumulates at the contact. This stress is partially accommodated by compressive flexing of the overlying North American plate. Figure 27 shows the development of the flexural bulge in the overlying plate and the subsequent rapid subsidence once slip occurs periodically at the boundary. This uplift is measurable using tide gauges and is occurring in southern Oregon at the rate of approximately 2 mm/yr (Figure 28) [*Wang et al.*, 2003]. Evidence of historic
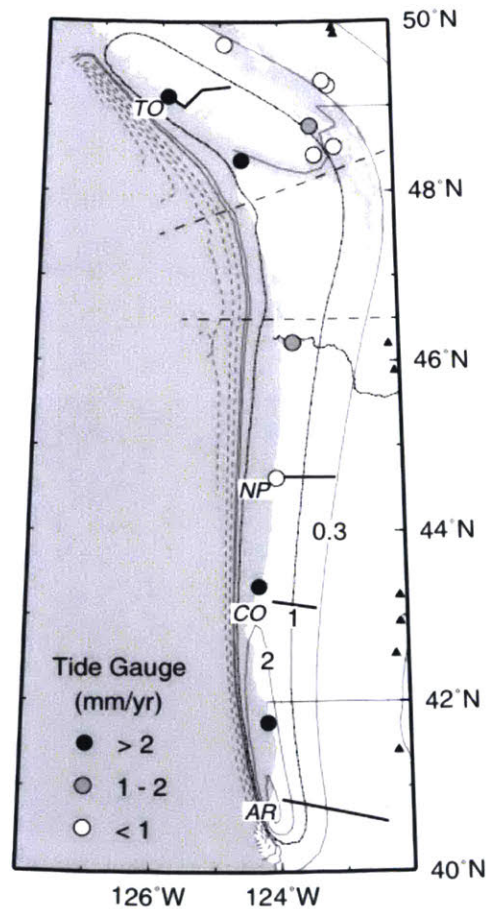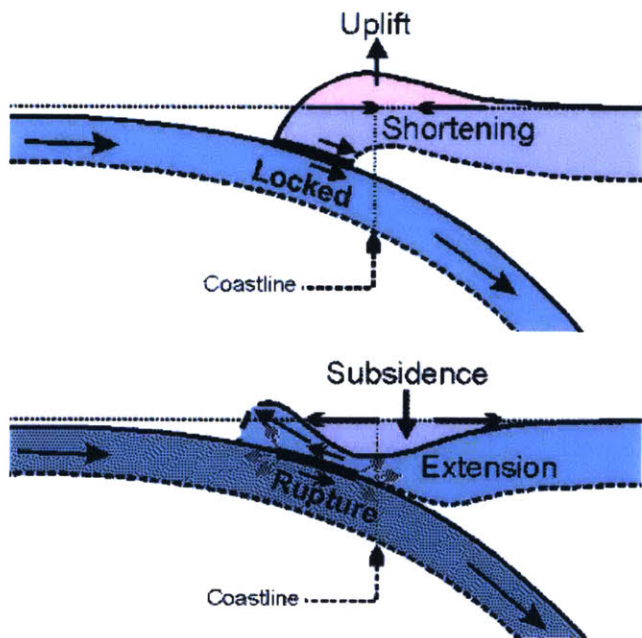
Left: Figure 27. Development and Release of Flexural Bulge, after *Hyndman et al.* [2008]. In a locked subduction zone, stress accumulates between the plates at the plate boundary, causing the overlying plate to bulge. When the locked zone ruptures, the overlying plate subsides rapidly.

Right: Figure 28. North American Uplift Rates, after *Wang et al.* [2003]. Contours measured in mm per year.

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rapid subsidence has also been found on the coasts of WA [*Atwater and Yamaguchi*, 1991].

Slip on the subduction zone can cause a large earthquake, up to M_W 9.5 [*Heaton and Hartzell*, 1987], but there has not been an interplate earthquake in recent history. Paleoseismic research that began in the late 1980s provides evidence that the last large earthquakes on this boundary occurred 300 years ago and 1700 years ago [e.g. *Atwater*, 1988; *Atwater and Yamaguchi*, 1991]. These large earthquakes are also accompanied by tsunami, which are generated as slip creates a momentary local minimum in sea level, propagating a wave with low frequency and water-column dependent amplitude. Interplate earthquakes are the only seismic events that generate large tsunami. The combination of rapid shoreline subsidence and high tsunami waves leaves behind marine sediments as paleomarkers in near-shore lakes and along the coasts of North America and Japan [*Atwater*, 1988; *Wang et al.*, 2003; *Kelsey et al.*, 2005]. Turbidites off the coast of Oregon and Washington show evidence of thirteen great Cascadia earthquakes over the last 7.7 ka [*Geist*, 2005]. Because there has not been any seismic activity along the subduction in recorded history, these records and current plates measurements are the only data geologists have to construct expected seismic activity and recurrence intervals.

The aspect ratio for the Cascadia Subduction Zone is far larger than other subduction zones around the world, with the rupture length-to-width ratio of approximately 10:1 (the aspect ratio of the 1960 Chile earthquake [M_W 9.5, the strongest ever recorded] is approximately 4:1) [*Geist*, 2005]. Faults with such high aspect ratios are complex to model, exhibiting strong heterogeneity in slip along strike and aperiodic recurrence intervals [*Geist*, 2005]. Despite the differences between the CSZ and other subduction zones, *Heaton and Hartzell* [1987] simulated ground shaking and tsunami responses for large events (M_W 8 and 9.5) using data from mid-level earthquakes, concluding that the destruction in the Willamette Valley could approximate the

damage from the 1960 Chile earthquake and coseismic tsunami, which are estimated to have killed 1886 people, displaced over 2 million and caused up to $5 billion in damages (adjusted to 2011 dollars) [*U.S. Geological Survey*, 2010]. The Pacific Northwest Seismic Network (PNSN), a group within the University of Washington Department of Earth and Planetary Sciences, estimates the recurrence interval for CSZ earthquakes at somewhere between 400-600 years, noting that the intervals between events are irregular (which could be due to activity in the ETS zone) [2002]. Also, *Nelson et al.* [2006] determined that the recurrence interval along strike of the subduction zone vary, with more regular events occurring in central and northern Cascadia.

Several groups have also attempted to model the probable hazards, including tsunami and ground shaking, for a large subduction zone earthquake. Because Portland is 60 miles inland from the coast, however, it is unlikely that the city would be directly impacted by a tsunami [*Pacific Northwest Seismic Net.*, 2002], so this section will focus on models of ground shaking. *Wong et al.* [2000b] produced several probabilistic seismic hazard analysis maps for a M_W 9.0 event along the subduction zone. They estimated peak horizontal ground acceleration (PGA) at the surface (for a particle) to range between 0.1-0.2 g (10-20% of gravity), which corresponds to approximately a VI on the Modified Mercalli Intensity (MMI) scale ("strong shaking felt by all, many frightened... a few instances of fallen plaster and damaged chimneys. Damage light" [*Wong et al.*, 2000b]). For an earthquake of moderate[5] frequency (5 Hz), *Wong et al.* found that the acceleration of buildings in the Portland Hills would reach up to 0.5 g; for earthquakes of low frequency (1 Hz), *Wong et al.* found an inverse relationship, with buildings in sediment infill areas at the greatest risk (see Figures 29, 30, and 31) [2000b]. *Campbell and Wang* [2001], estimate slightly lower accelerations, though their data are generalized for longitudinal regions of

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[5] Seismic waves attenuate as they move farther from the source, so frequency falls off with radial distance from the epicenter [*Barnett et al.*, 2009]. Thus, crustal earthquakes near Portland generate the highest frequency waves.
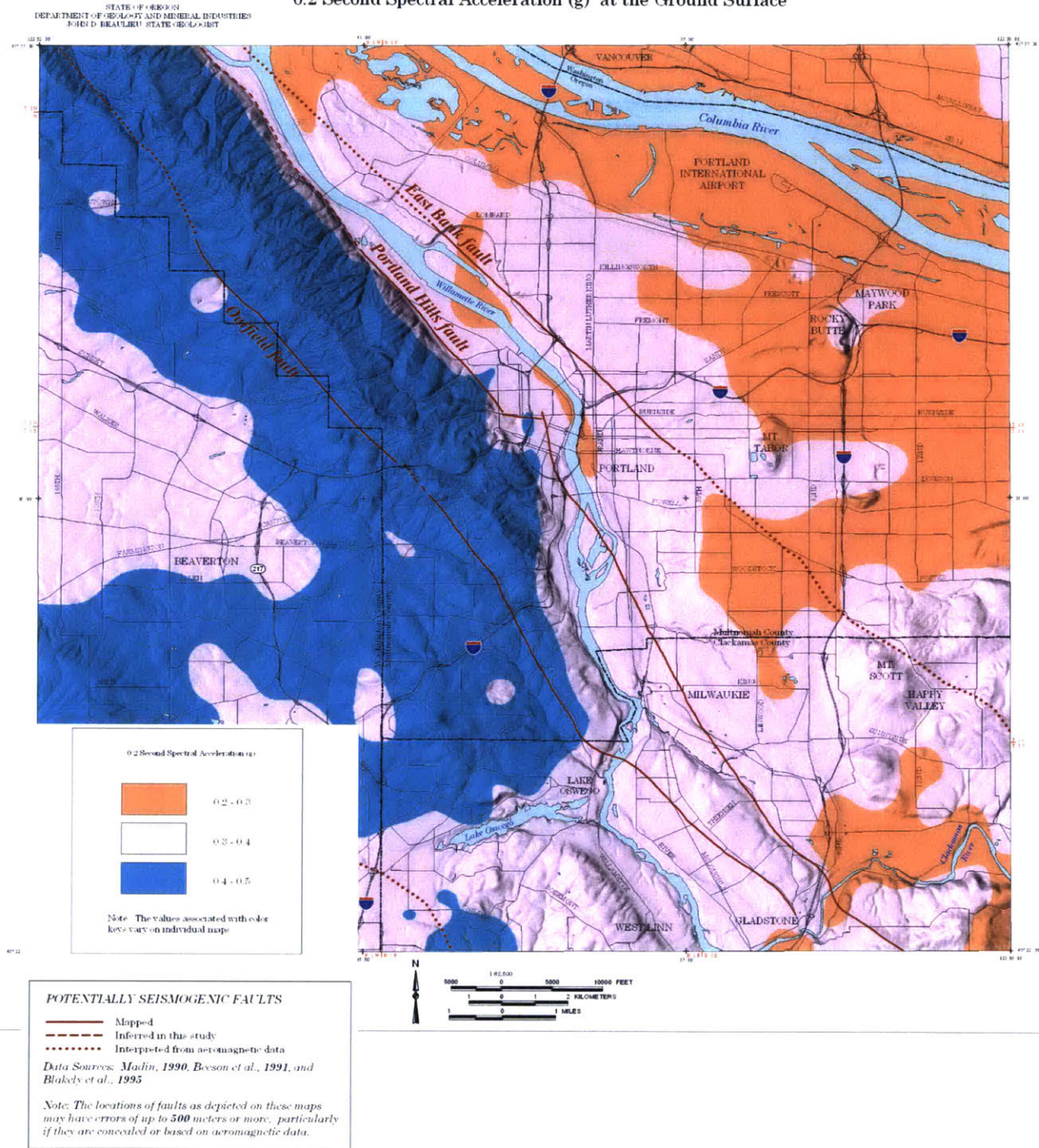
Oregon: they estimate PGA in Portland at 0.15 g for a M_W 9.0, and 0.3 g on "firm rock" for earthquakes at 5 Hz. The PNSN [2002] estimates shaking strength on rock at 0.3 g in urban areas, with larger accelerations expected on soft ground. The PNSN also estimated 1-3 minutes of strong ground shaking (0.3+ g), with several aftershocks up to M_W 7.5 [2002].
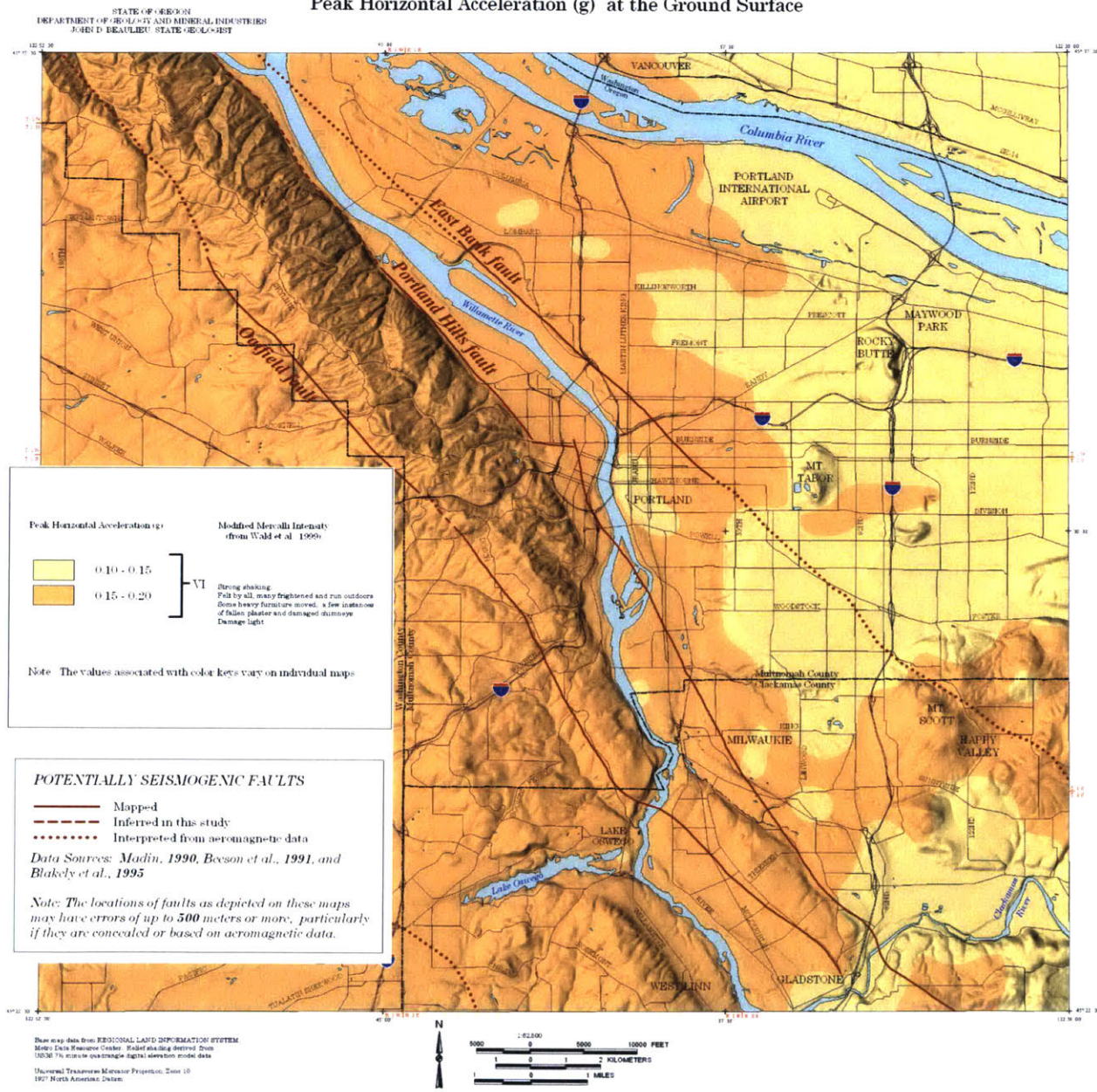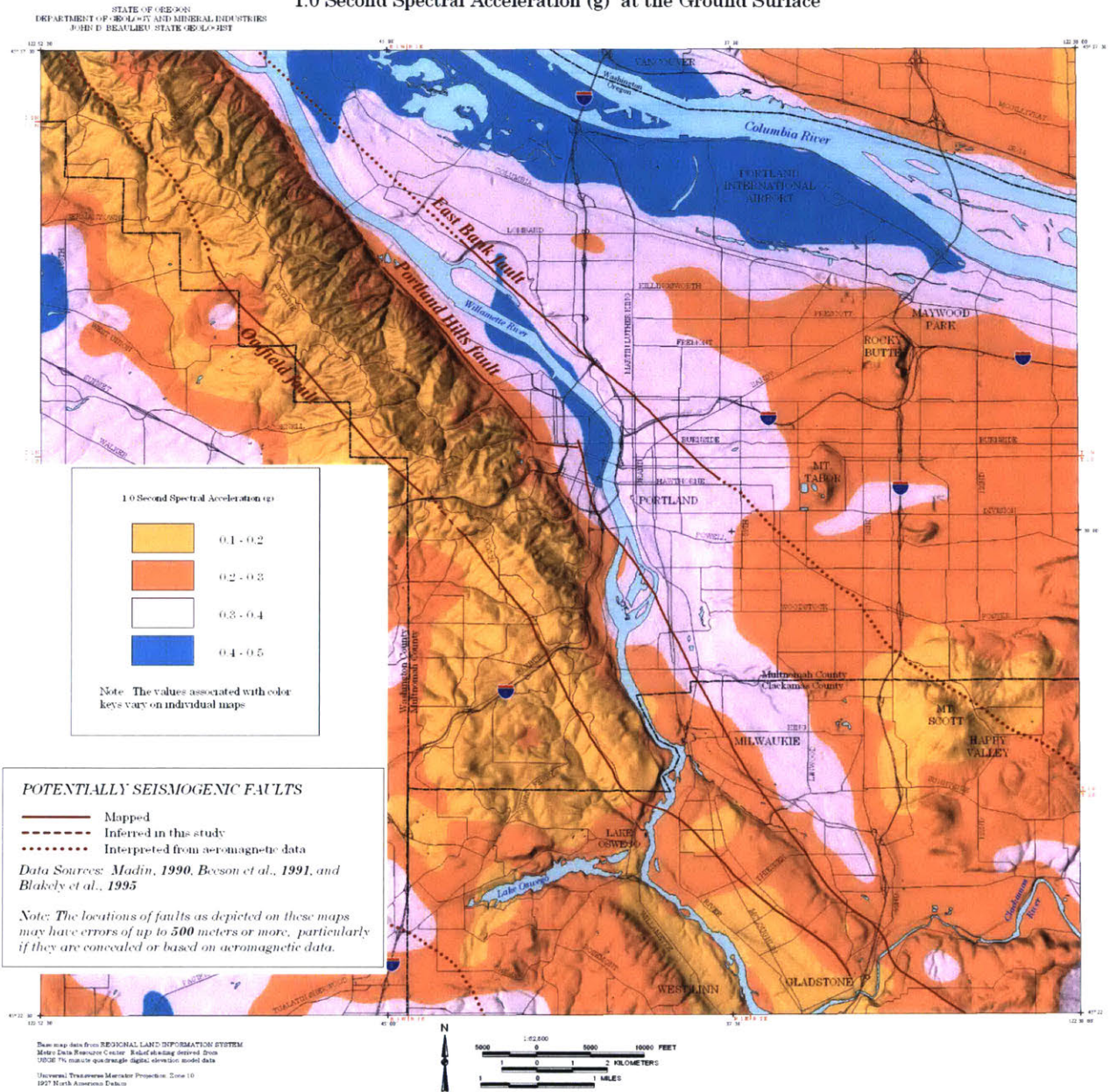

Figure 29. Peak Horizontal Ground Acceleration for M_W 9.0 Cascadia Subduction Zone Earthquake in Portland. This map, developed by *Wong et al.* [2000b], focuses on the PGA at the ground surface in downtown Portland. The map also includes the traces of the Portland Hills Faults, which will be discussed in the Crustal Earthquakes section in this chapter.

Figure 30. 5Hz Spectral Acceleration for M$_W$ 9.0 Cascadia Subduction Zone Earthquake in Portland. This map, developed by *Wong et al.* [2000b], shows the potential acceleration for buildings in Portland if the frequency of the earthquake is 5 Hz. Developments near the Portland Hills are at the greatest risk, and the high acceleration areas are not exclusively high elevation.

Figure 31. 1Hz Spectral Acceleration for M_W 9.0 Cascadia Subduction Zone Earthquake in Portland. This map, developed by *Wong et al.* [2000b], shows the potential acceleration for buildings in Portland if the frequency of the earthquake is 1 Hz. Developments in areas of loose, unconsolidated sediments are most at risk in this scenario.

INTRAPLATE EARTHQUAKES

Intraplate earthquakes occur within the subducting slab in what is known as a Wadati-Benioff Zone (beneath the overlying plate) or in the outer rise region (in this case, to the west of
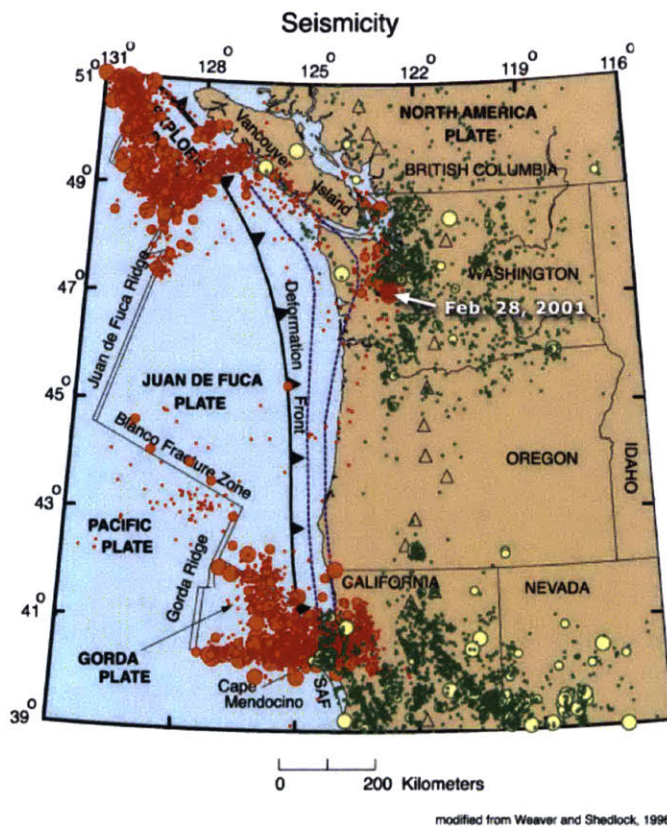
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the trench) [*Wong*, 2005]. For the purposes of this discussion, we will only focus on earthquakes within the Wadati-Benioff Zone, since these are most proximal to population centers. The Wadati-Benioff zone is simply the plane in a subduction zone along which deep earthquakes occur [*Stacy and Davis*, 2008]. Intraplate (deep) earthquakes are unique from ETS, which typically occurs along the subducting slab in between large earthquakes (interseismically) due to mechanisms *different* from those that govern intraslab seismicity [*Abers et al.*, 2009; *Kao et al.*, 2009].

Intraplate earthquakes are believed to be caused by three different mechanisms: the negative buoyancy of the slab (gravity), changes in subduction angle, and embrittlement due to dehydration of minerals in the down-going slab [*Stacy and Davis*, 2008]. Stresses on the subducting slab from its relatively high density (compared to the surrounding mantle) can cause tensile fractures within the slab [*Stacy and Davis*, 2008]. Intraplate earthquakes can also be caused by change in subduction angle or dehydration of serpentinite [*Wong*, 2005; *Abers et al.*, 2009]. Changes in subduction angle can induce extensional bending stresses, creating a zone of preferred deformation [*Wong*, 2005; *Barnett et al.*, 2009], while the release of fluid at depth from metamorphism of hydrous minerals in the subducting slab is also known to generate earthquakes [e.g. *Abers et al.*, 2009]. All other things being equal, old, cold lithosphere should produce more intraplate earthquakes because it accommodates brittle deformation rather than viscous or plastic deformation, which is expected in a warmer material [*Wong*, 2005].

These earthquake mechanisms have produced large earthquakes in the recorded history of the Pacific Northwest with notable damages due to ground shaking. There have been seven events in Oregon and Washington since 1870 with M_W 6 or greater [*Weaver and Shedlock*, 1996]. In 1949, a M_W 7.1 earthquake (the Olympia earthquake) cased significant damage in the

Puget Sound region of Washington; the event is estimated to have occurred at a depth of 54 km with no aftershocks [*Weaver and Shedlock,* 1996]. The 2001 M_W 6.8 Nisqually, WA, earthquake (note in Figure 32 with an arrow) also caused significant damages and is thought to be very similar to the Olympia earthquake [*Wong,* 2005]. The only notable known intraplate earthquake beneath the Willamette Valley in Oregon is the 1963 M_W 4.6 event northwest of Corvallis (south of Portland) [*Barnett et al.,* 2009]. No other large intraplate earthquakes have been recorded between southern Washington and southern Oregon (Figure 32).

Using measurements and inferred data from historic intraplate earthquakes throughout the Pacific Northwest, geologists have determined the range of expected Wadati-Benioff zone events and constructed ground shaking scenarios. The PNSN estimates the largest possible earthquake from this type of activity is a M_W 7.5 at 30-75 km depth, though they find M_W 6 more common [2002]. *Weaver and Sherlock* [1996] and *Hull et al.* [2003] come to a similar conclusion, predicting ruptures of M_W 7.5 at 60 km depth as far east as Portland. Though none of these papers gives ground shaking estimates, *Barnett et al.* [2009] modeled PGA for the Portland area between 0.2-0.3 g, based on wave attenuation from a depth of at least 35 km, noting that spectral acceleration

Figure 32. Intraplate and Crustal Seismicity in the Pacific Northwest. This map, taken from *Vidale and Creager*, [2009], shows notable intraplate seismicity in orange/red and crustal seismicity in green/yellow. Note the relative absence of intraplate seismicity in Oregon as compared to Washington and northern California.

could be higher, especially in soft soils. Shaking would likely last for 15-30 seconds, significantly shorter than shaking due to interplate or crustal quakes [*Pacific Northwest Seismic Network*, 2002]. Intraplate earthquakes are also generally devoid of foreshocks or aftershocks, distinguishing them from other seismic events [*Weaver and Shedlock*, 1996; *Pacific Northwest Seismic Network*, 2002]. Based on these characteristics, intraplate earthquakes are likely to be less damaging than other events, though the areal extent of shaking may be very large and the recurrence interval fairly frequent (approximately every 20 years) [*Pacific Northwest Seismic Network*, 2002; *Barnett et al.*, 2009].

Relative to other Wadati-Benioff earthquakes around the world, which can occur as deep as 700 km [*Stacey and Davis*, 2008], the events recorded in the Pacific Northwest are fairly shallow. The Juan de Fuca microplate is young and warm and does not accommodate much brittle deformation—this is known as thermal weakening [*Wong*, 2005]. Because the density contrast between the young lithosphere and the surrounding mantle is not as stark as older subduction zones, we expect the slab to subduct at a lower angle, which it does, resulting in shallower earthquakes [*Wong*, 2005]. Generally, shallower earthquakes (of any type, including intraplate) are more destructive than deep earthquakes because the seismic waves are less attenuated once they reach the surface. In Portland, however, shallow intraplate earthquakes may not be of major concern.

Though some of the literature describes the Wadati-Benioff zone in Cascasaia as the best understood earthquake source [*Weaver and Shedlock*, 1996], new information (such as the ETS) is being discovered and interpreted. The absence of seismic activity at depth beneath Oregon (Figure 32), what *Wong* [2005] terms the Central CSZ (south of the Puget Sound to the Oregon-California border), has raised questions about the intraplate earthquake potential near Portland.

The Juan de Fuca plate subducts non-uniformly underneath the North American plate along strike, which results in varying subduction angles and non-uniform distances between isotherms in the subducting slab [*Wong*, 2005]. Figure 33 shows the estimated depth contours within the Juan de Fuca plate, highlighting the bend in the plate beneath the Puget Sound and the relatively steep angle of the plate beneath the Central CSZ (see also Figure 34). Though the difference in subduction angle along strike is not well understood, geologists have attributed this change to increased seismic activity in the Puget Sound area [*Barnett et al.*, 2009] and decreased activity in the Central CSZ [*Wong*, 2005].
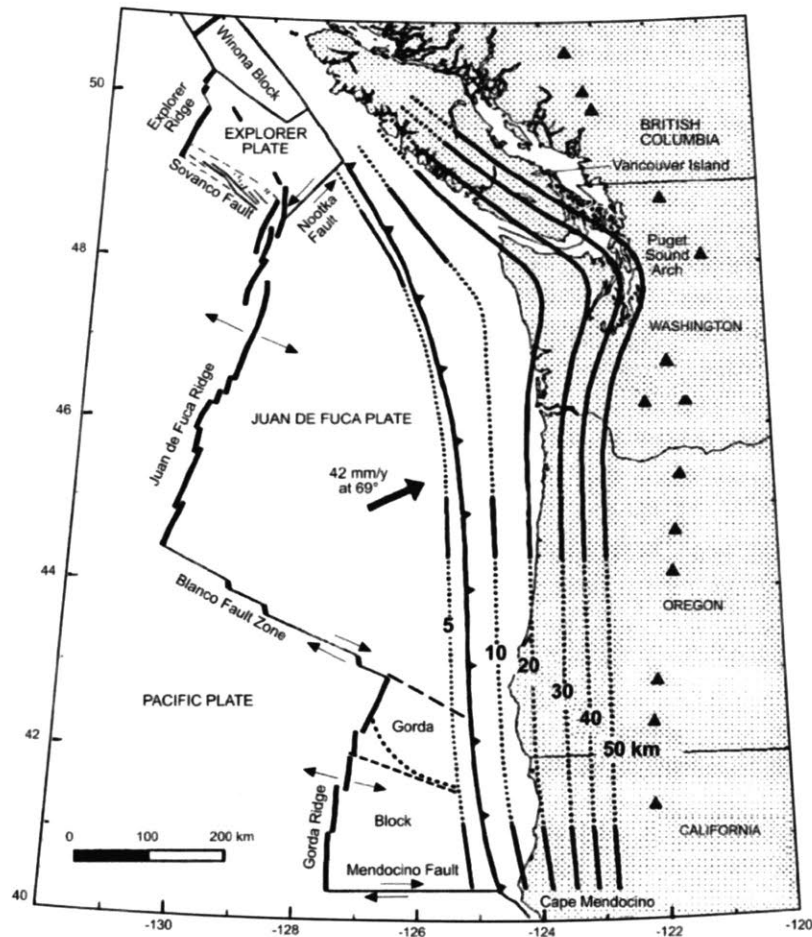
Figure 33. Depth Contours in the Juan de Fuca Plate Beneath the Pacific Northwest. The Central CSZ, which extends from south of Puget Sound to the northern boundary of the Gorda block, is characterized by a higher subduction angle than the Northern CSZ. Triangles represent Cascade volcanoes and dotted contours are inferred. Figure taken from *Wong* [2005].
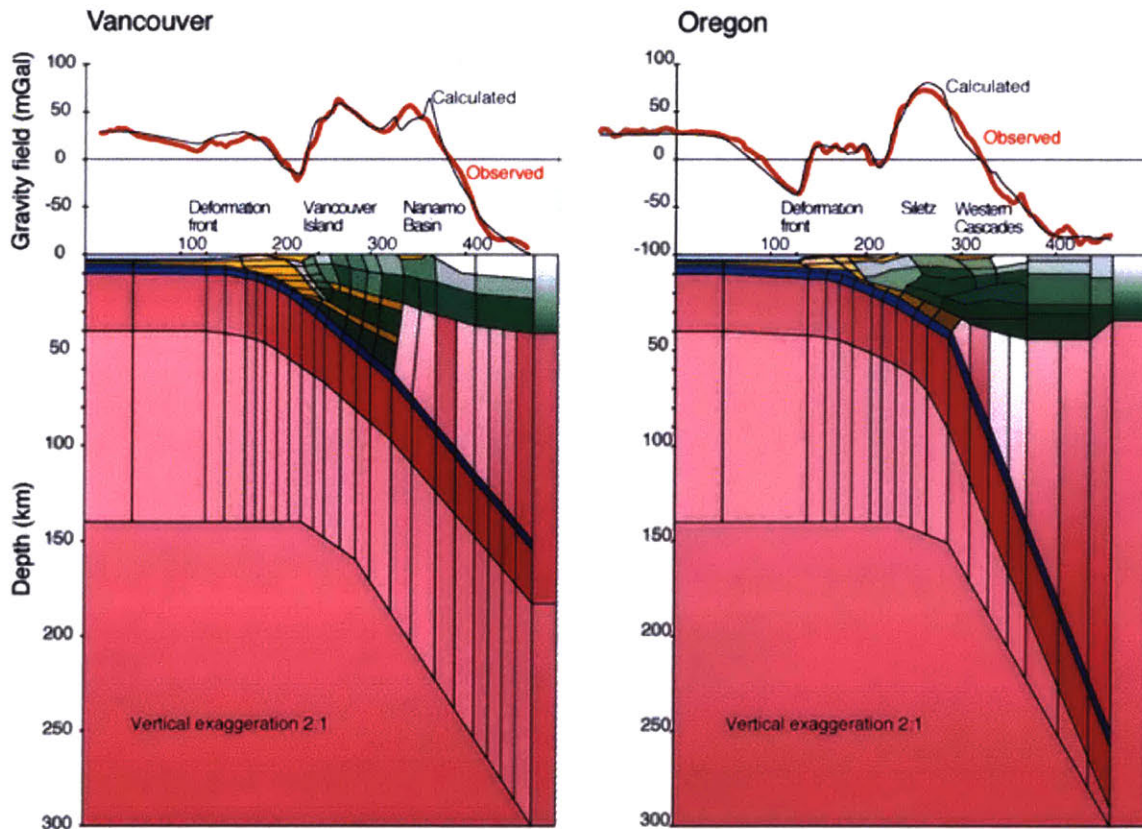
Figure 34. Density Profiles for the Subducting Slab in Vancouver and Northern Oregon. Profiles taken from *U.S. Geological Survey* [2009] reveal steeper subduction angle south of the Puget Sound, the most seismically active region of the Wadati-Benioff zone in the Pacific Northwest. Darker colors represent higher densities.

Barnett et al. [2009] and *Wong* [2005] argue that the high seismicity near the Puget Sound is unexpected given the shallow angle and age of the subducting slab, but correlates with the structure of the arch created by the "turn" in plate strike and the change in subduction angle. Major earthquakes cluster along a portion of the plate that could be undergoing bending stresses resulting from flexure [*Wong*, 2005].

Furthermore, there are additional criteria along the Central CSZ that could account for the complete absence of seismicity. The higher subduction angle indicates that the plate is likely warmer at a given distance from the trench than at latitudes near Vancouver. "The young plate age, slower convergence rate, and the insulating effect of the Siletz terrane above the plate" also likely contribute to high temperatures in the Central CSZ [*Wong*, 2005]. As stated before, higher

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temperatures lead to thermal weakening, a state in which the material is too viscous "to sustain stresses necessary for seismogenesis" [*Wong*, 2005]. Thermal models predict temperatures of 600° to 1200°C within the Juan de Fuca at depths of 40 to 70 km, which is well within range of the "cutoff temperature" for thermal weakening [*Wong*, 2005]. Alternative explanations for the historic aseismicity in the Central CSZ would be a tear in the slab at depth, which would reduce slab pull and thus tensile stresses on the slab [S. Rondenay, M.I.T., personal communication, May 2011].

The lack of observed intraslab seismicity in the Central CSZ likely indicates that these types of events present a lesser risk to the Portland population than other earthquakes. However, it is important to note that intraslab activity impacts very large areas far from the epicenter [*Barnett et al.*, 2009]. The 2001 Nisqually earthquake was felt in Portland and as far away as Salt Lake City, though the damage in Oregon was minor [*Wang et al*, 2001].


CRUSTAL EARTHQUAKES

In addition to the interplate and intraplate earthquakes that occur in response to stresses in the subduction zone, Portland is also subject to seismicity from shallow crustal earthquakes generated by faults within the North American plate. Because Portland lies in a tectonic transition zone between the more compressional arc in Washington and the extensional Basin and Range Province in south-central Oregon, the city is located in the vicinity of several shallow (<25 km) faults in the North American plate that accommodate oblique stresses [*Magill et al.*, 1982; *Wells,* 1990; *Blakely et al.*, 1995; *Wells et al.*, 1998]. Crustal earthquakes are by far the most abundant type of seismicity in Portland (see Figures 32 and 35), and they are also the most damaging [*Bott and Wong,* 1993; *Blakely et al.*, 2000; *Portland Off. of Emerg. Mgmt.*, 2010].

The Portland Halls Fault (PHF) zone is he most proximal active crustal feature. The PHF runs NW-SE through downtown Portland and contains several faults that have strong strike-slip and oblique thrust components (Figures 35 and 36) [*Blakely et al.*, 2000; *Wong et al.*, 2001; *Liberty et al.*, 2003]. The main faults that run through the Portland Hills are the East Bank Fault, the Portland Hills Fault, and the Sylvan Fault (formerly the Oatfield Fault) [*Blakely et al.*, 2004], but the displacement, seismic history, and earthquake potential of this fault zone is not well understood [*Wong et al.*, 2001; *Blakely et al.*, 2004]. This section discusses the crustal earthquake history in Portland, the current understanding of the PHF, expected earthquake activity on the PHF and the potential hazards from crustal faulting.
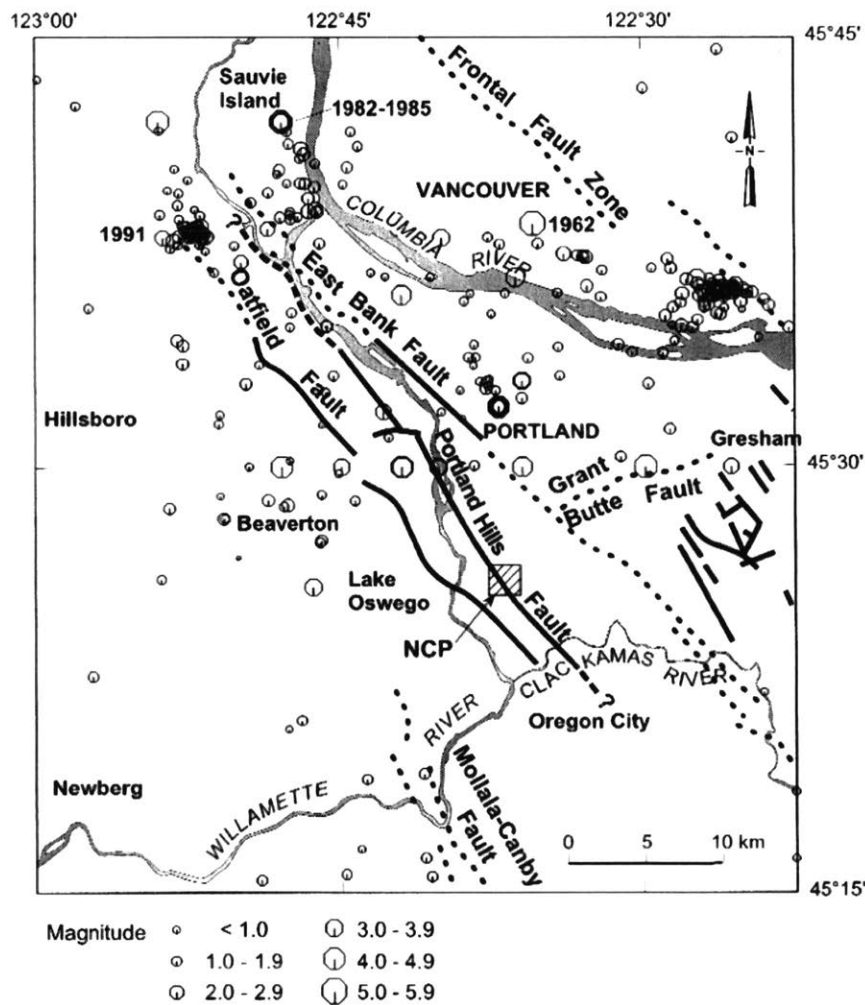
Figure 35. Seismicity from 1841-2000 and Crustal Faults in Portland. This map, developed by *Wong et al.* [2001], shows all crustal seismic activity (circles) in the Portland-Vancouver area from 1841-2000. Thick black lines are fault traces (dotted lines are inferred and dashed lines are buried). NCP is North Clackamas Park, the site of all seismic surveys in *Wong et al.* [2001].
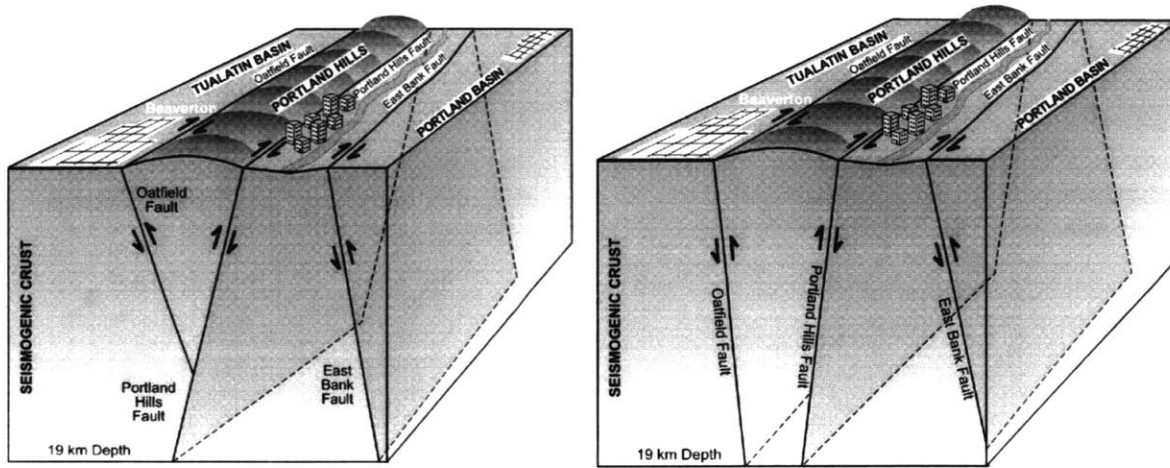
Figure 36. Two Proposed Block Models for the Portland Hills Fault Zone, after *Wong et al.* [2001]. These schematic diagrams are two possible interpretations of the three known fault planes in the Portland Hills. The Oatfield Fault is now known as the Sylvan Fault.

Geologists have a crustal seismic record for the Willamette Valley for roughly the last 160 yrs. In that time, Portland has experienced six crustal earthquakes between M_W 5 and M_W 6 [*Blakely et al.*, 2000]. The most recent large-scale crustal earthquake near Portland is the 1993 Scotts Mills M_W 5.6, the largest event on record in Oregon [*Bott and Wong*, 1993]. The epicenter of the Scott Mills earthquake is located 50 miles south of Portland, and the event caused $30 million in structural damages, with PGA less than 0.05 g [*Wong et al.*, 1993; *Blakely et al.*, 2000]. The second largest crustal event in recorded history also occurred near Portland: *Bott and Wong* [1993] estimate the maximum intensity of the November 1962 earthquake at MMI VII, with a magnitude M_L 5.5. The event cracked and toppled chimneys, broke windows and cracked plaster in Portland. The epicenter for the event is located 15 km northeast of downtown Portland, at a depth of 16 km [*Bott and Wong*, 1993]. Seismic events occurring in the Portland area (lat 44°-45°N and long 126°-122°W) between 1980 and 2000 are displayed in Figure 37.

Rigorous study of the PHF zone began in the early 1970s [*Balsillie and Benson*, 1971; *Schmela and Palmer*, 1972] as geologists tried to determine whether crustal faults existed in the

area, if so, whether they were active, and whether the magnitude of seismic events on the faults would be great enough to cause damage in Portland. Recent studies utilize aeromagnetic data, gravity data, GPS, seismic reflection, ground penetrating radar, bore hole data and trench sections to effectively trace the faults and determine their relative motions and offsets [e.g. *Wong et al.*, 2001], but "the lack of a geomorphic expression, extensive modern surface deposits, strike-slip displacement, and urbanization makes hazard assessment difficult using typical geologic mapping methods" [*Hemphill-Haley et al.*, 2003]. *Wong et al.* [2001] found 6 ft of movement (5 ft vertical displacement and 3 ft of shortening) in an excavation trench, determining that the fault has been active within the last 10,000 years or so. The most published study on the PHF analyzed gravity anomalies to conclude that the relative motion on the faults is oblique reverse displacement with significant strike-slip components [*Blakely et al.*, 2004]. Despite these measurements and recent seismic data (Figure 37), geologic studies have been unable to definitively conclude whether or not the PHZ is active and poses significant threats to Portland residents [*Hemphill-Haley et al.*, 2003; *Blakely et al.*, 2004]. Nonetheless, several studies have proposed maximum event values and peak acceleration models for crustal faults in the area in order to give emergency planners minimum standards for worst-case scenarios.
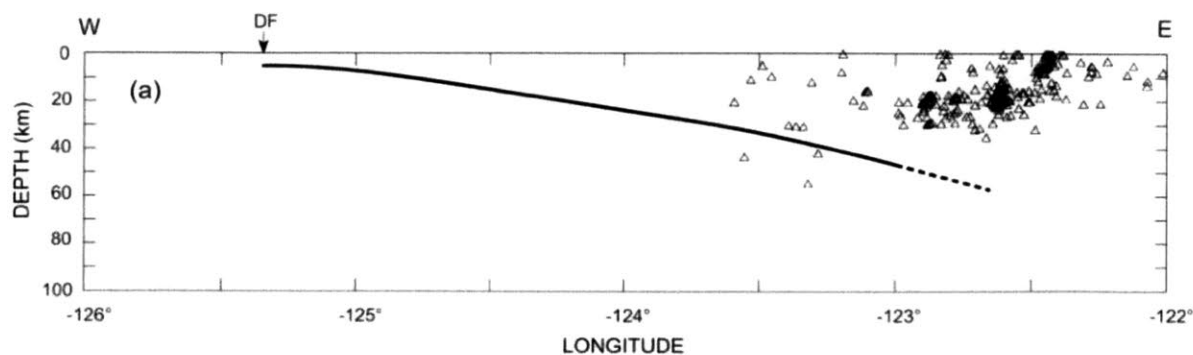
Figure 37. Cross Section of Seismicity at Lat 44°-45°N from 1980-2000, after *Wong* [2005]. This seismic profile shows that crustal earthquakes near the surface are the most common seismic events in Portland. The triangles represent

All models for crustal earthquakes near Portland use a maximum credible event between M_W 6 and M_W 7.5, though no earthquake greater than M_W 5.7 has been recorded in this region and most events register M_W 3-4. Table 4 displays maximum horizontal ground acceleration estimates from five separate studies for the Portland Hills Fault Zone. The highest estimates, from *Wong et al.* [2000a], correspond to areas of Portland directly on the fault trace (Figure 38). In this scenario, all of Portland would experience shaking between MMI VII and IX, in which IX corresponds to violent shaking and considerable damage even in specially designed structures. Though the estimates in Table 4 are useful for general guidelines, the map produced by *Wong et al.* [2000a] (Figure 38) is the most precise for planning mitigation strategies in Portland. When compared to the PGA for the Scotts Mills earthquake, these numbers are staggering and could mean significant loss of life and infrastructure. Furthermore, these estimates assume strike-slip motion, but *Wong et al.* [2001] estimate that earthquakes with predominantly reverse motion could be even more catastrophic. Ground shaking and damages could be analogous to the Northridge, CA, earthquake in 1994, which generated 1.9 g at the surface, caused 58 deaths, and damaged $20 billion in property [*Wong et al.*, 2001].

Table 5 contains estimates for spectral accelerations at 1 Hz and 5 Hz. Estimates from *Wong et al.* [2000b] correspond to Figures 39 and 40. These maps show areas that would be highly susceptible to wave amplification and attenuation at the interfaces of unconsolidated sediments and basement rock [*Pratt et al.*, 2001]. Similar to the constraints for the values in Table 4, Table 5 models do not consider rupture directivity effects, which would be propagated along the trace of the fault through downtown Portland [*Wong et al.*, 2001]. Downtown could experience greater long-period effects that are mostly likely to damage high-rise buildings, which are concentrated in the downtown area.

Finally, the PNSN estimates that an earthquake with a return interval of 250 years (M_W 7.4+) could sustain 20-60 seconds of strong shaking with several, unexpected aftershocks up to M_W 6.5 [2002]. These figures complete the portrait of potential crustal seismicity in Portland. As mentioned previously, crustal earthquakes have the potential to cause much more concentrated damage than either interplate or intraplate events [*Bott and Wong*, 1993], but uncertainty of local faults and their seismic potential makes it difficult to predict risks.

Table 4. Peak Ground Acceleration Estimates for the Portland Hills Fault.

Study	Magnitude (M_W)	Max. Acceleration (g)	Distance (km)
Idriss [1985][6]	6	0.36	5
	6	0.25	10
	6	0.18	15
	6.5	0.43	5
	6.5	0.30	10
	6.5	0.23	15
Campbell [1990][6]	6	0.37	5
	6	0.22	10
	6	0.15	15
	6.5	0.43	5
	6.5	0.28	10
	6.5	0.20	15
Wong et al. [2000a][7]	6.8	1.1	0
Campbell and Wang [2001]	6.5	0.5	1.6
	7	0.55	1.6
PNSN [2002]	7.4	> 0.5	--

Table 5. Spectral Acceleration Estimates for the Portland Hills Fault.

Study	Magnitude (M_W)	Max. Acceleration (g)	Period (sec)
Wong et al. [2000b][8]	6.8	3.0	0.2
	6.8	1.0	1.0
Campbell and Wang [2001]	6.5	1.1	0.2
	6.5	0.35	1.0
	7	1.2	0.2
	7	0.55	1.0

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[6] Described in *Wong et al.* [1993].
[7] See Figure 38.
[8] See Figures 39 and 40.
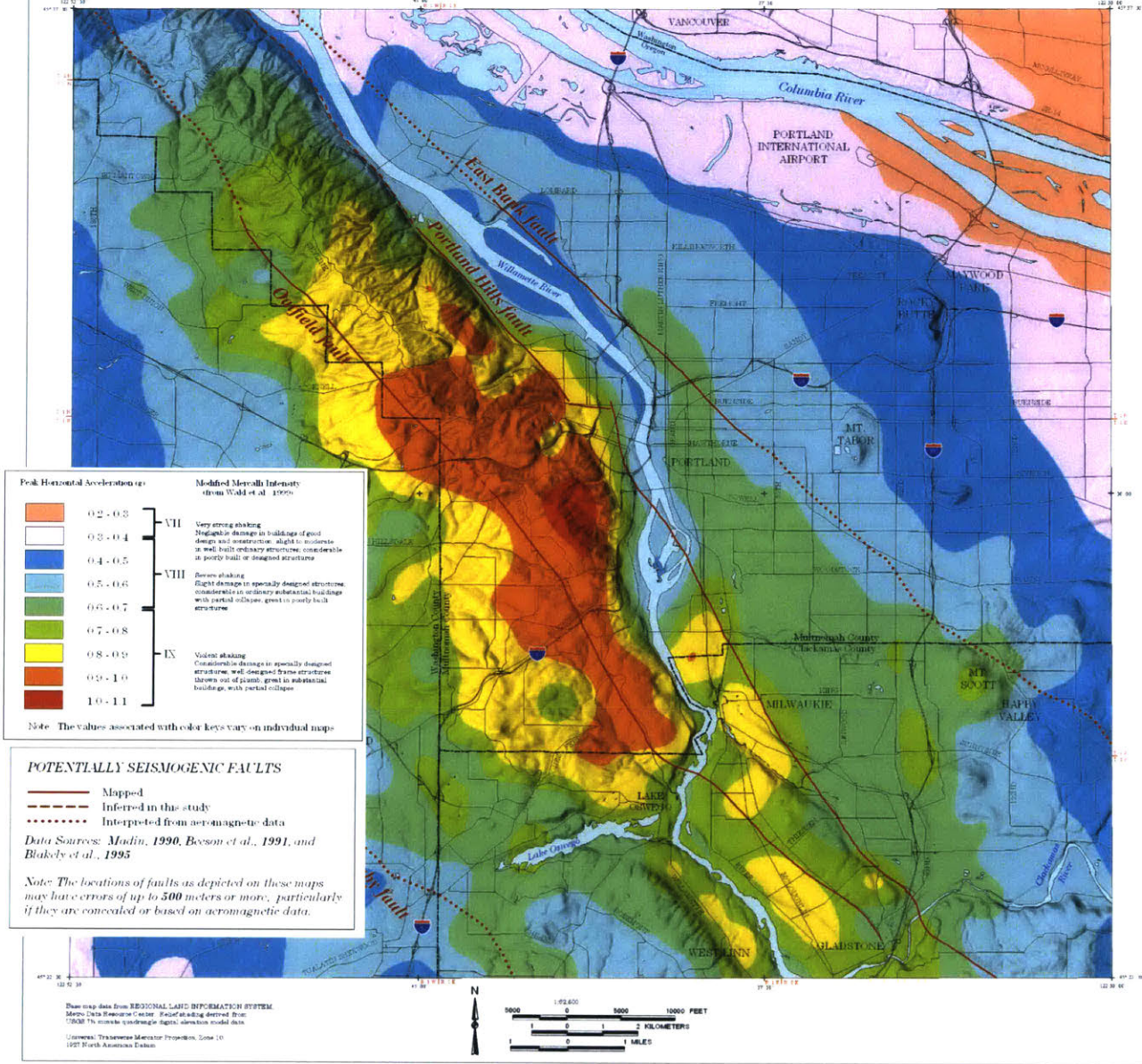
Figure 38. Peak Horizontal Ground Acceleration for M_W 6.8 Portland Hills Fault Earthquake. This map was developed by *Wong et al.* [2000a]. Though all areas of Portland receive significant shaking in the event of a M_W 6.8 crustal earthquake, the highest ground acceleration is in the rocky Portland Hills.

Figure 39. 5Hz Spectral Acceleration for M_W 6.8 Portland Hills Fault Earthquake. This map, developed by *Wong et al.* [2000b], shows the potential acceleration for buildings in Portland if the frequency of the earthquake is 5 Hz. Developments near the Portland Hills are at the greatest risk, and the high acceleration areas are not exclusively high elevation.
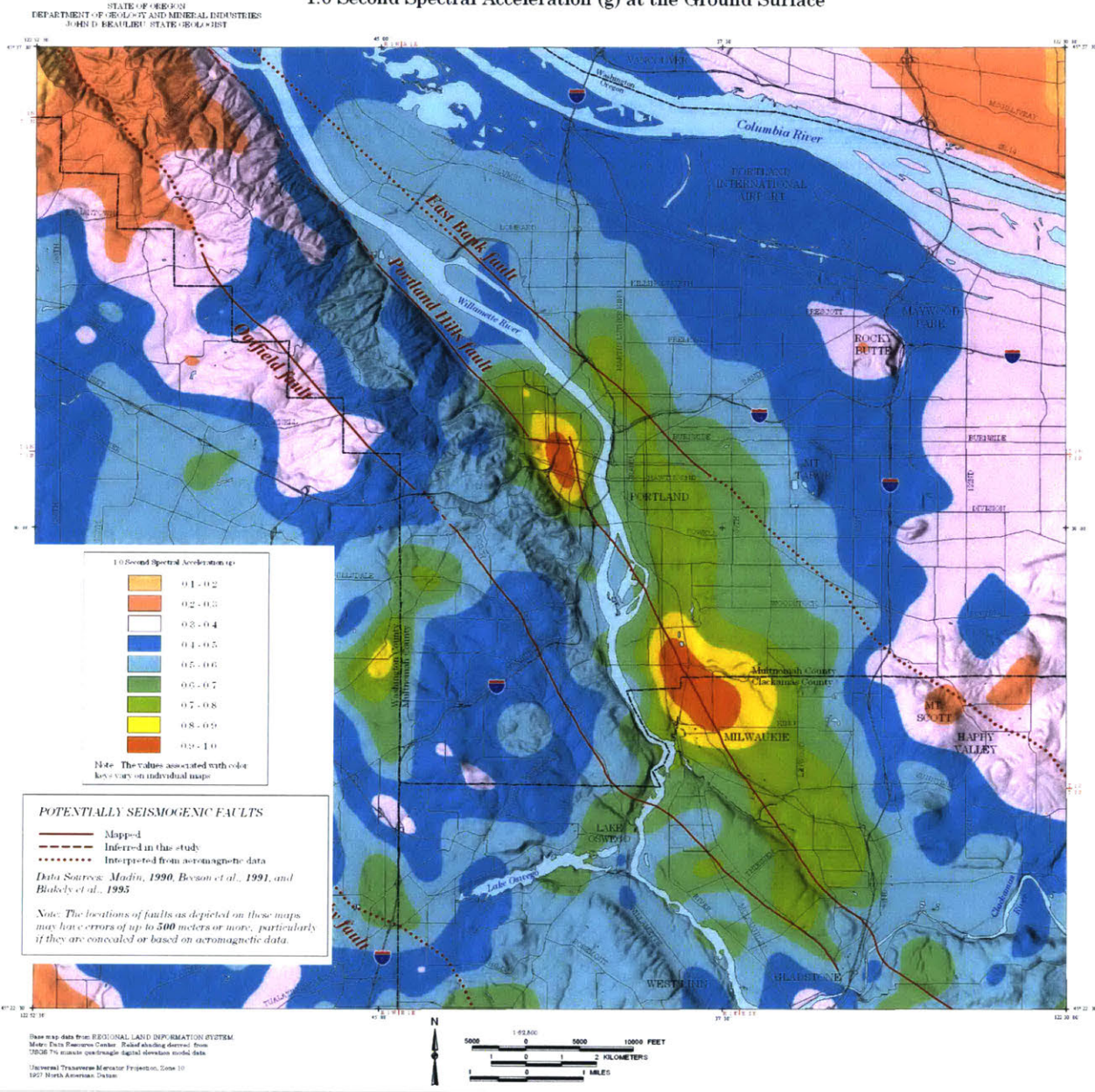
Figure 40. 1Hz Spectral Acceleration for M$_W$ 6.8 Portland Hills Fault Earthquake. This map, developed by *Wong et al.* [2000b], shows the potential acceleration for buildings in Portland if the frequency of the earthquake is 1 Hz. Ground shaking is concentrated along the trace of the fault.
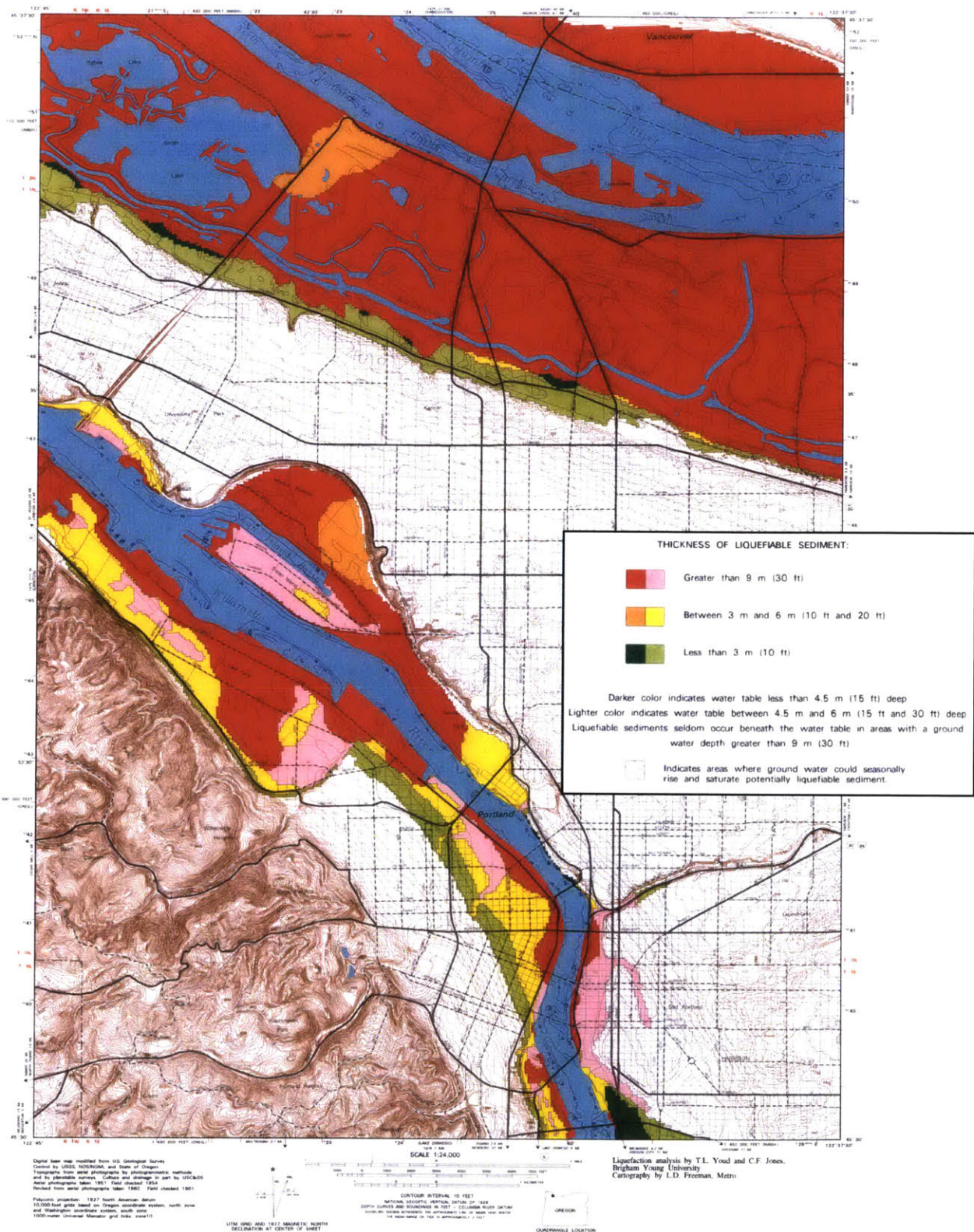
SEISMIC RISKS

Earthquakes create waves in two mediums: water and the lithosphere. Waves propagating through these different mediums can cause two basic hazards: tsunami and ground shaking.

Because Portland is located over 100 mi from the CSZ trench, this study does not cover the probabilities or impacts of tsunami hazards. Instead, this section discusses how ground shaking in Portland can exacerbate existing environmental and infrastructure vulnerabilities, thereby creating serious risks to residents and property.

Environmental vulnerability refers to susceptibility created by natural processes or the state of the natural environment. In Portland, environmental vulnerability is expressed as sediment saturation and sediment instability, which can lead to liquefaction and landslides when combined with ground shaking, respectively. Liquefaction occurs when sediments saturated with water become close-packed due to quaking. The water pore pressure exceeds the confining and gravitational stresses, thereby expelling water towards the surface and creating a ground sink. Landslides or debris flows occur on inclines when the shear stress on a plane, at some depth beneath the surface and approximately parallel to the slope, overcomes the cohesion of the slope material. Both liquefaction and landslides are triggered by ground shaking during an earthquake, and certain areas of Portland are particularly susceptible.

Portland rests in a basin on 500 m of unconsolidated sediments, much of which is soft alluvial silts [*Vessely et al.*, 1996; *Liberty et al.*, 2003]. Ground shaking can cause these deposits to liquefy, resulting in lateral displacement (commonly 10-15 ft but up to 100 ft), massive soil flows (up to 12 mi) and "loss of bearing strength… causing structures to settle or tip" [*Portland Off. of Emerg. Mgmt.*, 2010]. Figure 41 identifies the areas of Portland that are most susceptible to liquefaction. Most of downtown, where many businesses, tourist attractions and government buildings are located, is within the liquefaction zone, as is the Portland airport (PDX). If Portland experienced PGA from a large crustal quake, much of this area (if not all of it) would be liquefied.

THICKNESS OF LIQUEFIABLE SEDIMENT:

Greater than 9 m (30 ft)

Between 3 m and 6 m (10 ft and 20 ft)

Less than 3 m (10 ft)

Darker color indicates water table less than 4.5 m (15 ft) deep
Lighter color indicates water table between 4.5 m and 6 m (15 ft and 30 ft) deep
Liquefiable sediments seldom occur beneath the water table in areas with a ground
water depth greater than 9 m (30 ft)

Indicates areas where ground water could seasonally
rise and saturate potentially liquefiable sediment.

Figure 41. Liquefaction Susceptibility Map for Portland, after *Mabey et al.* [1993b]. This map shows the maximum vertical column that could be liquefied due to ground shaking in Portland. Red and pink areas, which could liquefy to a depth greater than 9 m, would have the greatest impact at the surface.
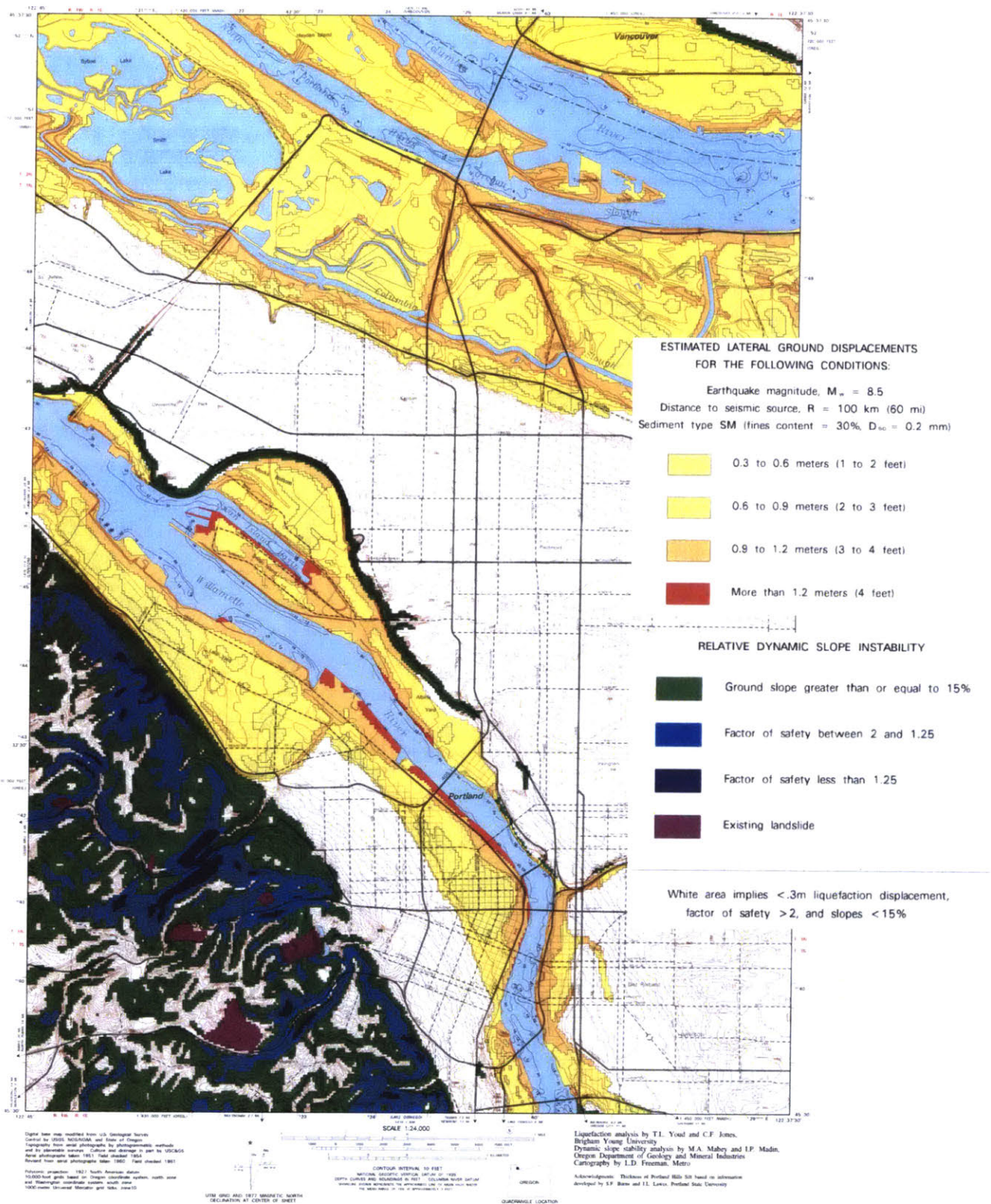
Figure 42. Lateral Displacement and Landslide Susceptibility Map for Portland, after *Mabey et al.* [1993a].
This map shows areas prone to landslides (cool colors) and the areas of maximum horizontal sediment displacement during a M_W 8.5 subduction earthquake (warm colors). Dark blue areas are most likely to experience slope failure, while pink areas can experience displacement of more than 4 ft in silty fine sand.

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Unlike liquefied sediments, landslides typically occur on steep slopes with loose sediment and can be triggered by water saturation, vegetation removal (urbanization) and seismic shaking [*Portland Off. of Emerg. Mgmt.*, 2010]. Many areas of Portland are susceptible to landslides and horizontal sediment displacement. The National Atlas, a governmental online mapping tool that utilizes USGS information, identifies Portland as an area of high landslide incidence (greater than 15% of the area): between 2005 and 2009, over 90 landslides were recorded in the Portland area [*Portland Off. of Emerg. Mgmt.*, 2010]. *Burns and Duplantis* [2010] mapped several areas within the Portland Hills, at the base of the Portland hills and along the east bank of the Willamette River as active landslides. Given that these slope instabilities have been triggered without any large, recent seismicity, we can assume that increased seismicity would exacerbate this existing vulnerability. Figure 42 is a map of dynamic slope instabilities (cool colors) and horizontal displacement of sediment on low (or zero) inclines during a subduction earthquake of M_W 8.5 (warm colors) [*Mabey et al.*, 1993a]. The map indicates that there are several areas within the Portland Hills and along the east bank of the Willamette, without existing landslides, that have low stability (cohesion is only slightly higher than shear stress). These regions are also generally bounded by areas that would experience, at minimum, 1-2 ft of lateral displacement within silty fine sand and, at maximum, more than 12 ft of displacement in poorly sorted sand areas [*Mabey et al.*, 1993a]. As with liquefaction, the regions of Portland most at risk include the airport and much of downtown. Continued expansion of the urban environment into and along the Portland Hills will only increase the risks due to landslides.

In addition to exacerbating environmental vulnerability, ground shaking can create risks when combined with infrastructure vulnerability (vulnerability of the built environment).

Infrastructure vulnerability includes public or private property, utilities and transportation systems that may sustain damage from an earthquake. In Portland, there are two categories of infrastructure that could fail and cause loss in human life or capital: buildings and lifelines.

Compressional and shear seismic waves can cause buildings to oscillate at critical frequencies, resulting in shattered windows, damaged plaster and chimneys, or total collapse. Certain buildings are more at risk than others, including structures with unreinforced masonry (URM) and high-rise buildings. Unreinforced masonry buildings have load bearing walls or other structures made of brick, cinderblock or other masonry material that is not braced by reinforcing beams, making them much more likely to collapse than specially designed facilities. According to POEM, there are approximately 1700 URM buildings in Portland, and many of them are located in high traffic areas with vulnerable populations[9] [2011]. Figure 43 denotes URM buildings that were constructed prior to 1978, when Portland first developed earthquake building codes [*Portland Off. of Emerg. Mgmt.*, 2010]. Additionally, over 60% of all buildings in Portland were constructed *after* the codes were developed [2010]. Comparing the URM map to Figures 41 and 42 highlights several areas where URM buildings rest on top of liquefiable or otherwise unstable sediments, primarily in downtown Portland. Comparisons to acceleration maps for interplate and crustal earthquakes show significant overlap between URM buildings and high PGA. As mentioned in the section on shallow crustal faults, high-rise buildings in the downtown area of Portland may also be at significant risk from low frequency waves concentrated along the trace of the PHF [*Wong et al.*, 2001].

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[9] Appendix A contains maps of Portland where income, race and poverty are broken down by neighborhood using Census 2000 data. These provide valuable insight to the location of many of the vulnerable populations identified in Chapter 3.

Ground shaking can also rupture or damage critical, lifeline infrastructure necessary for emergency response and recovery, as well as evacuation. Additionally, certain lifelines can leak hazardous materials or ignite fires if breached. *Barnett et al.* [2009] classify the following as lifeline infrastructure in Portland (Figure 44): water pipelines, wastewater pipelines, electrical power lines, natural gas pipelines, liquid natural gas pipelines, highways, railroads, airports and river ports. Each of these systems runs through at least one area with seismic hazards. Major segments of Interstate 5 (I-5), the central economic artery for the Pacific Northwest, would not be useable after a CSZ event ,because many older overpasses and river crossings have not been retrofitted [*Oregon Dept. of Trans.*, 2009]. POEM also estimates that, because most of the state's major medical facilities are within city limits, these critical structures could be at risk of suboptimal utilization during response and recover [2011]. The final concern from lifeline infrastructure failure or breach is hazardous waste release or fire. Failed sewage systems could present widespread health concerns during event recovery, while damaged power lines and natural gas pipelines could cause explosions or urban fires. Many of pipes are constructed of brittle material that is likely to fail if buried or built upon liquefied sediments [*Barnett et al.*, 2009]. Burst water pipelines can drain the system, resulting in a shortage of water for fire suppression; this has occurred in most major earthquakes in the last 100 years [*Barnett et al.*, 2009].

When considered holistically, the risks of loss of human life and capital to seismic hazards in Portland are tremendous. *Wang and Clark* [1999] modeled the losses using HAZUS for an interplate earthquake, M_W 8.5. For Oregon as a whole, they estimate 7800 deaths and casualties, 17,300 displaced households, 37,000 buildings in complete disrepair, 65% retention of essential facilities (police stations, fire stations, and emergency operations centers), 66%

retention of schools, $12 billion[10] in building losses, $370 million in highway and bridge losses, and $120 million in airport losses [*Wang and Clark*, 1999]. Multnomah County and Washington County would have the first and fourth highest total economic losses in the state, respectively. Though these estimates cannot be taken as definitive predictions, the potential devastation from earthquakes in Portland could be catastrophic without significant mitigation efforts and thorough, well exercised response plans.
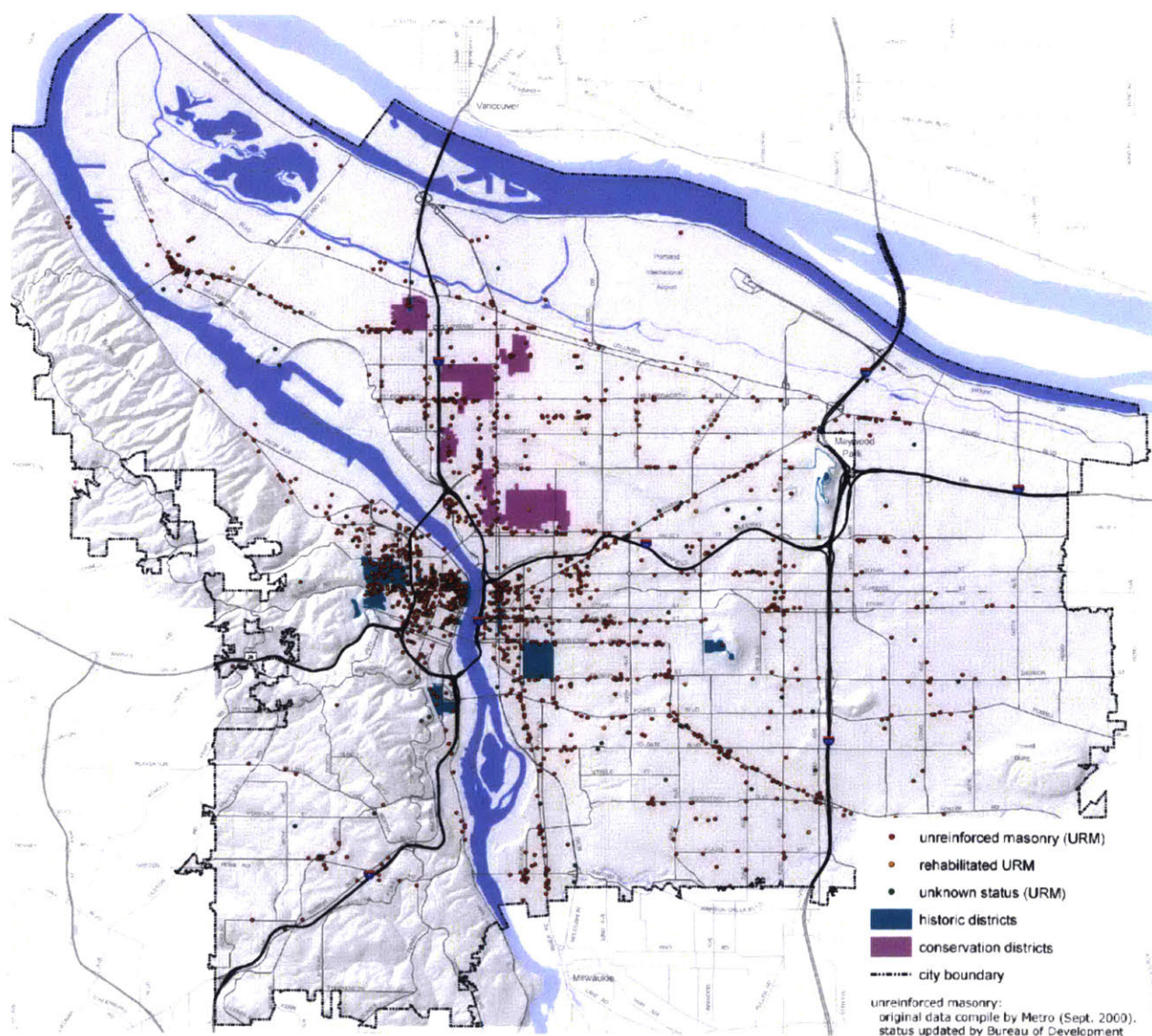
Figure 43. Unreinforced Masonry Buildings Map for Portland. This map was developed by *Starin and Mickel* [2009]. Many of the URM buildings are in areas prone to high levels of seismicity, liquefaction and landslides.
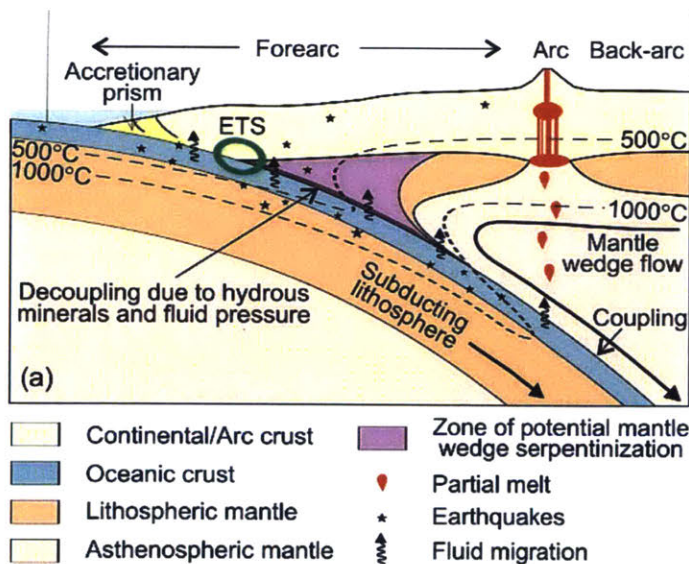
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[10] In 1999 dollars.
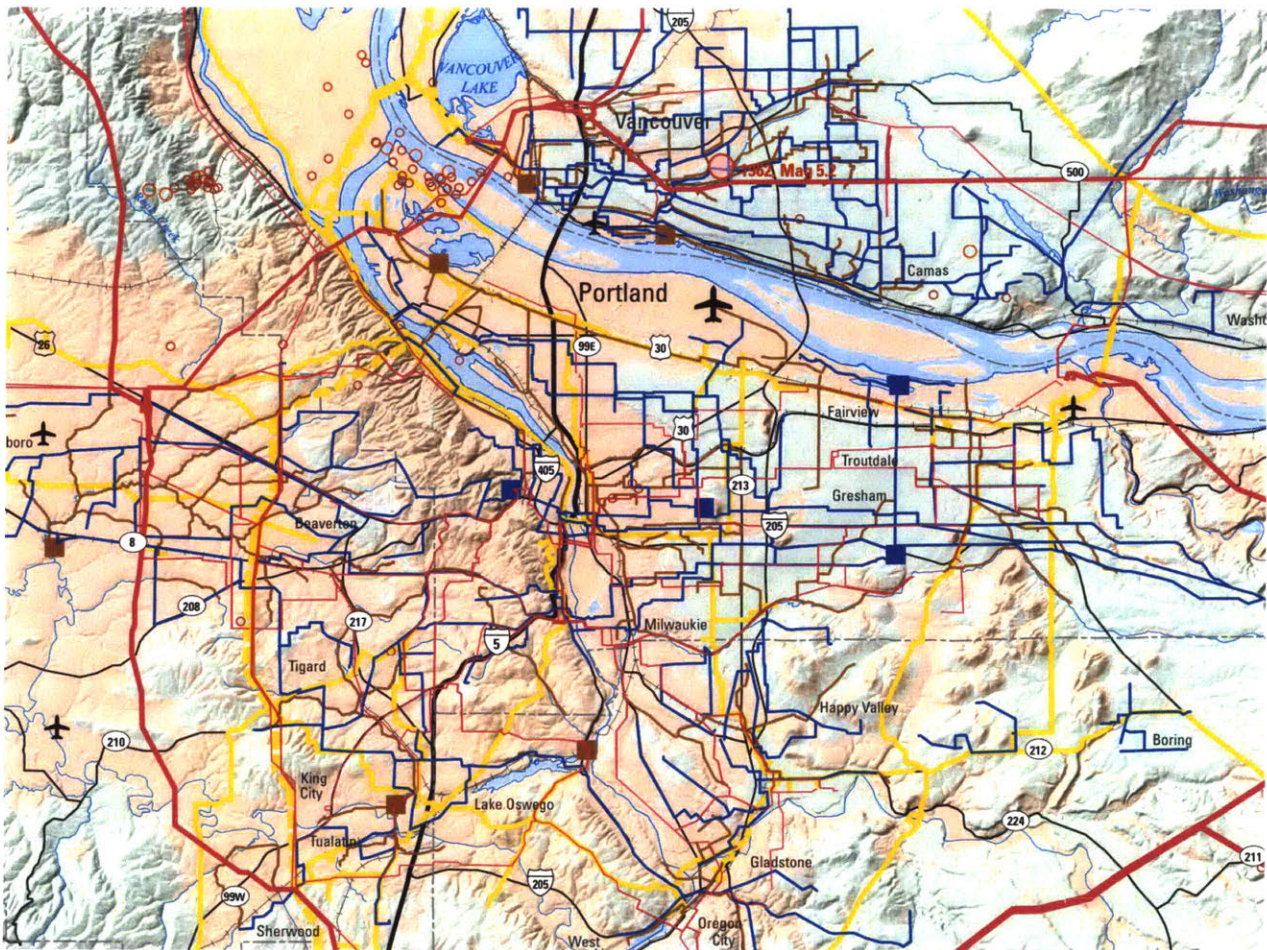
Figure 44. Lifeline Systems Map for Portland, after *Barnett et al.* [2009]. Critical lifeline infrastructure in Portland. Blue: water supply line (squares are treatment plants). Brown: sewer pipeline (squares are wastewater treatment). Pink: electric transmission lines. Yellow (solid): natural gas pipeline. Yellow (dashed): liquid natural gas pipeline. Black (thick): interstate highway. Black (thin): state highway and other roads. Black (ticked): railroads. Red circles: earthquakes up to 35 km deep from 1969-2007. Tan shading: unconsolidated deposits.

There is active volcanism in Oregon that could present a significant threat to residents of Portland. The continuous subduction of the Juan de Fuca plate under the North American plate has led to the development of the Cascadia volcanic arc, which acts as the eastern boundary of the Willamette Valley. Arc magmatism occurs when hydrated oceanic lithosphere and associated oceanic sediments are heated and pressurized to a regime where water (either bound or unbound) is no longer stable. The slab heats due to heat transfer from the overlying mantle wedge, increasing pressure at depth, and friction on the upper surface of the slab (shear-stress heating) [*Fowler*, 2005]. Figure 45 is a cross section of this process. Though most oceanic sediment is accreted onto the overlying plate at the trench (labeled as the accretionary prism), some may be subducted and melted fairly quickly in the subduction zone. These sediments add specific components (e.g. K) to the volatile dehydration stream that rises from the subducting slab. In addition to the overlying sediments, the basaltic (upper portion of the slab) and gabbroic (lower portion) components of the subducting plate will also undergo endothermic metamorphism and dehydration with depth [*Fowler*, 2005].

Figure 45. Cross Section of Warm Subduction Zone Arc Magmatism, after *Wada and Wang* [2009]. This schematic illustrates the dehydration of a young, warm down-going slab and the partial melting of the mantle wedge, which results in arc magmatism.

Dehydration of the slab and sediments releases water, which is positively buoyant. Water lowers the solidus (or the melting point) for mantle peridotite. At sufficient depth and

temperature (approximately 100 km and 1000°C), rising water triggers partial melting in the overlying mantle wedge [*Fowler*, 2005]. The dehydration of down-going slab increases pore pressures and can lead to embrittlement of the slab, resulting in tensile fractures that release the water (which would otherwise be trapped in the nonporous slab). The released water, partially melted mantle and associated volatiles then rise along shear zones (flow-lines) in the mantle wedge towards the surface [*Fowler*, 2005].

The resulting mantle melt is a mixture of very mafic mantle material, water and other volatiles, such as CO_2 and large-ion lithophile elements. The buoyant melt then rises to the crust, where it undergoes partial fractionation, precipitating out mafic minerals (such as clinopyroxene and olivine), and continues to rise as a lighter melt of basaltic or basaltic-andesitic composition. This partially fractionated melt may also assimilate some felsic crustal material, further increasing the silica content of the melt. The end products of this process are granitic or granitoid (granodiorite) plutons and basaltic to rhyolitic volcanoes (a scale relating silica content to magma type is located in Figure 46) [*Fowler*, 2005]. Volcano structure and hazards vary with the chemical composition of the magma. In the Cascades, the highest and most explosive peaks are formed by stratovolcanoes.

Stratovolcanoes are composites of lava, ash, cinders and volcanic bombs that build up high, steep slopes through periodic eruptions over time. The chemical composition of layered eruptions can range from non-explosive (low silica content, viscosity and volatile content) to highly explosive rhyolite (high silica content, viscosity and volatile content). Because stratovolcanoes can erupt explosively, the hazards are more numerous and distal than mafic or shield volcanoes. Figure 46 is a cross section through a typical Cascade stratovolcano, with the associated volcanic hazards labeled, including lava flows, pyroclastic flows, tephra, volcanic

bombs, fumaroles, dome collapse, landslides and lahars. The figure does not show the low-level seismic activity[11] that can accompany or precede eruptions [*U.S. Geological Survey*, 2009b], nor does it indicate that many of these hazards, including fumaroles, landslides and lahars, can occur in between events.

Figure 46. Stratovolcano Profile and Hazards, after *Myers et al.* [1998]. Stratovolcanoes have relatively high slopes built up from numerous periodic eruptions of viscous magma. The conduit system of a stratovolcano connects the vent to the subsurface magma chamber in the crust. When the volcano is inactive, the conduits are plugged with plutons or dikes. Though all of the depicted hazards can result from an explosive eruption, many can occur without any eruption at all, including lahars, landslides and fumaroles. The scale in the lower left gives the silica content of different stratovolcano magma compositions. Higher silica content results in higher viscosity and more explosive eruptions.
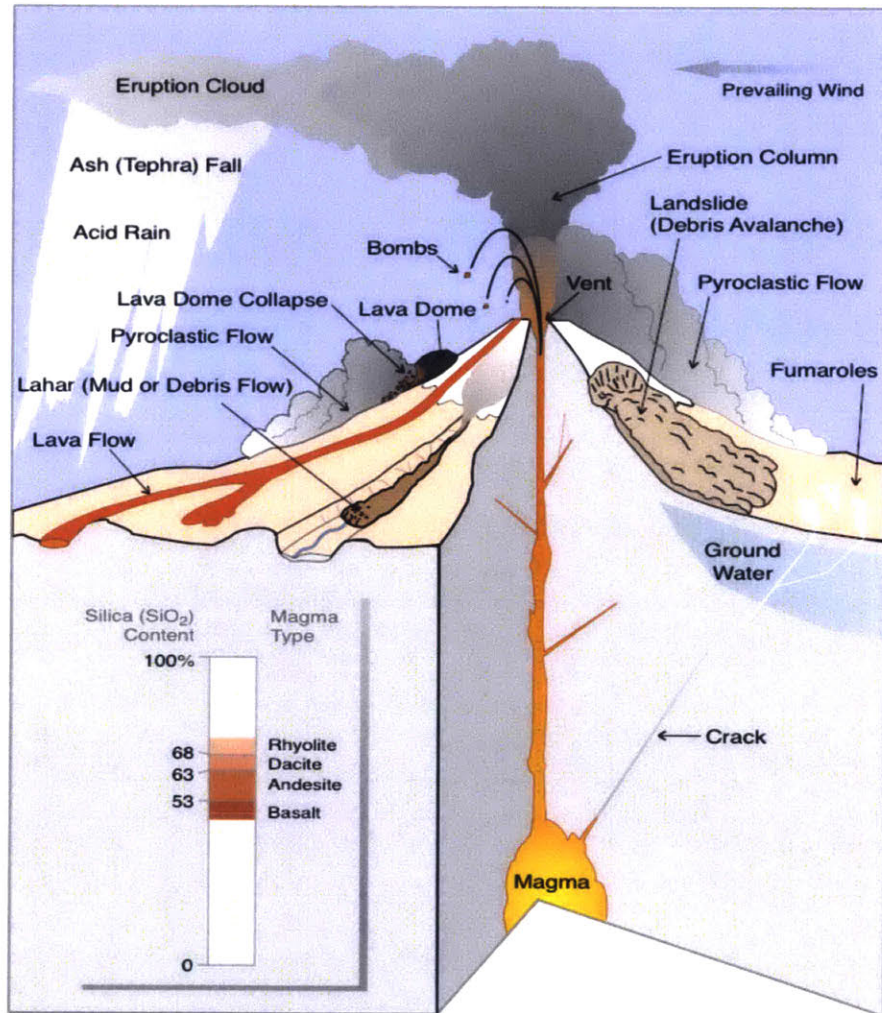
Non-eruptive activity and volcanic seismicity can be used to monitor volcanoes and derive short-term predictions. Generally, both volatile gas emissions and earthquake activity will increase prior to an eruption [*Chouet*, 1996; *Daag et al.*, 1996]. Fumaroles emit gas composed

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[11] According to data collected by the PNSN, seismic events during non-eruptive periods in the Cascades rarely exceed M_W 2 [2011a, 2011b, 2011c].

mostly of water vapor, but also of other volatiles such as CO_2, SO_2, HCl, H_2 and HF. Many active volcanoes have continuously emitting fumaroles due to degassing of magma bodies over time, and the composition of this gas is an indicator of volcanic activity [*Casadevall et al.*, 1983; *Fischer et al.*, 1996]. Changes in the concentration of any of these gases indicate increased magmatism and the volatile content of a magma body, which is correlated to the "energy available to power gas-driven" eruptions [*Casadevall et al.*, 1982]. Gas emissions are monitored constantly at active sites around the world and are frequently used as warnings of impending volcanism: geologists used SO_2 emissions to track development of and predict the 1991 Mount Pinatubo eruption in the Philippines [*Daag et al.*, 1996]. Similarly, volcanic seismicity is continuously monitored for indications of fluid (gas or magma) movement through conduits or cracks beneath the volcano. Though most volcanic seismicity is of very low magnitude, different frequencies can indicate various subsurface activity: short-period earthquakes signify fracture associated with changing stresses in the chamber; long-period events and tremors originate from pressure instabilities within fluids, including changes in volume [*Chouet*, 1996; *U.S. Geological Survey*, 2009b]. Both are signs of renewed activity and can precede an eruption by days to years or days to weeks, respectively [*Chouet*, 1996]. Both of these techniques, in addition to surveys of eruptive history, ground deformation at the site, thermal emissions and electromagnetic imaging, can aid in evaluating volcanic hazards and probable risks. Geologists are currently monitoring the activity of three volcanoes within the vicinity of Portland—Mount Adams, Mount St. Helens and Mount Hood—to determine risks to populations and provide information to emergency planning operations. Appendix B contains detailed hazard zonation maps for each volcano.
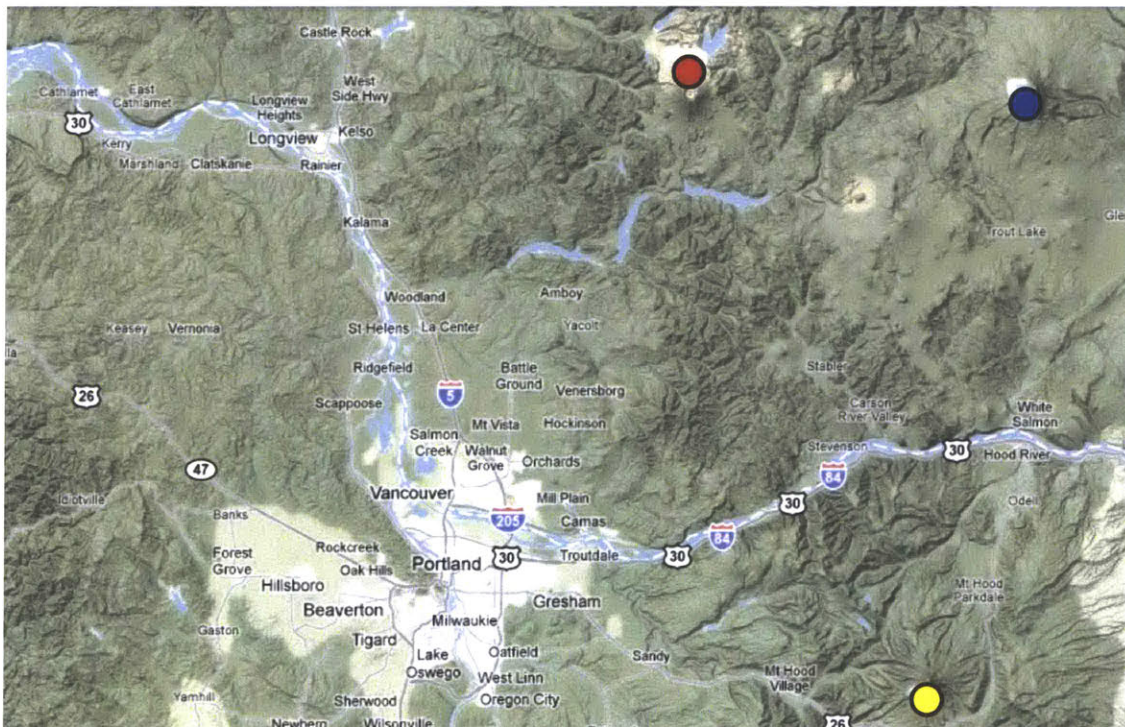
In addition to many small cinder cones, there are four stratovolcanoes in the Cascade Range within 110 km of Portland, three of which are designated as active by the USGS. Figure

47 shows the most recent Holocene activity for all of the major volcanoes in the Cascades, including Mount Jefferson, Mount Hood, Mount St. Helens and Mount Adams, the four volcanoes closest to Portland. Mount Jefferson last erupted approximately 15 ka and is considered to be dormant by the USGS [*Walder et al.*, 1999]. This section discusses the current and historic activity and risks of the three active volcanoes nearest to Portland (Figure 48).
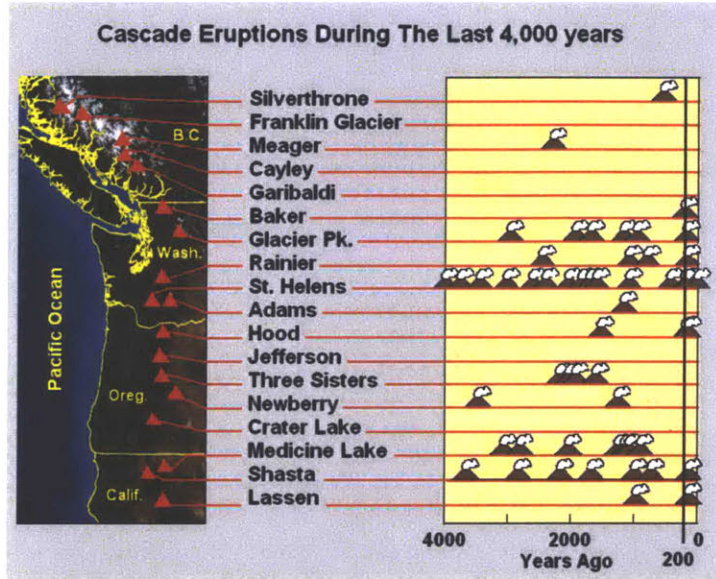
Left: Figure 47. Cascade Eruptions During the Last 4 ka. Of the 15 Cascade volcanoes mentioned in this map, produced by *NASA World Wind* [2008], Mount St. Helens has been the most active in the last 4 ka. Mount Hood and Mount Adams have also erupted in recent history.

Bottom: Figure 48. Volcanoes Proximal to Portland. The spatial relationship between Portland, the Columbia River, and peaks of Mount Hood (yellow), Mount St. Helens (red) and Mount Adams (blue) can be seen in this topographic image taken using Google Earth. For reference, the distance between Mount St. Helens and Mount Adams is 30 miles.

Mount Adams is the main stratovolcano that is the center of the Adams volcanic field, which covers an area of 1250 km^2 in Washington State, approximately 110 km from downtown Portland [*Scott et al.*, 1995]. Amongst all Cascade volcanoes, Mount Adams is second in eruptive volume only to Mount Shasta in California [*Cascade Volcano Observatory*, 2006]. Adams experienced a period of rapid cone growth between 20-30 ka, with several lava flows and tephra eruptions. Lava flows continued intermittent with lahars and debris flows until 2 ka. The most recent eruptive activity, tephra falls and small lava flows, occurred approximately 1 ka. Since this time, two major debris avalanches and one lahar have inundated the Salt Creek valley to the southwest of the central vent, the most recent in 1921 [*Scott et al.*, 1995]. In total, the USGS estimates that Adams volcanic field has erupted 8 times in the last 10 ka, producing mostly basaltic and andesitic lavas of a non-explosive nature [*Scott et al.*, 1995; *Cascade Volcano Observatory*, 2006]. Lava flows on Mount Adams traveled at most 50 km from vents and tephra typically blanketed areas within a few kilometers of vents up to several centimeters thick.

Mount Adams is currently emitting steam and H_2S through fumaroles near the crater area, and small earthquakes occur a few times a year. The earthquakes

Figure 49. Glacial Coverage of Mount Adams. This map, produced by *Hekkers and Thorneycroft* [2010], shows 9 of the 11 named glaciers on Mount Adams.

recorded since 2006 occurred between the surface and 9 km beneath the volcano and measured no greater than M_L 2.4 [*Cascade Volcano Observatory*, 2006; *Pacific Northwest Seismic Network*, 2011a]. Neither seismic nor gas measurements indicate imminent eruptions on Mount Adams, though such an eruption would likely be lava dominated rather than tephra, due to the relatively low silica content of past eruptions [*Scott et al.*, 1995]. The most threatening hazards from Mount Adams are lahars and debris flows.

Large landslides and lahars unrelated to eruptions "probably pose the most destructive, far-reaching hazard of Mount Adams" [*Scott et al.*, 1995]. Over the last 10 ka, glaciers have covered the summit and flanks of Mount Adams, eroding the cone to produce steep and unstable slopes (Figure 49). Geothermal fluids have circulated underneath these glaciers and within porous zones of the cone to further weaken slopes. These unstable areas are prone to debris avalanches, which can travel up to 50 km down valleys at speeds over 160 km/hr. If thermal activity increases, avalanches could transform into lahars if combined with significant glacial melting [*Scott et al.*, 1995].

For Portland, however, Mount Adams is not a risk. The distance between Portland and the Adams volcanic field rule out any direct impact from lava flows, lahars and debris avalanches. Historically low silica content magmas at Adams indicate the explosive eruptions of tephra and pyroclastic flows are unlikely at Mount Adams, though pyroclastic flows would not reach Portland regardless. If Adams alters its eruption pattern and expels large amounts of tephra, Portland may receive minimal coverage, though prevailing winds would push the vast majority of tephra to the east [*Scott et al.*, 1995]. It is likely that the only risks to Portland from an eruption or other event at Mount Adams would be indirect, either due to volcanic flows

reaching the Columbia River (which flows 50 km south of the main vent of Mount Adams) or to refugees from towns closer to the eruptive center.
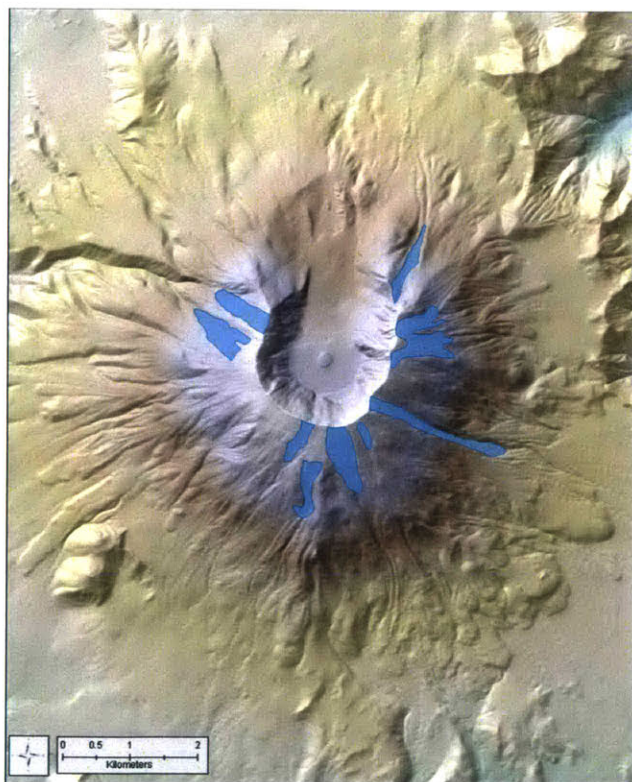
MOUNT ST. HELENS

Mount St. Helens is a stratovolcano in Washington, located 50 km west of Mount Adams and 80 km north of Portland. "Mount St. Helens is much younger and has been more explosively active recently than other major Cascade Range volcanoes" (Figure 47): episodic cone building of tephra and dacitic lava began 40-50 ka, while rocks from other Cascade volcanoes are over 100 ka [*Mullineaux*, 1996]. Over the past 4 ka, after a dormant period, Mount St. Helens has produced more than 60 tephra eruptions, in addition to several silica-rich lava domes, pyroclastic flows and lahars [*Cascade Volcano Observatory*, 2008b]. Most of these events produced dacite tephra, domes and pyroclastic flows, though some produced basaltic and andesitic tephra and flows [*Swanson et al.*, 1989]. The most recent large event occurred on May 18, 1980, when a large landslide asymmetrically released pressure on the dome and resulted in large lateral blast to the north of the main vent (Figure 50).

The May 1980 eruption was preceded by several indicators for at least two months prior to the eruption: geologists monitoring the volcano observed elevated seismicity, phreatic explosions, ground deformation along the flanks (bulging) and new fumarole activity [*Swanson et al.*, 1989]. On the morning of May18, an earthquake of M_W 5.1 was recorded at the same time a landslide, in three blocks totaling 2.7 km^3, removed the observed flank bulge as well as the upper 400 m of the volcano, "leaving a 600-meter-deep crater 2 kilometers wide rim-to-rim" [*Swanson et al.*, 1989]. The landslide turned into a debris avalanche that buried Toutle valley beneath 50 m of volcanic material. Following the landslide, depressurized volcanic gases and

water vapor exploded laterally, collapsing the north flank and triggering a 9 hr eruption of dacitic tephra into a Plinian column more than 20 km high [*Christiansen and Peterson*, 1981]. During this period, several lahars drained into streams along the north, south and east flanks fed by groundwater and rapid melting of snow and flank glaciers [*Swanson et al.*, 1989]. Figure 50 maps the extent of the glaciers post-eruption [*Hekkers and Thorneycroft*, 2010].

The May 18, 1980, eruption caused more damage than any other volcano in American history [*Tilling et al.*, 1990]. Fifty-seven people were killed; scores were injured; hundreds of houses were destroyed; over 185 miles of roads and 15 miles of railways were destroyed; the Columbia River was inundated with lahar material 8 m deep, stranding 31 ships in upstream ports; and the costs of damages and disaster relief topped $2 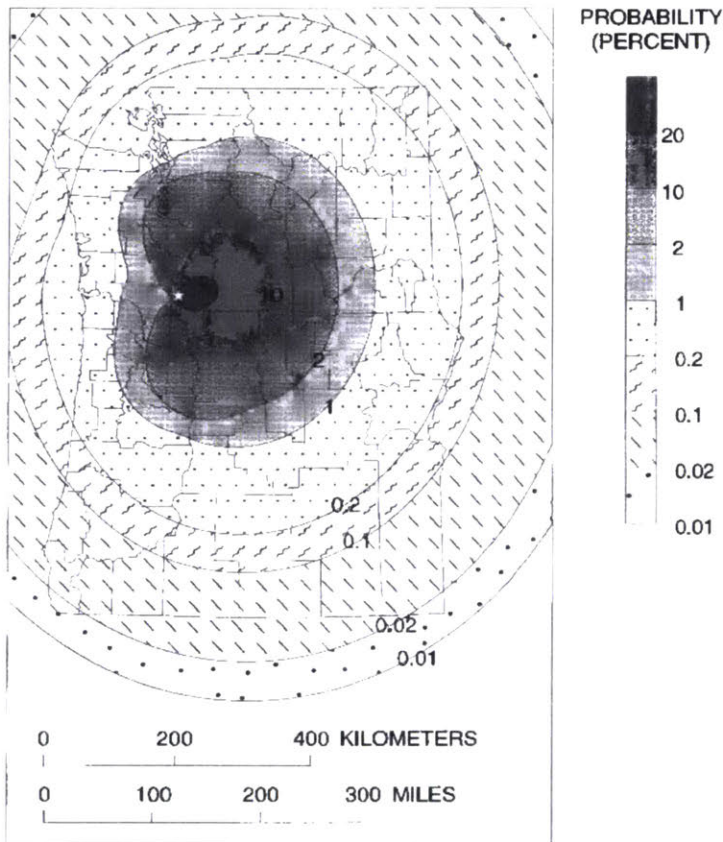billion [*Swanson et al.*, 1989; *Tipping et al.*, 1990]. For a short period after the eruption (weeks to months), unemployment rose tenfold and tourism dropped substantially [*Tipping et al.*, 1990].

Figure 50. Glaciers on Mount St. Helens Following the May 18, 1980, Eruption. This DEM map, taken from *Hekkers and Thorneycroft* [2010]

Mount St. Helens has remained active since the 1980 eruption through a series of phreatic explosions, pyroclastic flows, dome building and lahars [*Tipping et al*, 1990; *Brantley and Myers*, 2000; *Cascades Volcano Observatory*, 2009]. In the remaining months of 1980, several smaller eruptions produced ash columns and pyroclastic columns. Between 1980 and 1986, 17 eruptive episodes

built up a new dome 876 ft above the crater floor [*Brantley and Myers*. 2000], and a second dome-building period began in October 2004 and ended in January 2008 [*Cascade Volcano Observatory*, 2008]. Since January 2008, seismic events, gas emissions and ground deformation have persisted, though the levels are not indicative of an eruption in the immediate future.

Renewed eruptions of Mount St. Helens are imminent and could include basaltic or andesitic tephra and lava flows or explosive eruptions of dacitic tephra and pyroclastic flows. Lahars from snow and glacial melt would be likely to accompany any of these events, though lahars could occur without an eruption [*Wolfe and Pierson*, 1995]. Of these possible volcanic hazards, Portland is most at risk from tephra falls. Pyroclastic and lava flows are proximal hazards that would not extend much beyond the flanks of the

Figure 51. Probability for 10+ cm Tephra Cover due to a Large Mount St. Helens Eruption. This map, developed by *Wolfe and Pierson* [1995], indicated that Portland has a 2% chance of 10+ cm tephra coverage in the event of a large eruption. Factors used to model probabilities are wind direction and the probability of 10+ cm of tephra being emitted in a large eruption.

volcano itself or the nearby river valleys [*Wolfe and Pierson*, 1995]. As shown in Figure 48, the only tributary that connects Mount St. Helens and the Columbia River is upstream of Portland. Lahars could drain into the Columbia River at Longview or Woodland, thereby stranding boats in the Portland Port, but this would not dramatically impact the lives or livelihoods of Portland

residents. More likely to cause transportation problems is volcanic ash or tephra, which could blanket an area of 40,000 square miles or more [*Portland Off. of Emerg. Mgmt.*, 2010]. Figure 51 is an ash-cover probability map for the largest probable eruption of Mount St. Helens, indicating that there is a 2% probability Portland could be covered in 10 cm or more of tephra. Though annual probabilities are much lower (0.01% probability of 10+ cm of tephra cover from an Cascade volcano [*Wolfe and Pierson*, 1995]), it is essential to plan for such a hazard, especially because Mount St. Helens is the most active volcano in the Cascades.

Tephra poses risks to health and infrastructure. The small particles can cause eye and respiratory problems and disrupt air quality at hospitals and other critical facilities [*Wolfe and Pierson*, 1995]. If ejected into the atmosphere, which is likely to occur in an explosive eruption, tephra can darken the skies and reduce visibility on highways. After the 1980 Mount St. Helens eruption, some roads were closed for weeks due to reduced visibility, and several airports were closed for two weeks and over 1000 commercial flights were cancelled due to poor visibility [*Tilling et al.*, 1990]. Flights were also grounded due to the risks of engine failure. Hot ash can flash cool into glass, clogging internal combustion engines or other unprotected machinery, pumps and filtration systems. Just the weight of tephra can cause significant property damage, and wet tephra poses an even greater threat. Wet deposits can short-circuit electrical transformers and power lines; the 1980 eruption caused several blackouts [*Tilling et al.*, 1990]. Removal costs after the 1980 eruption totaled $2.2 million and took 10 weeks to complete in certain counties near the volcano [*Tipping et al.*, 1990]. Though deposits in Portland are unlikely to be as thick as cities closer to Mount St. Helens, the costs of damaged machinery and removal, in addition to air quality problems, could significantly impact the city in the event of a large eruption.

Mount Hood, Oregon's highest peak and most recently active volcano, is the closest stratovolcano to Portland at a distance of 75 km to the east of the city. The volcano has erupted repeatedly for hundreds of thousands of years, and the cone consists of primarily andesite and some dacite, though the dacitic products have only erupted in the last 15,000 years [*Cascade Volcano Observatory*, 2008a]. Unlike Mount St. Helens, Mount Hood has not produced violent, explosive eruptions. The last 30,000 years of Mount Hood's history is dominated by growth and collapse of domes, which lead to pyroclastic flows and lahars [*Gardner et al.*, 2000]. Between 15-12 ka, pyroclastic and debris flows covered the flanks of Mount Hood. This period was followed by approximately 10,000 years of dormancy, until Mount Hood again began to produce pyrsoclastic flows and debris avalanches [*Cascade Volcano Observatory*, 2008a]. One of the two most recent eruptions (Figure 47) occurred during this time. The most recent eruptive period, known as the Old Maid eruptions, spanned 1760-1810 CE. A dacite dome was erupted and collapsed, producing debris flows that traveled the White and Sandy River valleys into the Columbia River [*Cascade Volcano Observatory*, 2008a]. Recent seismicity, ground temperatures and fumarole activity for Mount Hood is normal and does not indicate an imminent eruption [*Cascade Volcano Observatory*, 2008a].

Because no eruptions of Mount Hood have occurred in recorded history, we cannot examine the hazards and risks in terms of recent destruction as we can with Mount St. Helens. Instead, geologists rely on historical eruption patterns and current activity to determine which hazards pose the most risk. Figure 52 maps all hazards from Mount Hood as proximal (P) and distal (D) based on the vent location (A or B). Though lava flows and domes are the most common eruptive source at Mount Hood, most flows reach a distance, at most, of 6 to 8 miles

from their source, and pyroclastic flows resulting from dome collapse would not travel more than 8 miles from the source [*Gardner et al.*, 2000]. Nether of these hazards would pose an immediate risk to any Portland residents or infrastructure. Similar to Mount St. Helens, much of the summit of Mount Hood has experienced alternation due to geothermal fluids, making the flanks susceptible to debris avalanches [*Cascades Volcano Observatory*, 2008a], though these events are infrequent and usually triggered by eruptions [*Gardner et al.*, 2000]. As presented in Figure 52, the most potentially damaging volcanic hazard from Mount Hood is a lahar.
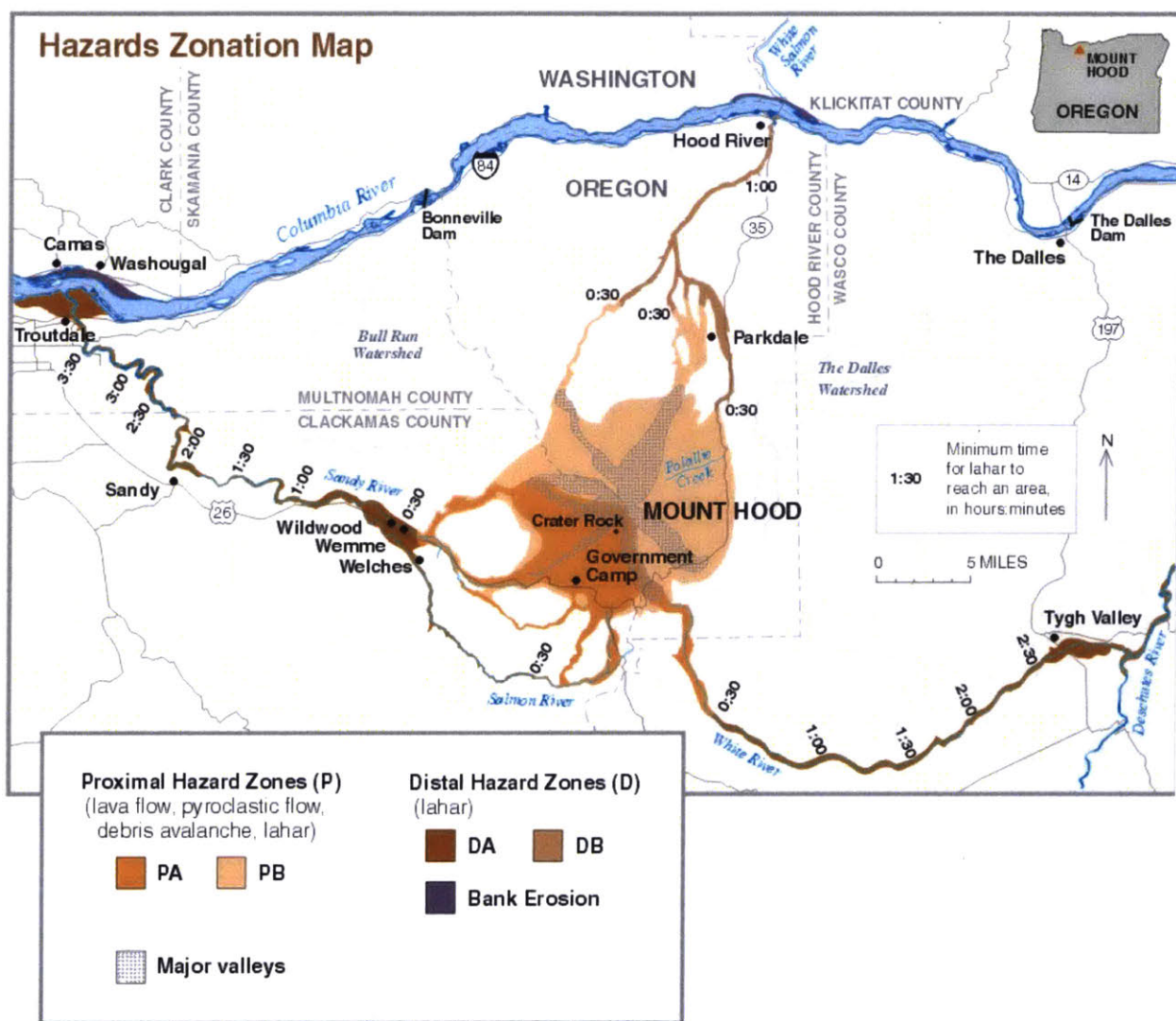
Figure 52. Hazards Zonation Map for Mount Hood, after *Scott et al.* [1997]. Approximate extent and timing of lahar flows, lava flows, pyroclastic flows and debris avalanches for Mount Hood. Areas of bank erosion imply debris accumulation on the opposite bank of the river due to lahar deposits.

One hundred thousand years ago, the entire north flank and summit of Mount Hood collapsed, resulting in a debris avalanche that transformed into a lahar. The lahar traveled down the Hood River valley to the confluence of the Hood River and the Columbia River, where the town of Hood River is currently located. The lahar was so great that it buried this area under 400 feet of volcanic mud [*Gardner et al.*, 2000]. More recently, approximately 1,500 years ago, a lahar flowed down Sandy River valley and altered the course of the Columbia River, creating the bend at Troutdale that can be seen in Figure 52 [*Gardner et al.*, 2000]. Lahars on Mount Hood can occur in between eruptive episodes. If glaciers or groundwater are heated by subsurface flow, massive outflows of water can remove already unstable slope material and inundate nearby river valleys. Mount Hood is almost completely covered in perennial ice between elevations of 1295 m and 3420 m, with 12 named glaciers (Figure 53) [*Jackson*, 2010]. Lahars would not reach the city limits of Portland, but they are likely to disrupt flow on the Columbia River or breach nearby dams, such as the Bonneville dam.
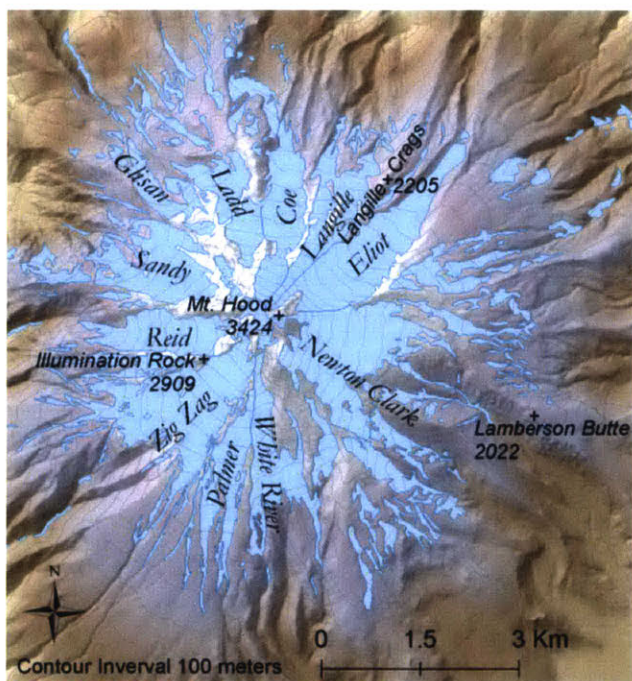
Figure 53. Glaciers of Mount Hood, after *Jackson* [2010]. Mapped extent of glaciers on Mount Hood show significant coverage.

VII. CONCLUSIONS

This final chapter combines information about the hazards, vulnerability and emergency response plans of Portland to evaluate the preparedness of the city and to make recommendations for improving resiliency. Natural events become natural disasters when hazards encounter communities with existing vulnerabilities. Portland cannot prevent earthquakes or volcanic eruptions to reduce the probability or severity of natural hazards, so the city must instead focus its energy on reducing vulnerability, exercising response techniques and plans, and preparing recovery plans. Reducing vulnerability requires preventative (mitigation) actions before an event; responding effectively requires immediate and efficient coordination during an event; and swift recovery requires adequate planning and preparation.

Many of the cataclysmic events discussed in Chapters 5 and 6 represent large-scale destruction (multi-county or multi-state) that would necessitate involvement and resources from the state and/or federal government. However, involvement of higher authorities does not mean that the city becomes obsolete. Response to an unexpected event, such as an earthquake, will always begin with the city as the first responder. Response to forecasted events, such as volcanoes, may allow for higher authority involvement but will still require mitigation and recovery efforts from the city. Thus, it is imperative to critically analyze the state of city emergency response operations. The Portland Office of Emergency Management (POEM) identifies their responsibilities as "planning, training, exercising and documenting the systems that will need to be applied to prepare, mitigate, respond and recover from disaster" [2011]. This chapter discusses the state of risk reduction strategies in Portland for volcano-tectonic hazards and offers specific recommendations for immediate action.

Information presented in Chapters 5 and 6 indicates that Portland is most at risk from infrastructure shaking damage in the Portland Hills, in downtown at the base of the Portland Hills and along the Willamette River (Figures 29, 30, 31, 38, 39, 40, 43 and 44); from liquefaction in downtown along the Willamette River and along the banks of the Columbia River (Figure 41); from landslides in and at the base of the Portland Hills (Figure 42); from Mount St. Helens tephra fall throughout the city (Figure 51); and from Mount Hood lahar interference with the Columbia River (Figure 52). These hazards present the greatest risk because critical infrastructure or vulnerable populations are likely to be impacted. High-rise buildings, unreinforced masonry, highways, bridges, and old pipelines are most at risk from ground shaking, liquefaction and landslides. Water treatment facilities, the Portland International Airport, Columbia River shipping operations and dams are most risk from volcanic hazards, though sufficient tephra fall could cause universal damage to private and public property. In addition to these economic impacts, earthquakes and volcanoes pose threats to human health and life: all seismic hazards can result in serious injury or death from falling objects and buildings, while tephra inhalation can cause eye and respiratory problems. Impacts on the lives and livelihoods of Portland residents will also vary greatly by location and personal vulnerability. Risks are compounded for many of Portland's socially vulnerable residents (the poor), who are concentrated in neighborhoods likely to receive the most damage from seismic hazards (see Appendix A). Many persons in poverty or with annual income below $25,000 live along the Willamette River, in or around the susceptible downtown district. For more information on the spatial distribution of vulnerable populations, see *Dickman et al.* [2007], which summarizes GIS and HAZUS-MH studies that identify downtown and several surrounding areas as the most at

risk neighborhoods and the neighborhoods with the highest concentrations of vulnerable populations. Figure 54 is a map of these neighborhoods.
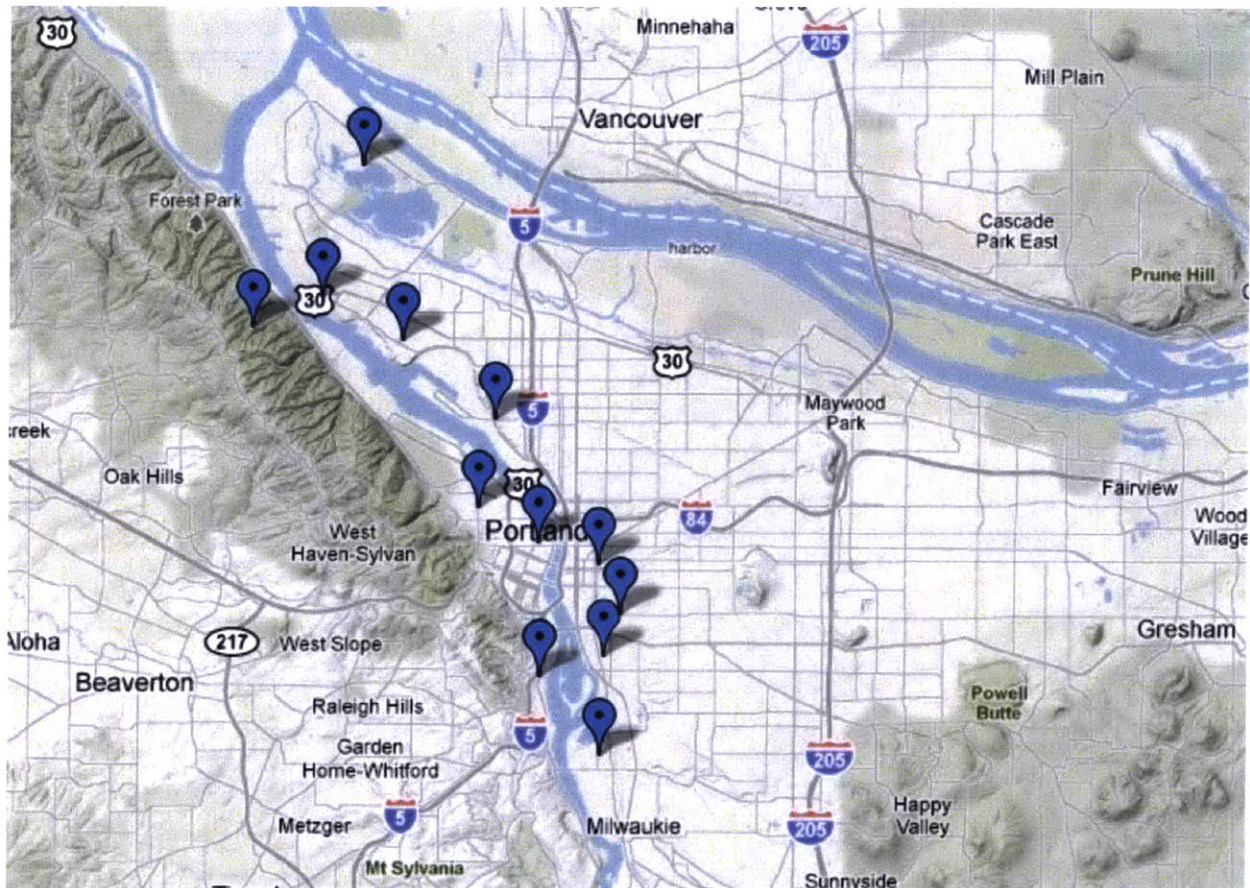
Figure 54. Triple Hazard Neighborhoods in Portland. This terrain map was generated from data provided by *Dickman et al.* [2007] using Google Maps. Blue balloons represent neighborhoods with at the greatest risk from earthquake, flood and toxic release hazards. The twelve neighborhoods identified here also have the highest populations of vulnerable persons.

REDUCING VULNERABILITY

There have been no large-scale earthquake or volcanic disasters in the United States in recent history. The only emergency response operations to a comparable natural disaster is the August 2005 FEMA response to Hurricane Katrina. Katrina was forecasted to make landfall in Mississippi and Louisiana on August 26 by the *National Hurricane Center* [2005], three days prior to the storm hitting New Orleans. This gave President Bush, Governor Blanco and Mayor Nagin sufficient time to declare emergencies, order evacuations and request federal assistance

from FEMA and the national guard. But unlike severe weather storms, earthquakes often occur without warning signs. Even foreshocks, which do not accompany of earthquakes [*Pacific Northwest Seismic Network*, 2002], can be devastating in their own right if the city has not taken mitigation action prior to events. And though volcanic eruptions can be successfully predicted, as was demonstrated in 1991 prior to the Mount Pinatubo eruption in the Philippines [*Wolfe and Hoblitt*, 1996], vulnerable infrastructure will be devastated by tephra or lahars without long-term mitigation strategies, such as enclosing water treatment and filtration systems. In order to reduce the potential loss of life and property from these hazards, emergency mitigation must be a continuous priority of the city to reduce its vulnerability and thus prevent large losses.

POEM's 2011 draft Basic Emergency Operations Plan (BEOP) identifies the Hazard Specific Appendices and the Natural Hazard Mitigation Plan as the key components of their mitigation strategies and plans (see Figure 23 for the structure of Portland's Comprehensive Emergency Management Plan). The City Auditor, LaVonne Griffin-Valade, released a report in May 2010 on the state of the Portland Emergency Management Office. The report, "Emergency Management: Coordination limited and essential functions incomplete," determined that POEM is not focusing its resources on the highest risk areas, nor has it completed several components of emergency planning and preparedness. Missing components essential to mitigation and prevention include sporadic public education and information outreach, incomplete response plans and unclear approval processes for plans, and disaggregated risk assessments. Though the subsequent release of POEM's Natural Hazard Mitigation Plan in 2010 and the revised BEOP in 2011 address the Auditor's findings to some extent, it remains to be seen whether these documents will prioritize and streamline preventative measures in Portland. The Hazard Specific Appendices are not complete as of this writing (Figure 23), and the implementation status of

mitigation goals from the Natural Hazard Plan is unknown. The BEOP contains no "best practices" or suggested preventative measures. Presumably, some mitigation takes place at the bureau level, but the information on mitigation projects and progress is not centralized or readily available.

Many mitigation strategies are costly and are thus given lesser priority than low hanging fruit. Often, our society tends to forego long-term prevention in favor of short-term fixes. For residents of New Orleans, this resulted in massive flooding due to breached levees that were poorly designed and improperly maintained. In Portland, failure to prioritize preventative measures could result in enormous economic losses, numerous deaths and widespread infrastructure failure. Recommended mitigation actions include retrofits, assessment of critical facilities, city zoning reform and comprehensive and intensive community education.

[1] As USGS geologist Mary Lou Zoback stated in her paper on lessons learned from the 1906 San Francisco earthquake, "earthquakes do not kill people, buildings do" [2006]. Portland needs to retrofit URM and high-rise buildings, highways (especially I-5) and bridges in areas of high PGA and liquefiable sediments, primarily in downtown Portland, the Portland Hills, and along the banks of the Willamette and Columbia Rivers. Portland is currently receiving federal grant money to retrofit fire stations and schools, but similar services are needed for numerous other facilities, especially those in densely populated areas.

[2] Assessments for the Columbia Boulevard Wastewater Treatment Plant[12] and other major water, electricity and natural gas facilities are also necessary to reduce volcanic hazard damage and coseismic urban hazards, and to ensure access to lifeline resources during response. Open-air water facilities can become clogged due to tephra inundation, and lahar flows can

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[12] This facility is denoted by a brown square at the confluence of the Willamette and Columbia Rivers in Figure 44.

damage dams or water treatment plants located along riverbanks. Seismic activity can rupture gas or power lines, leading to urban fires, or breach hazardous material storage units. Over 28,000 buildings were destroyed in the 1906 San Francisco earthquake (M_W 7.9) and between 80-85% of that damage is estimated to be due to fire [*Zoback*, 2006; *U.S. Geological Survey*, 2009c]. San Francisco burned to the ground because water mains, gas mains and electricity lines were ruptured. Failing to properly retrofit these lifelines could result in similar scenarios in Portland.

[3] Portland needs to reconsider zoning laws to mitigate public exposure to natural hazards and reduce urban contributions to environmental vulnerability. By zoning riverbanks as parks or public recreation areas, the city can prevent more structures from being built on liquefiable sediments. Similarly, rezoning the Portland Hills could be vital to slowing urbanization in areas already prone to land slides.

[4] Finally, POEM needs to develop a comprehensive public education plan and public information network. This particular recommendation echoes the comments of the City Auditor, who reported that POEM falsified information on their website to give the appearance of public involvement on the Natural Hazard Mitigation Plan, when in fact no public comment period or public meeting ever occurred [*Griffin-Valade et al.*, 2010]. Residents need to be aware of natural hazard risks and develop connections to authorities that are in place to keep them safe. When Mayor Nagin ordered an evacuation of New Orleans, over 70,000 residents failed to leave the city before Hurricane Katrina made landfall [*Select Bipartisan Comm.*, 2006]. Though we cannot definitively state *why* these residents failed to evacuate, some studies point to distrust of authority, which is more prevalent amongst racial or ethnic minorities [*Cordasco et al.*, 2007]. In

Portland, failure to target education and outreach to the most vulnerable persons, most of whom are minorities, could result in significant disparities in casualties across social groups.

IMPROVING RESPONSE

In addition to emergency mitigation, response plans and frameworks must be in place and ready for effective utilization the moment an event occurs. The common format used for emergency response plans at the city, county, state and federal level, are not truly "plans" in the traditional sense. These documents assign responsibility, outline reporting structures and provide some incident specific information (such as which buildings are most vulnerable to liquefaction), but they do not outline specific steps to take during a response. This is likely because emergency operations plans are designed to be one size fits all and applicable to any event of any magnitude. While this type of planning is not inherently deficient, it does require that all agencies and actors participating in a response are comfortable with the procedures and adaptable to new situations. A nonspecific framework also increases the importance of detailed support annexes and appendices for specific hazards, such as a terrorist attack.

All levels of emergency management plans covering Portland are incomplete, and components of some plans have failed to be exercised or trained effectively. The City Auditor reported that POEM "lacks clarity of roles, a long-term strategy, and accountability for implementation," resulting in failure to complete plans, fulfill mandates and exercise plans effectively [*Griffin-Valade et al.*, 2010]. Lessons from the 2005 Hurricane Katrina response efforts prove that failures of leadership to act decisively can result in catastrophic losses [*Select Bipartisan Comm.*, 2006]. In an interview with the New York Times, Michael Brown, the former director of FEMA during the Katrina response, stated that establishing an unified command

center was nearly impossible due to the multitude of authorities participating, a lack of control and insufficient coordination of resources [*Kirkpatrick and Shane*, 2005]. FEMA had completed a national hurricane exercise for fictitious Hurricane Pam only a year prior to Katrina (July 2004), utilizing the flexible national response framework designed specifically to coordinate multiple agencies and their resources in response to a cataclysmic disaster in New Orleans [*Select Bipartisan Comm.*, 2006]. By all accounts, government should have been prepared to evacuate New Orleans and respond immediately. Former FEMA director Brown reflected upon his lack of decisive action to evacuate and call in federal troops, stating, "Until you have been there, you don't realize it is in the middle of a hurricane" [*Kirkpatrick and Shane*, 2005]. This sentiment reflects the absolute necessity of complete, detailed response plans and agile, equipped responders. In Portland, both of these critical components of response are lacking.

Chapter 4 outlined the city, county and state comprehensive emergency response plans, specifying the incomplete components. Of greatest concern are the incomplete earthquake and volcano annexes for the Portland BEOP and the Portland evacuation plan. In 2006, a POEM preliminary assessment of hazards recommended creating separate plans for the most frequent natural hazards, including earthquakes [*Griffin-Valade*, 2010]. There has been no such plan created since POEM was established in 2003, and the existing plan has no information specific to the seismic hazards most relevant to Portland residents or regions of the city that are most vulnerable.[13] But preparedness for earthquake hazards exceeds any city planning for volcanic hazards. Until the publication of the Natural Hazard Mitigation Plan (NHMP), Portland had not assessed the city's risks due to volcanic eruptions or made any plans to prepare for hazards. As of this writing, there are still no plans to direct response actions in the event of tephra or lahar

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[13] The City of Portland Earthquake Plan is no longer publicly available. References in this paper are to an archived copy, downloaded on December 13, 2010, from the Portland Office of Emergency Management website.

hazards. The NHMP described tephra falls from Mount St. Helens as "limited" and "negligible," ignoring potential impacts from lahars. The only volcanic risk reduction strategies are vulnerability assessments of critical facilities, with no mention of formalizing plans [*Portland Off. of Emerg. Mgmt.*, 2010]. The State of Oregon offers a completely different assessment of the risk, identifying Mount Hood as "the greatest potential volcanic hazard to Oregonians," stating that "the Northern Willamette Valley/Portland Metro Region and the Mid-Columbia Region would both be impacted... [and] the potential for a large disaster exists" [*Ecology and Environment*, 2010e]. Though POEM does not recognize lahars as a threat to Portland, the Oregon EOP identifies lahars from Mount Hood, Mount St. Helens, and Mount Adams as threats to the Portland metropolitan area. Lahars from these three volcanoes could affect the Columbia River (including any dams or levees), and lahars from Mount Hood could impact the Bull Run Reservoir, which supplies Portland's water [*Ecology and Environment*, 2010e].

The second planning concern is the evacuation strategy for Portland. There is no publicly available evacuation plan, and reports about the existence and efficacy of such a plan are inconsistent. In May 2010, the City Auditor reported,

> The Police Bureau developed a plan for evacuation, which was adopted by the City Council as City policy in September 2007. In March 2008, POEM hired a consultant to produce a new evacuation plan, with $200,000 in federal money. No new evacuation plan has been approved or disseminated. [*Griffin-Valade et al.*, 2010]

In a conflicting report, the Federal Highway Administration (FHWA), part of the U.S. Department of Transportation, released an assessment of Portland's highway evacuation plan in April 2010, stating that the city had conducted a "2008 Gap analysis... as a needed component of the City of Portland Evacuation Annex update" [*Vásconez and Kehrli*, 2010]. The report details numerous problem areas with the evacuation plan, including coordination and collaborative planning failures with neighboring jurisdictions and the absence of an annex that integrates

multiple modes of transportation. Another report from the FHWA, released in 2006, states, "the Portland region does not spend very much time or energy executing the plans through testing or training" [*Pretorious et al.,* 2006]. Both FHWA reports indicate that responsibility for the evacuation plans is distributed amongst several authorities, and Portland planners believe full-scale evacuations to be unlikely (which may account for the infrequent evacuation exercises).

As the response to Hurricane Katrina revealed, simply having emergency response plans is not enough—responders must be well-trained in using plans, with experience of how to work with other agencies to address large problems. The City Auditor interviewed Portland bureau emergency managers, who consistently expressed concern over the lack of training and exercises for city employees, a responsibility that is assigned to POEM in the City Code [*Griffin-Valade et al.,* 2010]. The Auditor found that nearly all the exercises POEM did participate in were in support capacities for other entities' exercises, and that the office had not initiated any city exercises based on identified risks to Portland [*Griffin-Valade et al.,* 2010]. Additionally, POEM failed to complete after-exercise evaluations, which are an essential part of the response planning cycle. Feedback from city employees trained to staff the emergency coordination center (ECC) indicated that just over 50% felt confident in other ECC responders' abilities to staff the ECC, and under 70% felt prepared to assume their own roles at the ECC [*Griffin-Valade et al.,* 2010].

Since the Auditor's report, POEM has participated in or conducted two emergency response exercises as part of a time series simulation of an earthquake on the East Bank Fault, with a related exercise planned for September 2011. The Office is also planning a Cascadia Subduction Zone earthquake tabletop for November 2011 [P. Hopkins, Portland Office of Emergency Management, personal communication, May 2011]. The message from the Auditor

seems to have been received on this issue, but lack of published after-exercise summaries and improvement plans make it impossible to assess recent changes.

The City Auditor attributes the want of completed plans, exercises and follow-up to a lack of leadership and long-term strategic planning in POEM. It is possible that with more direction, POEM could improve its efficiency to meet the planning needs of Portland residents. In addition to revisiting POEM's mission and goals, there are concrete action items that could significantly improve Portland's response preparedness.

[5] POEM needs to reassess the volcanic hazards facing Portland. Working with the Oregon Department of Geology and Mineral Industries can close the gaps between state and city response plans while ensuring that POEM's assessments reflect true geologic hazards. This information should be included in the BEOP as an hazard specific annex for volcanoes.

[6] POEM needs to develop a specific, up-to-date earthquake response plan. Improvements to the 2003 earthquake plan should include specific mitigation strategies, vulnerability assessments of critical infrastructure, likely failure areas and response priority regions based on probable hazards and vulnerable neighborhoods.

[7] The evacuation plan for Portland is not well defined or understood, and studies of evacuation measures have identified critical gaps in planning. POEM should circulate a draft of the evacuation plan to all city bureaus for comments and additional information. This is especially important, since the report of the City Auditor indicates insufficient knowledge of the plan amongst city agencies. Once a finalized plan is approved by the City Council, POEM and the Portland Department of Transportation should organize multi-agency evacuation exercises.

[8] In keeping with the previous recommendation for evacuation plans, POEM should reevaluate the goals of exercise and training programs to prioritize training for different hazards.

In addition to developing an exercise schedule and priority list, POEM needs to engage bureau emergency managers for feedback on what training city employees need most and how to best deliver that training. After-training follow-up with bureaus and suggested improvements to plans should become a formalized component of POEM's exercise program.

PREPARING FOR RECOVERY

The final component of emergence management is recovery operations. Though recovery plans, like response plans, need to be flexible to fit any possible event at any possible scale, cities can prioritize recovery operations in order to prevent additional loss of life, property and jobs. As stated in the POEM BEOP, "the first phase [of recovery] overlaps with emergency response… to stabilize the situation, reduce life-safety hazards and make short-term repairs" [2011]. POEM further defines the second step of recovery as returning families and essential infrastructure back to functional conditions, and the third step as rebuilding damaged infrastructure and resuming normal community life. The City of New Orleans learned from first-hand experience that not having a recovery plan only compounds damages from natural disasters. After waiting 19 months for federal recovery aid, the city and state governments released a recovery plan primarily funded by bonds with hope for private investment [*McCulley*, 2007]. Within that time period, less than half of the city's original 500,000 residents had returned, and much of the city remained abandoned. Census data for 2010 show that the state has still not fully recovered, resulting in the loss of a congressional seat in the House of Representatives [*Mildenberg*, 2011].

As of this publication, POEM has not established a recovery plan, nor is there record of the city of Portland ever having such a plan. Multnomah County is currently reviewing their recovery plan, which was completed by a contractor in December 2010 [S. Sharp, Multnomah

County Emergency Management, personal communication, May 2011]. Oregon Emergency Management included a recovery plan in their comprehensive plan structure (Figure 24), but the plan is not complete as of this writing. Portland is currently without any organized recovery plans, exposing the city to greater losses if a natural disaster occurs. Thus the only recommendation for recovery operations is to develop a plan.

[9] POEM needs to identify the short-term and long-term recovery priorities for Portland and create a plan to aid response and recovery personnel. At minimum, a recovery plan should designate responsibilities to the various bureaus, identify the use and location of critical recovery resources (such as river dredges) and institutionalize after-action assessments for mitigation, response and recovery actions. Appendices should include hazard-specific prioritizations and considerations.

SUMMARY OF RECOMMENDATIONS

The City of Portland is at risk from seismic and volcanic hazards; environmental, infrastructure and social vulnerability; and inadequate emergency preparedness. Though the city cannot prevent natural hazards from occurring, effective mitigation, response and recovery operations can reduce the damages from natural disasters. The following recommendations are the first steps POEM should take to reduce the risks to Portland residents:

[1] Retrofit URM and high-rise buildings, highways and bridges;

[2] Conduct assessments of critical water, sewage, gas and electricity facilities and conduct necessary retrofits;

[3] Rezone areas with pre-existing environmental vulnerability;

[4] Implement a comprehensive public education campaign;

[5] Work with DOGAMI to assess volcanic hazards in Portland and prepare an hazard specific annex;

[6] Revise and publish a new earthquake plan;

[7] Finalize and exercise a city emergency evacuation plan;

[8] Prioritize training programs and integrate feedback from bureaus;

[9] And develop a recovery plan with short- and long-term recovery priorities.

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This appendix contains additional figures from Chapter 3, specifically the neighborhood boundaries map for Portland and graphs from the section on vulnerable populations, as well as additional figures from Chapter 5, including maps of race, income and poverty by neighborhood.
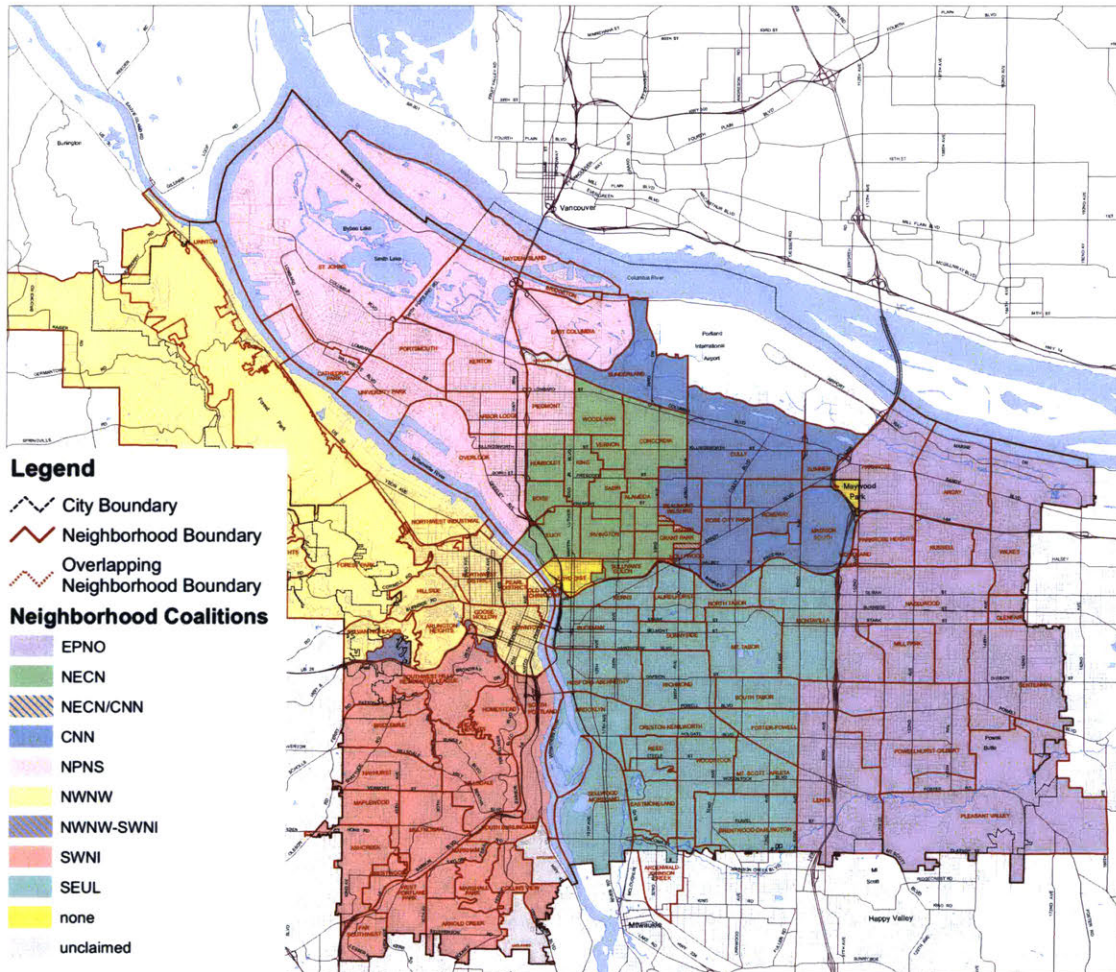
Neighborhood Associations and Coalitions of Portland. This map is produced by the Portland Bureau of Planning and Sustainability [2010]. Downtown Portland, the central business and government areas, and the tourist areas are along the Willamette River at and just north of the boundary between NWNW and SWNI. EPNO: East Portland Neighborhood Office. NECN: Northeast Coalition of Neighborhoods. CNN: Central Northeast Neighbors, Inc. NPNS: North Portland Neighborhood Services. NWNW: Neighbors West/Northwest.

All data for the following tables and figures was taken from surveys by the U.S. Census Bureau. See the References section for details.

Employment Status of Oregon Residents in Poverty, 2009

- Employed
- Unemployed
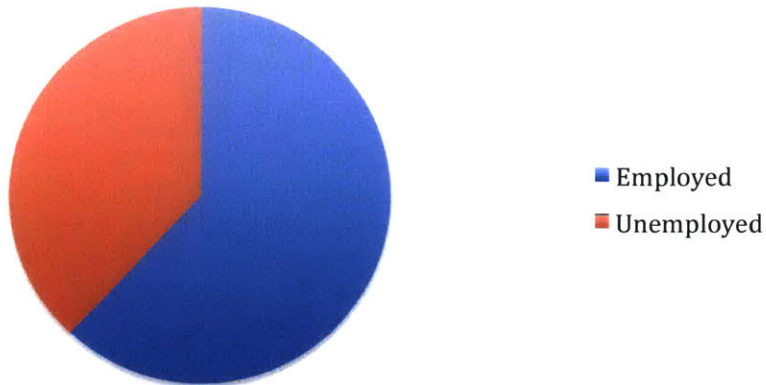
Employment Status of Oregon Residents not in Poverty, 2009

- Employed
- Unemployed
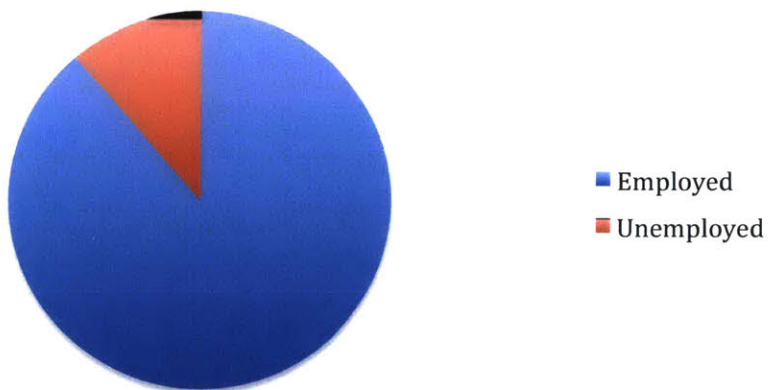
Health Insurance by Poverty Status, Oregon 2009
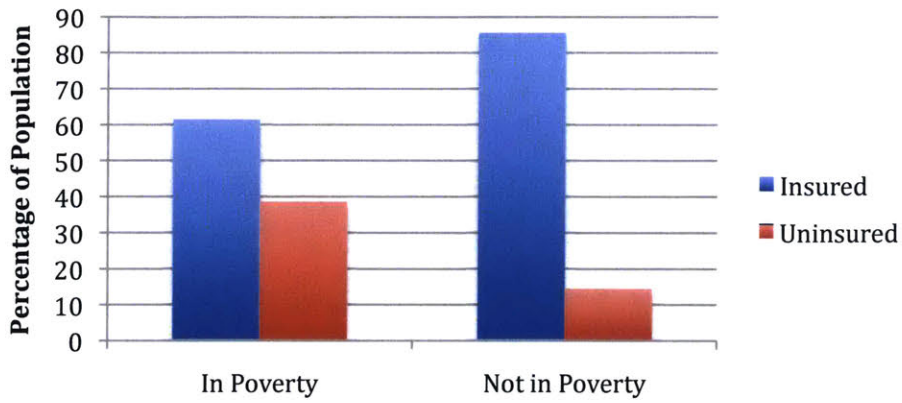
Education of White Population in Portland

- Less than high school diploma
- High school graduate, GED, or alternative
- Some college or associate's degree
- Bachelor's degree or higher
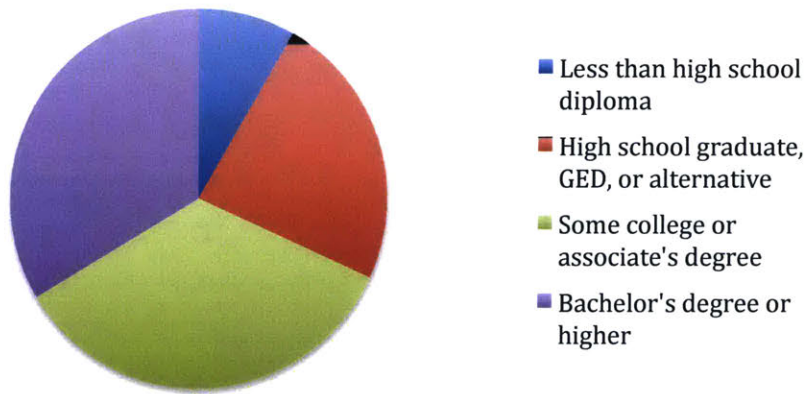
Education of Black Population in Portland

- Less than high school diploma
- High school graduate, GED, or alternative
- Some college or associate's degree
- Bachelor's degree or higher
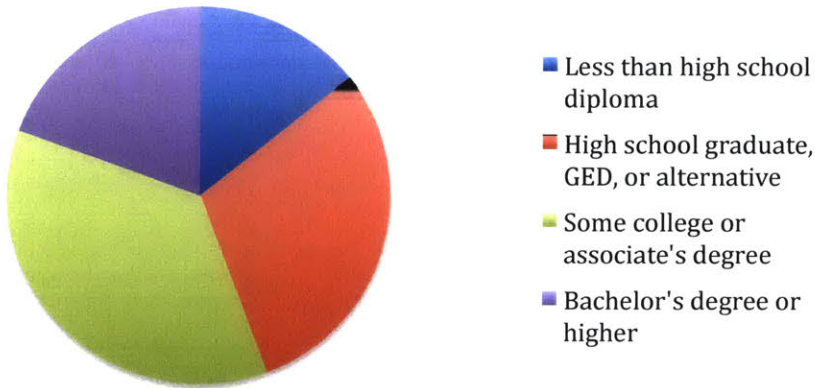
Housing Tenure by Income in Portland
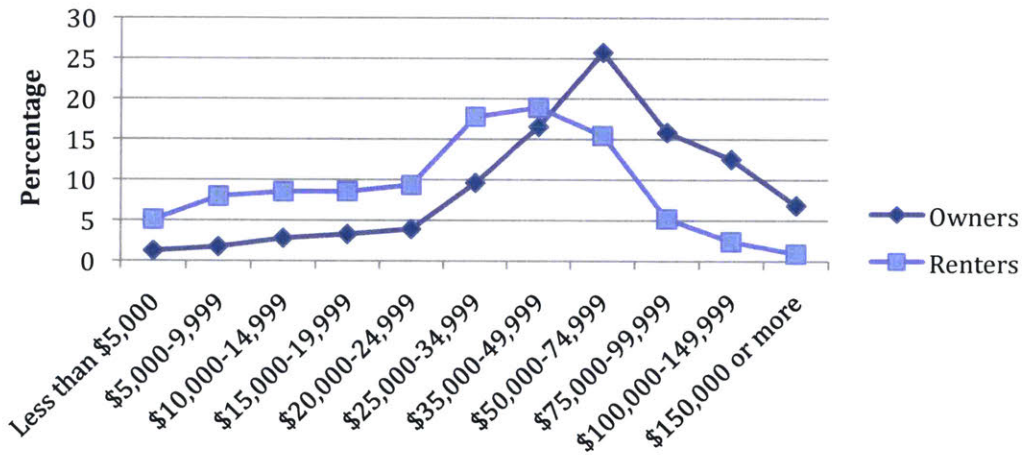
Unemployment Rates by Race in Portland, 2005-2009
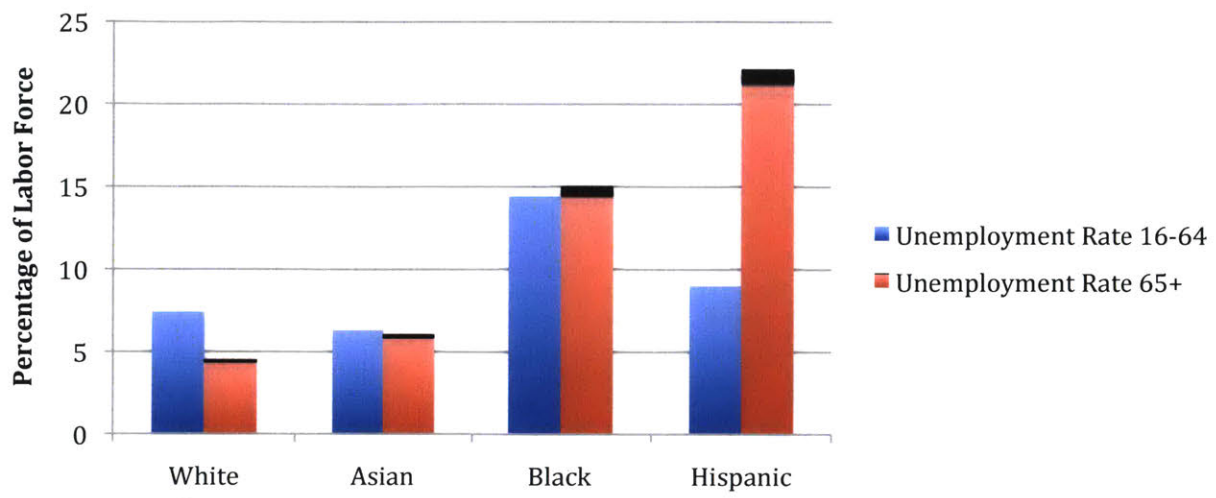
The following neighborhood maps were developed by the City of Portland for the *Portland Plan* [2010] project. The online link to these maps is listed in the References section.

Portland Neighborhoods by Race (2009)
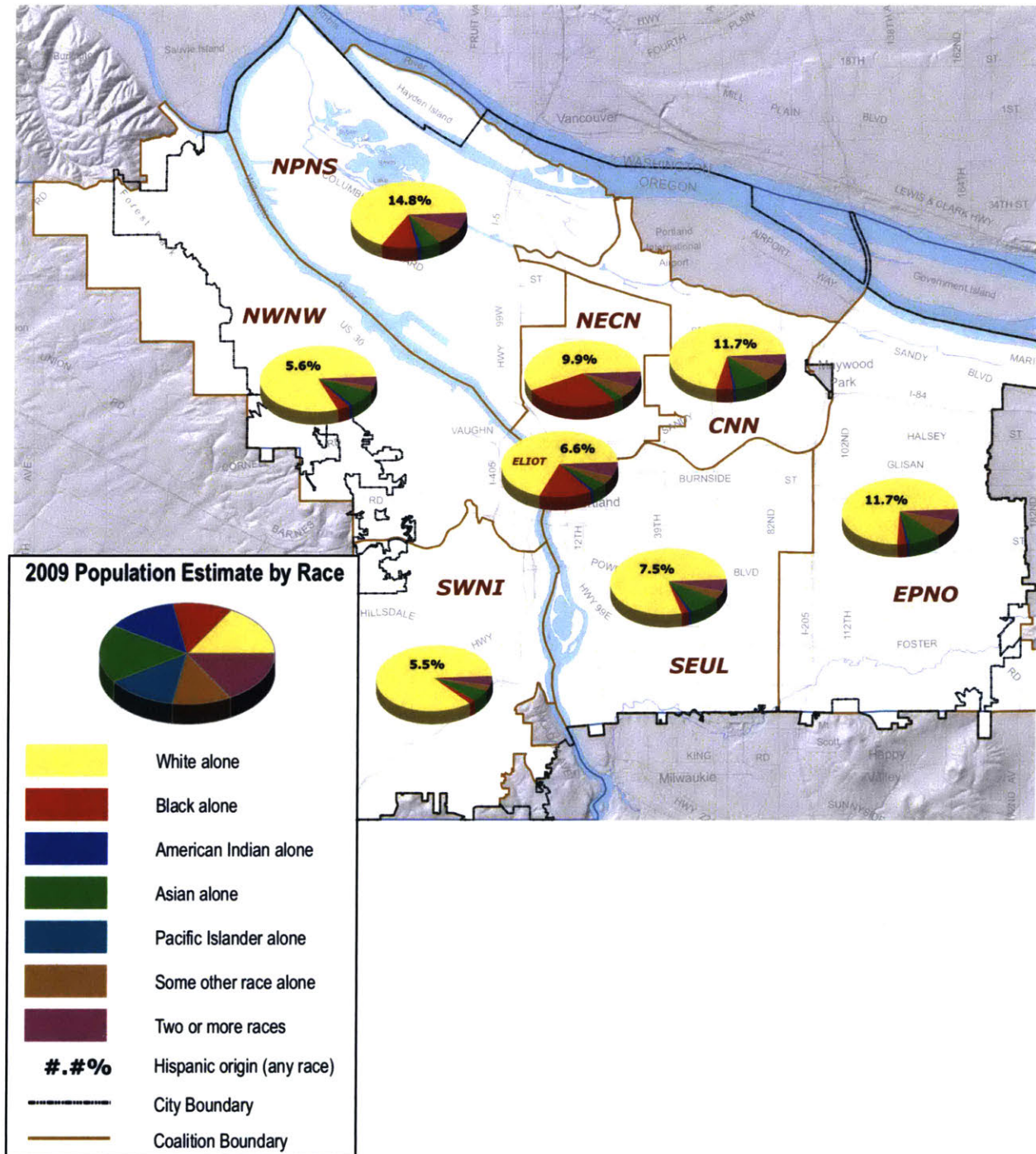
Persons Below Poverty in Portland Neighborhoods (2000)
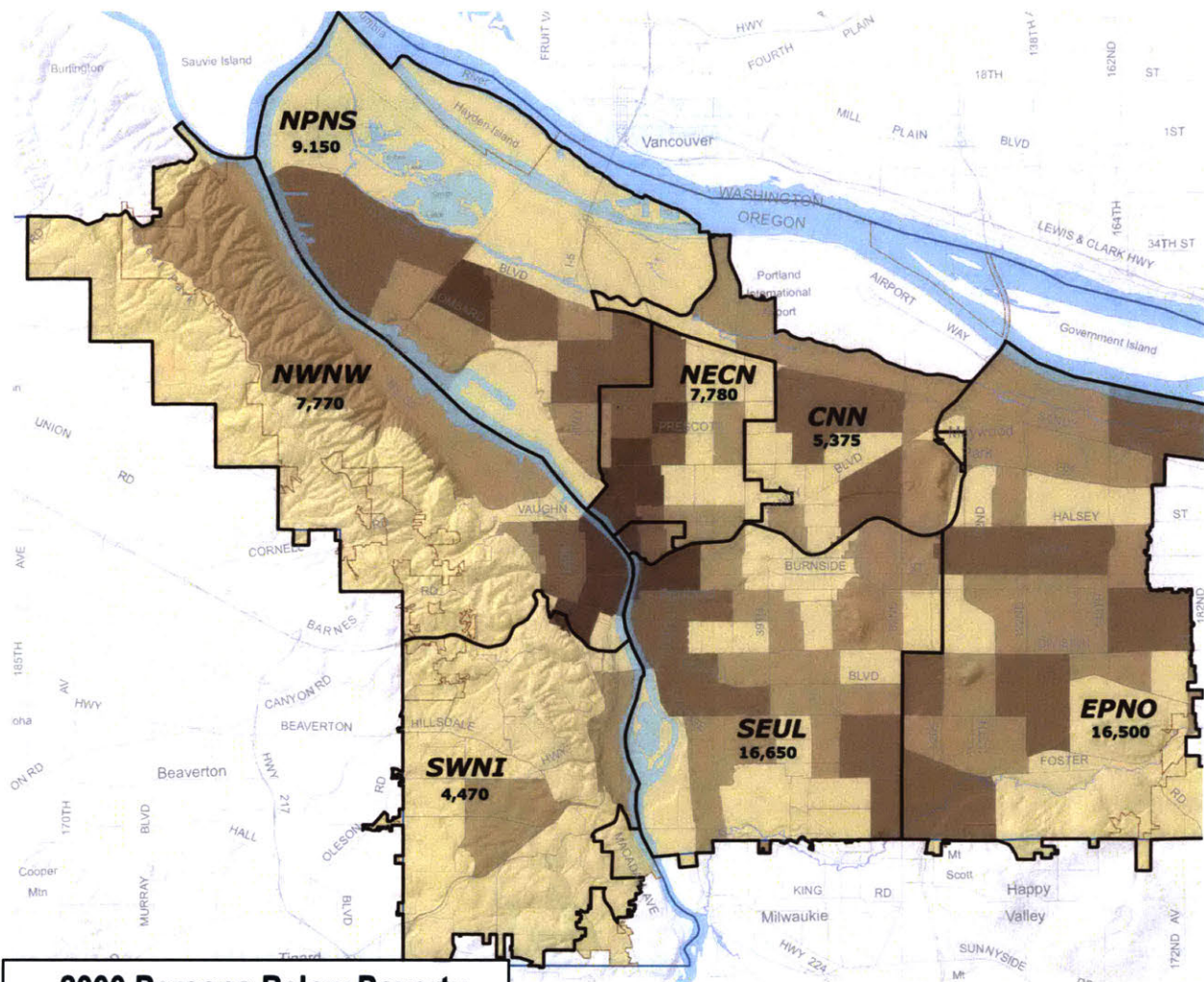
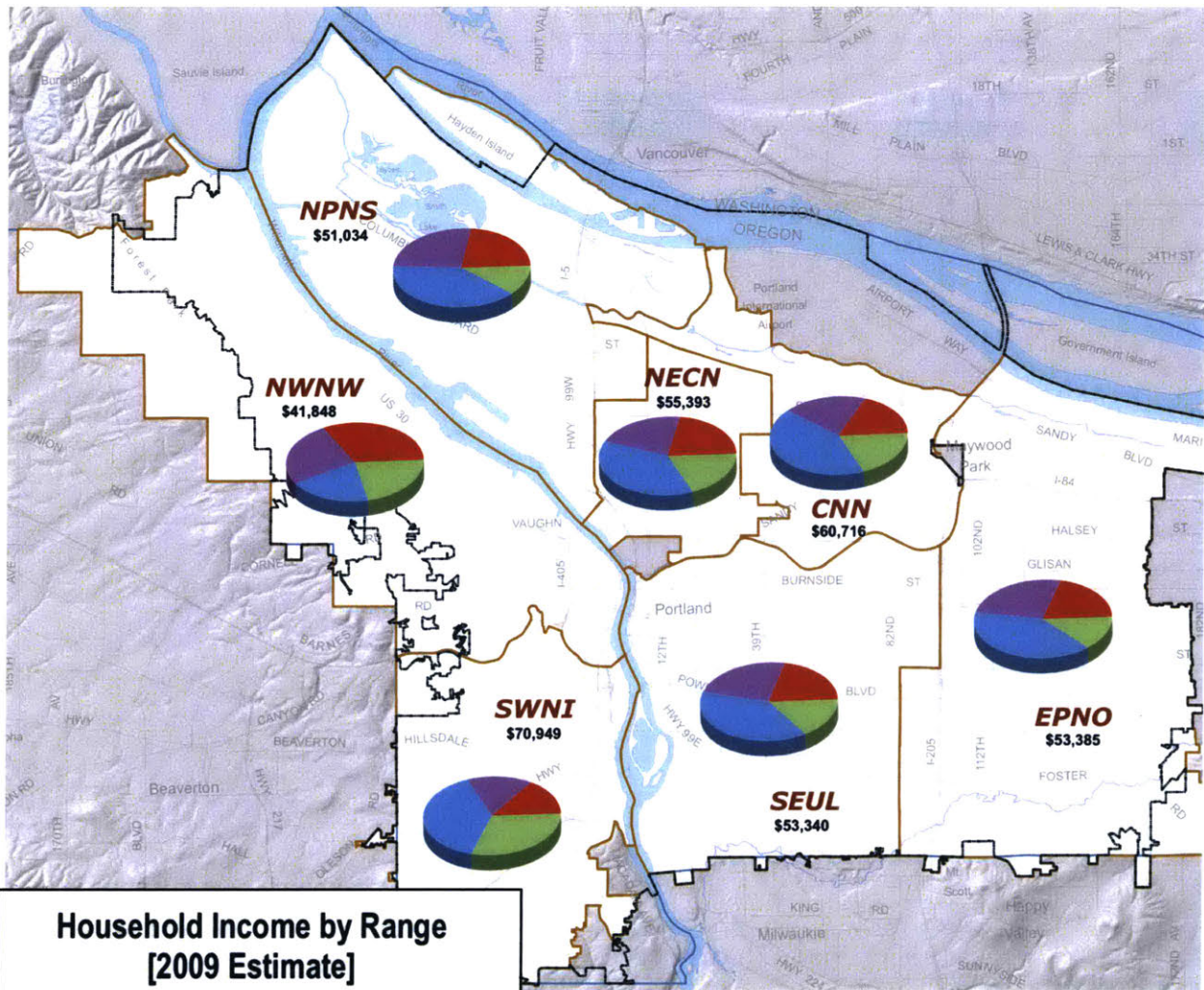**2000 Persons Below Poverty by Census Tract**

% persons below poverty

- 0% - 10%
- 11% - 15%
- 16% - 26%
- 27% - 62%
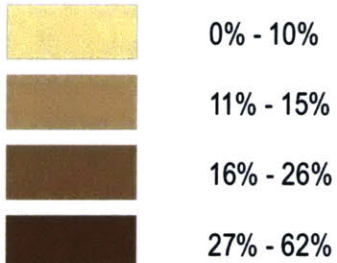
#,### Actural number persons below poverty

City Boundary

Coalition Boundary

Portland Neighborhoods by Income Range (2009)

NPNS
$51,034

NWNW
$41,848

NECN
$55,393

CNN
$60,716

EPNO
$53,385

SWNI
$70,949

SEUL
$53,340

Household Income by Range [2009 Estimate]

🟥	less than $25,000
🟪	$25,000 - $49,999
🟦	$50,000 - $99,000
🟩	$100,000 and greater
$00,000	Median Income for Coalition
▬▬▬	City Boundary
——	Coalition Boundary

This appendix contains figures from Chapter 6, including large U.S. Geologic Survey hazard zonation maps for Mount Adams, Mount St. Helens and Mount Hood. The map for Mount Adams was developed by *Scott et al.* [1995]; the map for Mount St. Helens was developed by *Wolfe and Pierson* [1995]; and the map for Mount Hood was developed by *Scott et al.* [2007].
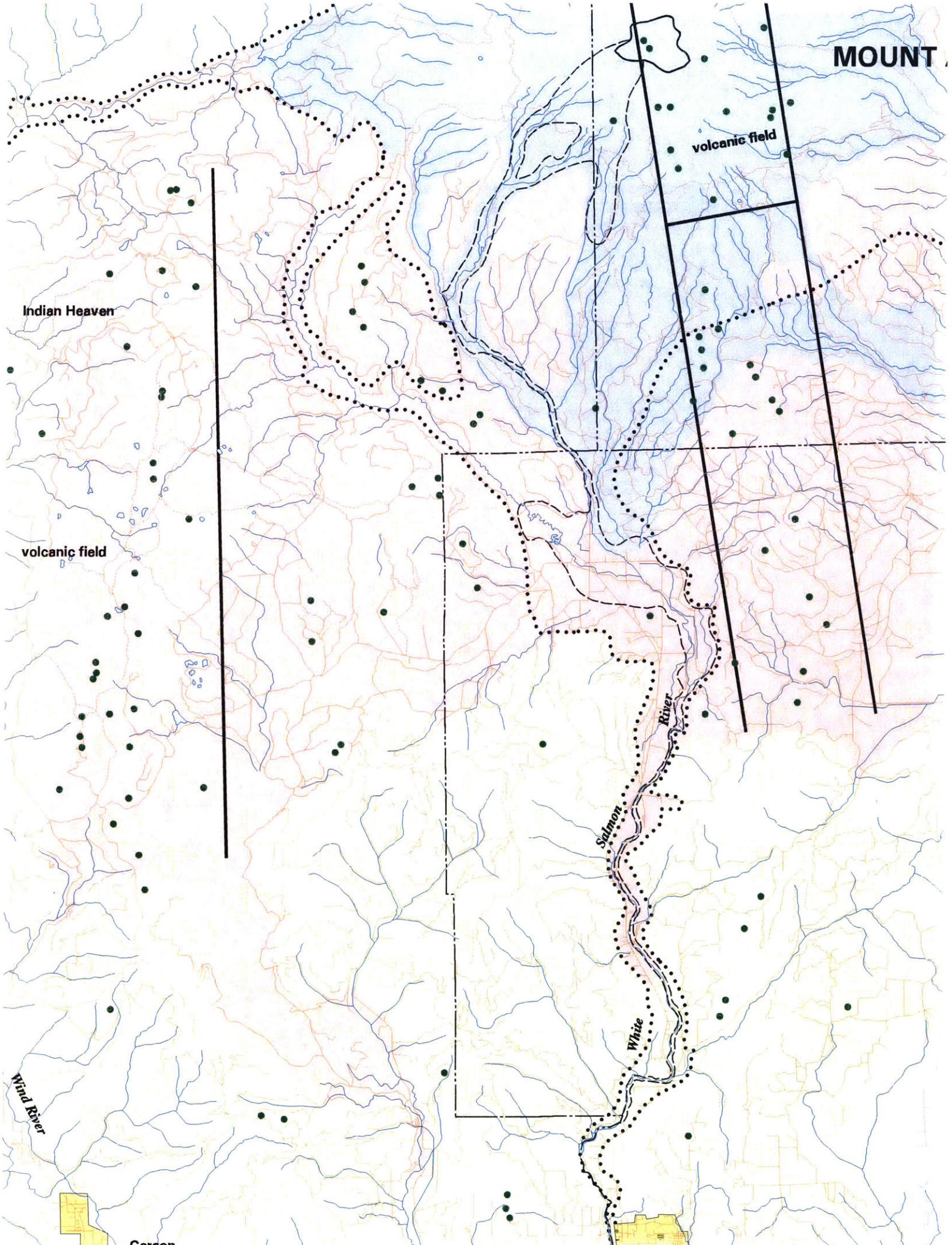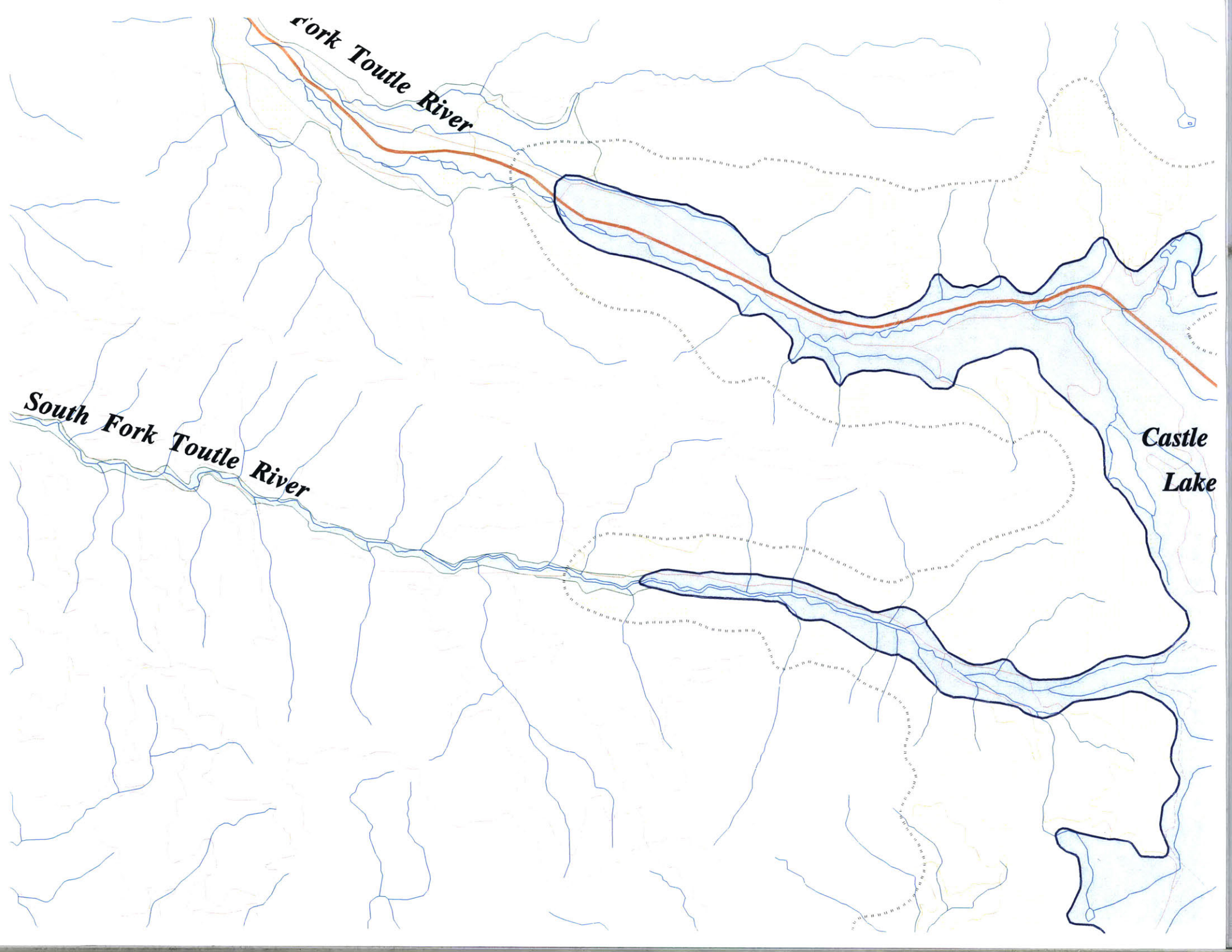
Indian Heaven

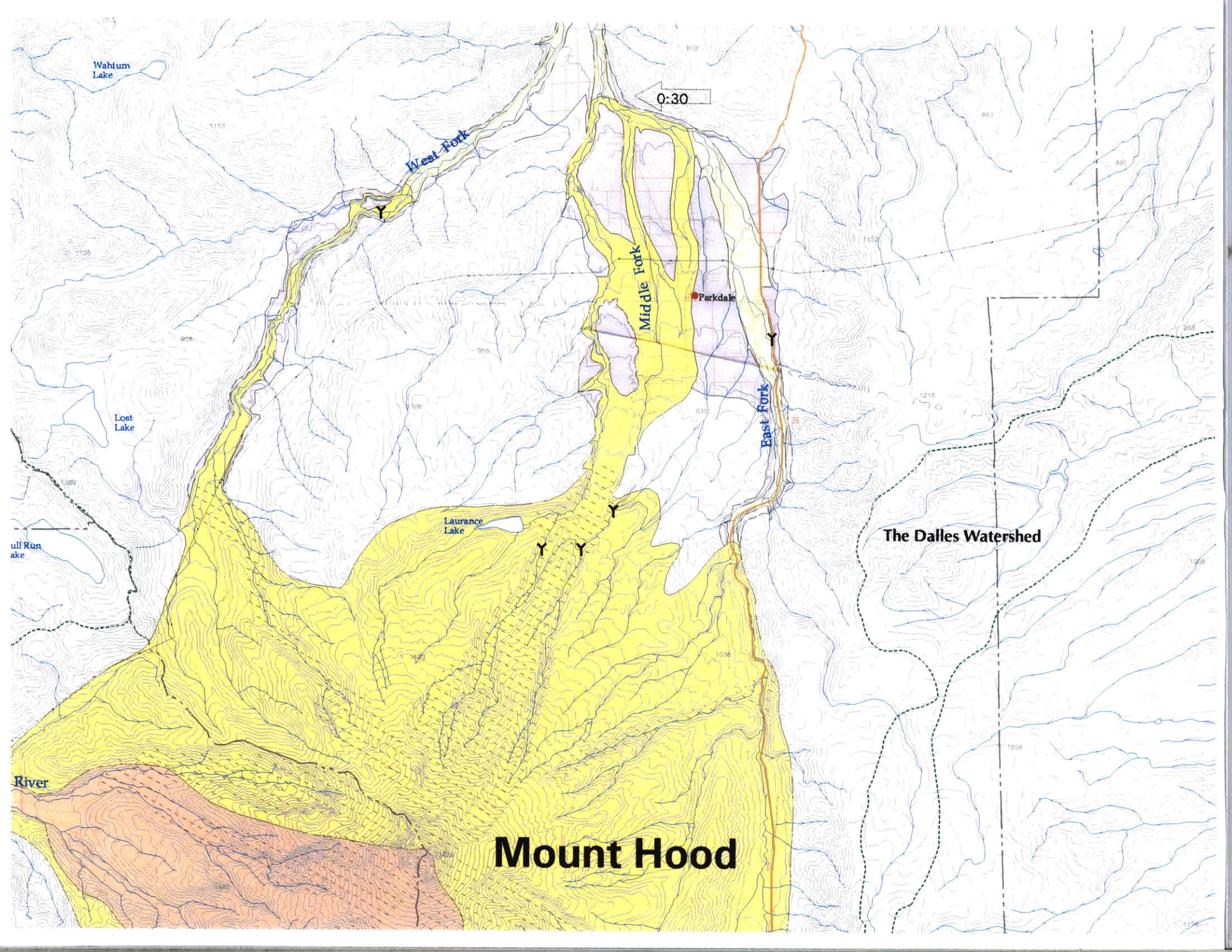volcanic field

volcanic field

MOUNT

Salmon

River

White

Wind River

Carson