SOURCE PARAMETER STUDIES OF HISTORICAL (1939 – 1965) INTRASLAB EARTHQUAKES OF THE CASCADIA SUBDUCTION ZONE IN WASHINGTON

KATY R. WIEST, B.S.

Department of Geological Sciences

APPROVED:

____
Diane I. Doser, Ph.D., Chair

____
Aaron A. Velasco, Ph. D.

____
Benjamin Flores, Ph. D.

____
Charles H. Ambler, Ph. D.
Dean of the Graduate School

For my Dad and Mom

SOURCE PARAMETER STUDIES OF HISTORICAL (1939 – 1965) INTRASLAB EARTHQUAKES OF THE CASCADIA SUBDUCTION ZONE IN WASHINGTON

by

KATY R. WIEST, B.S.

THESIS

Presented to the Faculty of the Graduate School of

THE UNIVERSITY OF TEXAS AT EL PASO

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Geological Sciences

THE UNIVERSITY OF TEXAS AT EL PASO

May 2005

UMI Number: 1430957

UMI

UMI Microform 1430957

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

ACKNOWLEDGEMENTS

For all of their support I would like to thank my parents, Robert and Margaret Wiest, as well as my fiancé, Kevin Lohr. I would like to thank Dr. Diane Doser, Dr. Aaron Velasco, and Dr. José Hurtado for all of their advising and support throughout the completion of my Master's thesis. Thank you to Dr. Lewis Brown, my undergraduate advisor, for giving me the confidence to attend graduate school and helping me get there. Thank you to all of my friends in the geology department at UTEP, but especially Victor Avila (Yogui), Vicki Gee, Olubunmi Elebiju, Todd Theiner, Hector Casillas, and Leandro Treviño. You have enriched my life in so many ways and I couldn't have made it with out you! This thesis was submitted to my supervising committee on May 6, 2005.

ABSTRACT

At the Cascadia Subduction Zone in Washington and Oregon, the Juan de Fuca plate subducts beneath the North American plate at a rate of about 4 cm/year. Earthquake hazards in the region are associated with plate interface, intraslab, and crustal earthquakes. All have the potential to cause significant physical and monetary damage, and, as population and infrastructure continue to grow, the possibility of more extensive damage from seismicity in the region also grows. This study examines and models regional and teleseismic seismograms for historic, intraslab events of M > 5.5 occurring within the Pacific Northwest region to better determine their source locations, source mechanisms, and rupture histories. It focuses on the seismograms of four intraslab earthquakes that occurred in western Washington between 1939 and 1965. Digital seismograms of recent (post-1990) intraslab events with well-determined focal depths and mechanisms, and that were recorded in the same locations as the historic events, were used to aid in the interpretation of the historical seismograms. Some of the recent events were used as empirical Green's functions to more accurately determine the rupture processes of the historic earthquakes. My results revise the original depths and relative magnitudes previously published for the historical events. I also find evidence for directivity associated with the 1949 Olympia event that may be the cause of increased intensity observed to the south. Finally, I observe similarities between two event pairs: (1) the 1939 South Puget Sound and 1965 Sea-Tac events; and (2) the 1949 Olympia and 2001 Nisqually events. These similarities have implications for hazards in the Seattle-Olympia region because they may indicate characteristic earthquakes periodically rupturing along the same faults.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The Cascadia Subduction Zone (CSZ) in Washington and Oregon is a highly complex, geologically diverse, and potentially hazardous region due to the collision of the Juan de Fuca and Explorer plates with the North American plate (Figure 1). The CSZ extends across the western margin of North America, from Cape Mendocino in the south to the northern edge of Vancouver Island. The CSZ has Chilean type characteristics, wherein the subducting lithosphere is young (<50 Ma), thin, and buoyant (Kirby and Wang, 2002). This creates a tectonically complex environment with accretion of allocthonous terranes building thick accretionary prisms in the forearc region and active compression in the backarc region.

Seismic hazards associated with the Cascadia Subduction Zone include: crustal, interface, and intraslab earthquakes (Figures 2 and 3). Crustal earthquakes occur above the plate interface. They have the capability to cause substantial damage due to their shallow depths and the extensive shaking of sedimentary basins they cause. Interface earthquakes occur along the boundary between the subducting and overriding plates and have potential to be very large (M~9). The last known interface event to occur in the CSZ was in 1700 (Atwater and Hemphill-Haley, 1997). Intraslab events occur within the downgoing slab. They contribute the most to hazards in the CSZ region due to their high rate of occurrence and their characteristically strong ground motions (Cassidy and Waldhauser, 2003). Examples of instraslab events occurring within the Juan de Fuca plate include the M_w = 6.5 Olympia (1949), Sea-Tac (1965) and Nisqually (2001) earthquakes (Figures 2 and 3). As society and infrastructure continue to expand, so does the possibility of more extensive damage from each of these seismic processes.

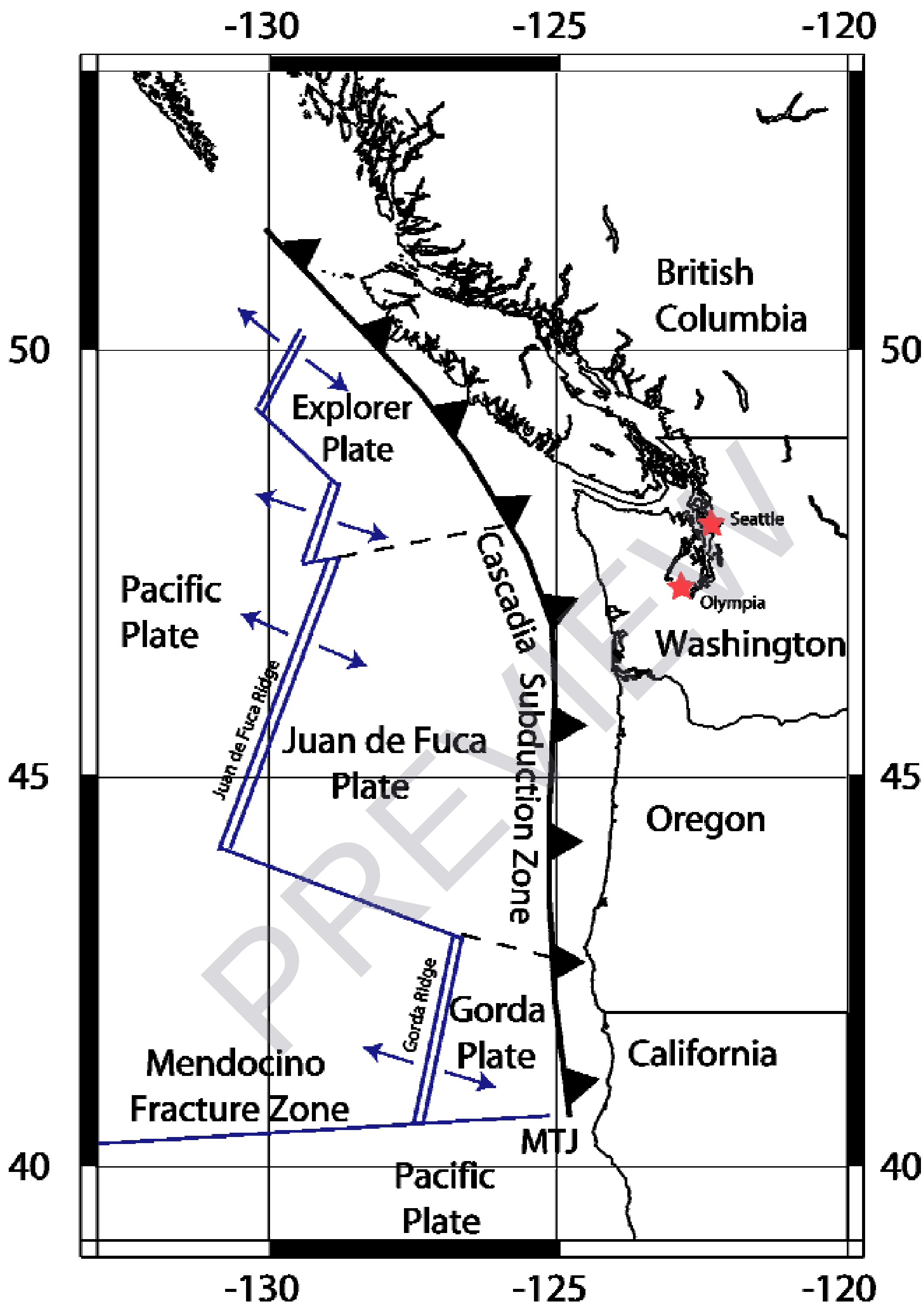

Figure 1: Location map showing the Cascadia Subduction Zone and related plates. MTJ = Mendocino Triple Junction.

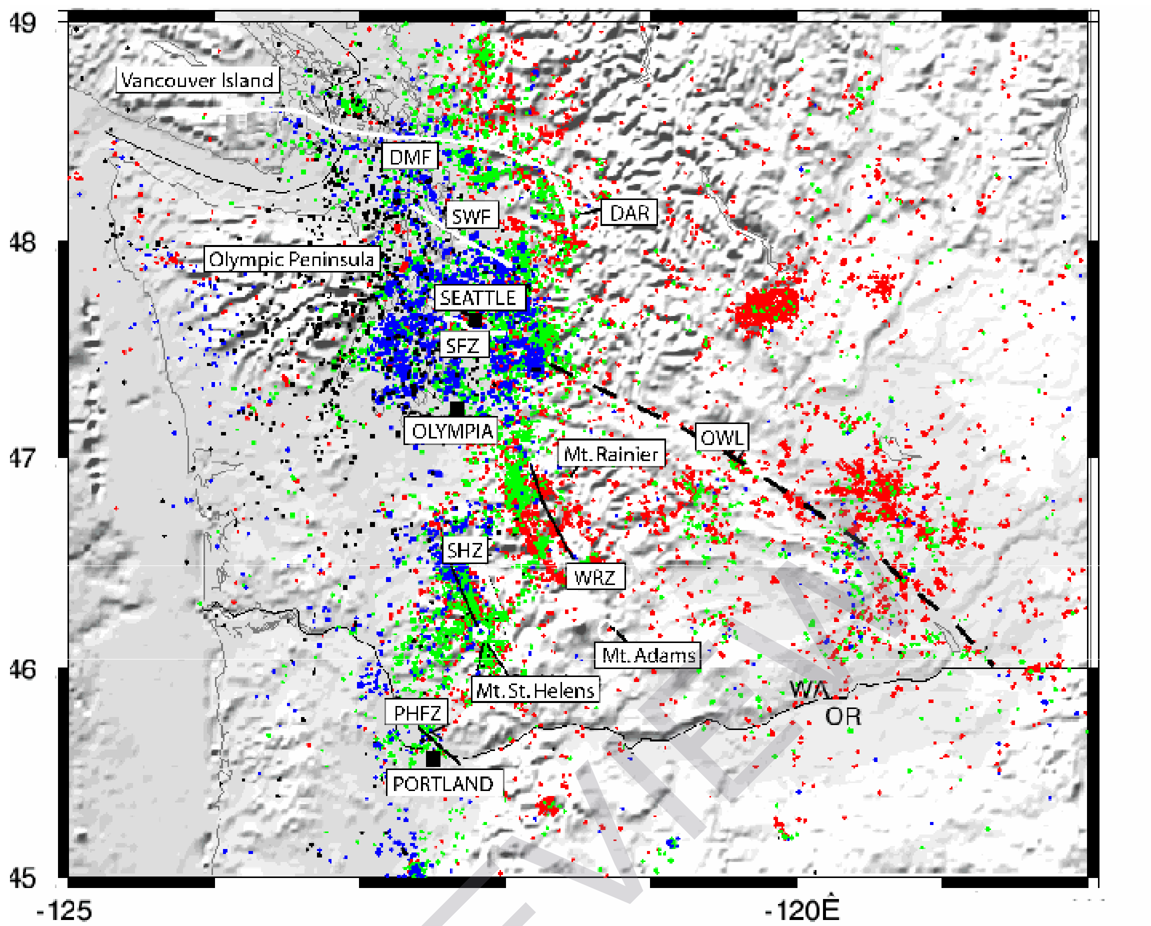

Figure 2: Earthquakes detected by the Pacific Northwest Seismic Network (PNSN) from 1970 to 1995. The colors represent depth ranges for the earthquakes: red = 0-10 km; green = 10-20 km; blue = 20-30 km; black = 30-60 km. PHFZ=Portland Hills fault zone, SHZ=St. Helens zone, WRZ=western Rainier zone, SFZ=Seattle fault zone, SWF=South Whidbey Island fault, LRT=Leech River thrust, DMF=Devils Mt. fault zone, DAR=Darrington fault zone, OWL=Olympic-Wallowa lineament. From Stanley et al. (1999).

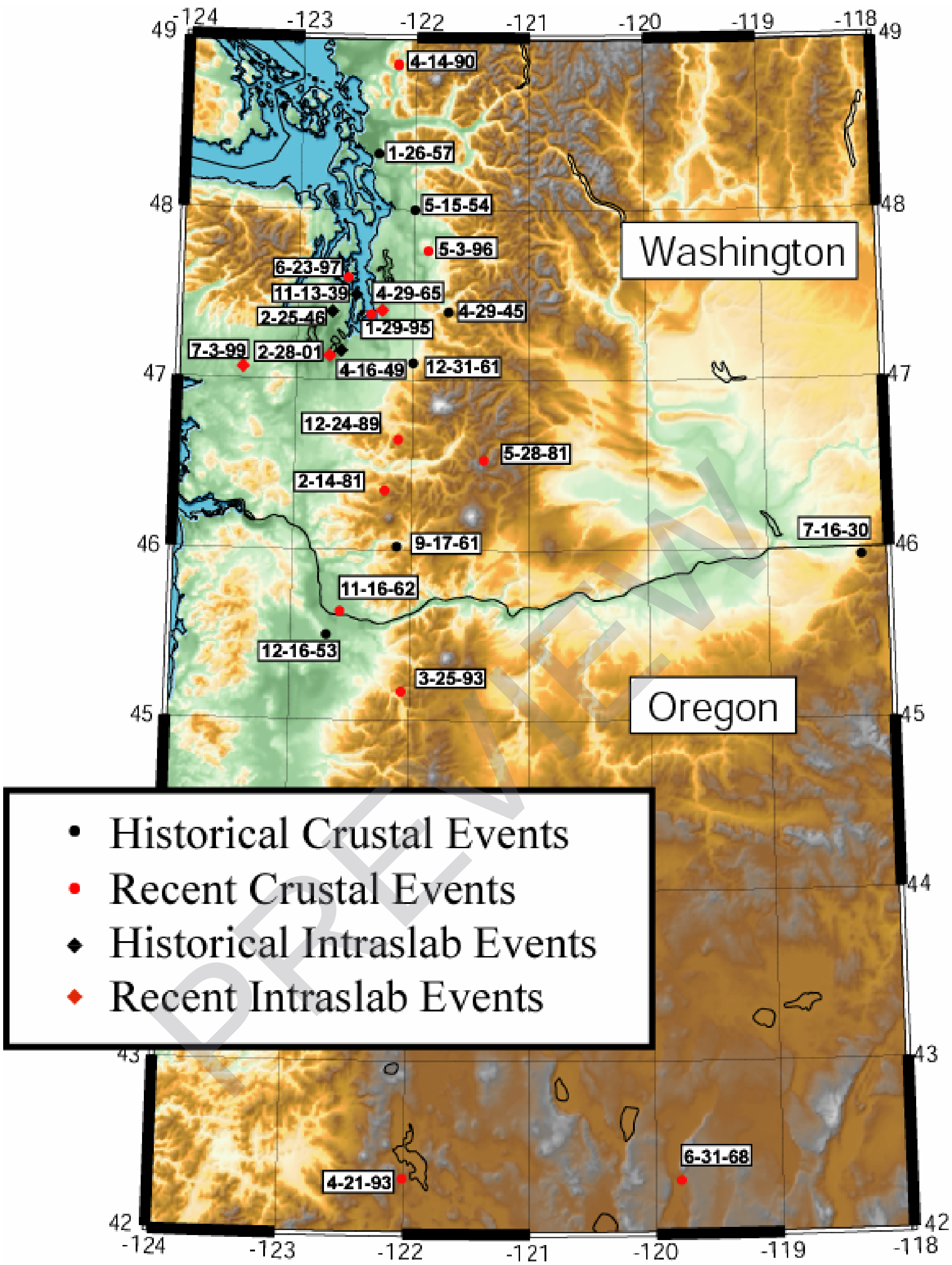

Figure 3: Locations of intraslab and crustal earthquakes with M>5.5 occurring in the Washington and Oregon region over the last century.

Within the last century, the largest and most damaging earthquakes in this region have been intraslab events. In order to better characterize this important style of seismicity, I have evaluated regional and teleseismic seismograms for historic (1939-1965) intraslab events of M > 5.5 occurring within the Pacific Northwest region of Washington and Oregon (Figures 2 and 3). This research will provide important earthquake source characteristics – including source locations, source mechanisms and rupture histories – needed to refine ground-shaking models for the Cascadia region. A better understanding of the depth range and rupture extent of these events will aid other researchers in determining the physical processes (e.g. dehydration, phase changes) that control slab rupture. The results may also yield important insight into why there is such a strong concentration of large intraslab events on the southern side of the arch in the subducting slab (Crosson and Owens, 1987; Weaver and Baker, 1988). This, in turn, affects hazards assessment for the Seattle-Olympic region.

2. TECTONIC SETTING

The Cascadia Subduction Zone (CSZ) is the dominant tectonic feature in the Pacific Northwest region. It is approximately 1200 km long and comprises the Gorda, Juan de Fuca, and Explorer plates, all of which are subducting beneath the North American Plate (Figure 1). The rate of subduction varies from ~3.2 cm/year near Cape Mendocino to ~4.2 cm/year near the Strait of Juan de Fuca (Wilson, 1993; Riddihough, 1984).

Although the CSZ displays many typical Chilean-type characteristics, it has several unique features. For instance, the subducting Juan de Fuca slab is very young,

approximately 10 Ma in age (Kirby and Wang, 2002), and the Juan de Fuca ridge is actively producing new oceanic crust very close to (< 500 km) from the convergent margin (DeMets et al., 1990). The typical effects of subducting such young, active oceanic lithosphere include: buoyancy beneath the overriding continental plate, smaller slab diving angles, large amounts of seismic activity, and strong coupling between the oceanic and continental plates. The CSZ is believed to exhibit all of the above as a result of subducting the Juan de Fuca plate. However, it has not experienced as many historical, great, plate interface earthquakes as other, similar subduction zones (Kirby and Wang, 2002). Despite this, the geologic record has shown that great subduction zone earthquakes have affected the Washington-Oregon coast in the past (Adams, 1990; Nelson et al., 1996; Meyers et al., 1996), and interpretation of geological evidence, including tsunami deposits and records of subsidence, suggests that great earthquakes (M>8) within the CSZ have a recurrence interval of hundreds of years (Meyers et al., 1996). Turbidite sequences cored off the Washington-Oregon margin record as many as 13 events that may have resulted from great earthquakes in the CSZ between 7500 and 300 years ago (Adams, 1990; Nelson, et al.; 1996). Meyers et al. (1996) identified eight buried shorelines near Willapa Bay, Washington that are thought to have resulted from instantaneous submersion during great subduction zone earthquakes between 5800 and 300 years ago. The most recent plate interface earthquake in the CSZ occurred 300 years ago (Atwater and Hemphill-Haley, 1997) and was determined to have occurred in January 1700 based on tsunami records in Japan (Satake et al., 1996).

There are two main theories that explain the lack of great thrust earthquakes along the plate interface in the CSZ region. The first hypothesizes that there is a large locked

portion of the subduction zone, approximately 60 km in width (Dragert et al., 2001). Under this premise, the subduction zone is capable of a M=9 earthquake if the whole locked zone fails in a single event. The other theory is that aseismic slip occurs along the plate interface (Thatcher, 2001). Some studies (e.g. Dragert et al., 2001) suggest that both hypotheses may be correct, and that the CSZ is locked along the upper margin of the subduction zone, while aseismic slip occurs in the lower portion of the subduction zone. Geodetic surveys have shown that the Washington coastal region is actively rising relative to sea level and accumulating strain (Savage et al., 1981). The uplift is partially due to buoyancy of the subducting Juan de Fuca plate, however, Kelsey et al. (1994) showed that some of the uplift appears to be caused by interseismic strain accumulation. This is an indication that there is a locked portion of the subduction zone offshore. If this is the case, and if the aseismic activity is adding stresses to the locked section, this process may be an important potential triggering mechanism for the next great earthquake.

Within the subducting Juan de Fuca plate, there are two seismically active areas where large intraslab events concentrate at 40 – 60 km depth. One area is located beneath southern Puget Sound, and the other is located beneath the southern Georgia Strait, near edges of a bend in the subducted slab (Cassidy and Ellis, 1993) (Figure 4). It has been noted, however, that there has been a lack of large intraslab earthquakes beneath much of Oregon. Instead, strike-slip and normal focal mechanisms are common in this area, with extension generally oriented in the down-dip direction of the slab (Ma et al., 1996).

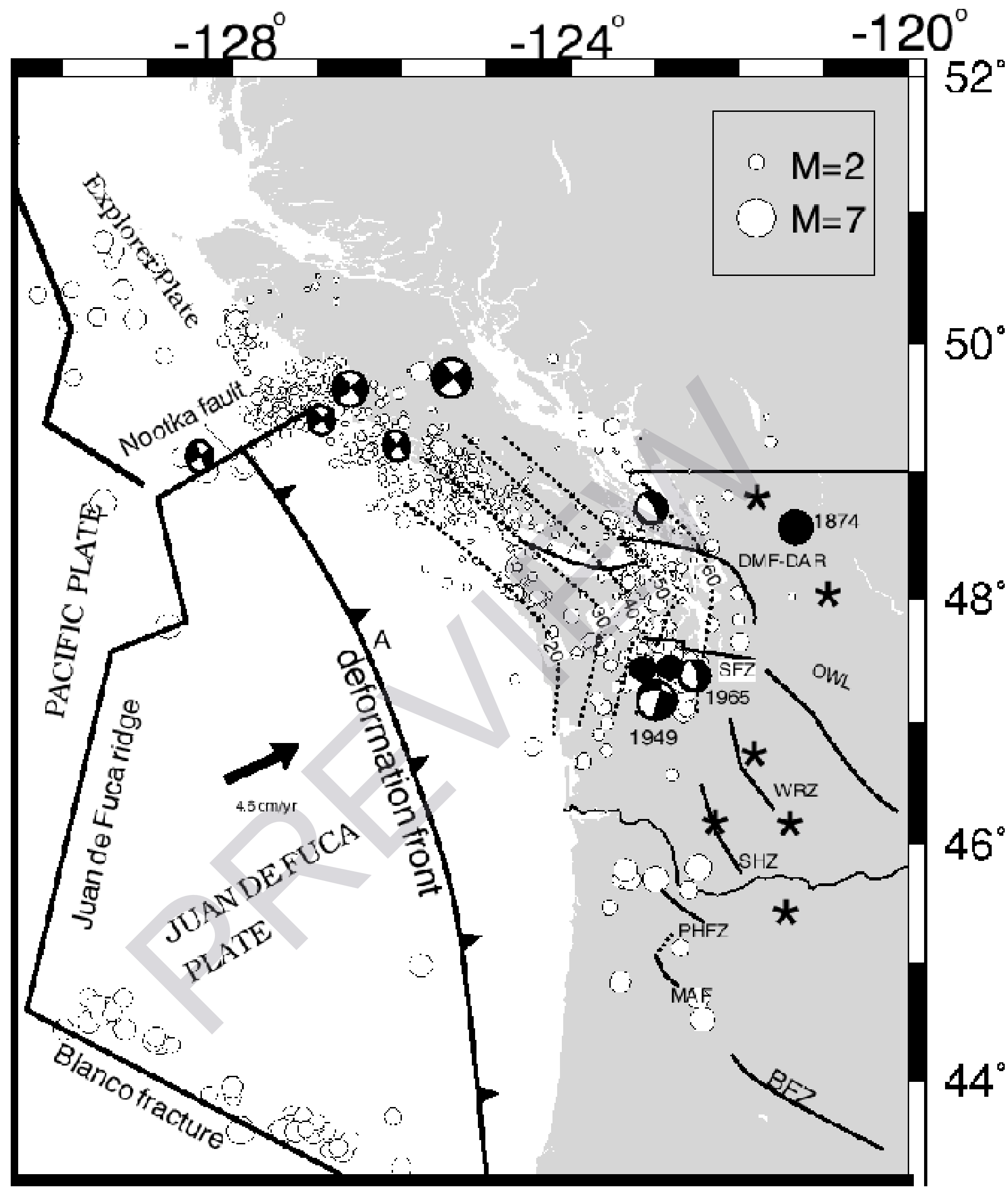

Figure 4: Focal mechanisms and locations of earthquakes with M > 4.0 and depths greater than 30 km. Dotted structure contours show the location of a bend in the subducting slab. From Stanley et al. (1999).

Kirby and Wang (2002) have recognized that earthquakes deeper than 40 km are unlikely to occur from normal brittle fracture and frictional sliding. Many researches (e.g. Kirby and Wang, 2002; Preston et al., 2003) suggest that metamorphic dehydration reactions may be triggering these deep intraslab events. The faults created at mid-ocean ridges and fracture zones may be reactivated in down-going slabs by dehydration embrittlement. The dehydration reactions involved in this process also serve to densify the subducting oceanic crust. The volume changes associated with densifying the crust could also play an important part in internal slab stresses, particularly if the crust does not detach from the more stable mantle. Variations in these stresses, along with possible changes in slab composition and/or upper plate composition, may play a role in the lack of intraslab events occurring beneath Oregon (Peacock and Wang, 1999).

A recent seismic study was conducted by Parsons et al. (1998) to determine which major structures within the CSZ contribute to seismogenic deformation. They collected and interpreted a 530-km long, wide-angle, onshore-offshore seismic transect across the subduction zone and volcanic arc (Figure 5). Several characteristics of the subducting slab became evident as a result this study. First, there is an increase in the angle of subduction, from ~5° to 12°, as the Juan de Fuca plate encounters the 20-km thick Siletz terrane. Also noted by Parsons et al. (1998) was a transition from Siletz crust to Cascade Arc crust that corresponds to the Mount St. Helens seismic zone. This is consistent with earlier hypotheses that the Siletz crust focuses seismic deformation at its edges (e.g. Wells, 1990; England and Wells, 1991, Trehu et al., 1994; Stanley et al., 1996). Finally, Parsons et al. (1998) found a crustal root beneath the Cascade Range that extends to depths between 35 and 45 km.

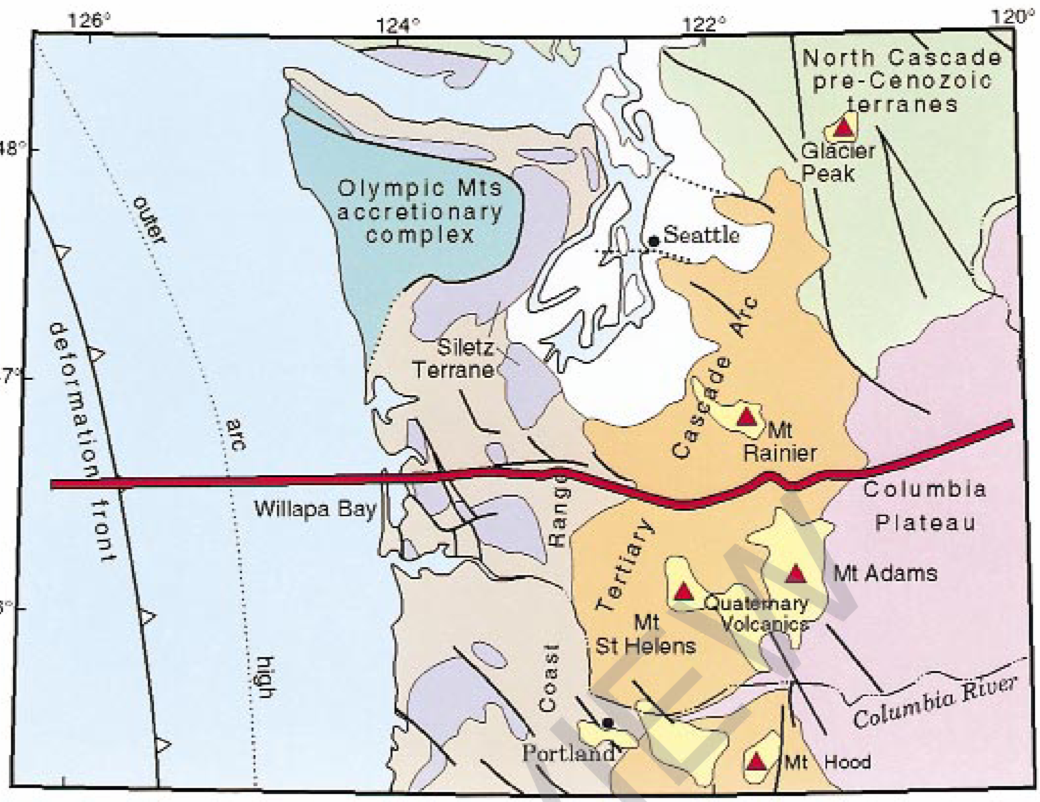

Figure 5: Map showing various accreted terranes of the Cascadia Subduction Zone. From Parsons et al. (1998).

3. PREVIOUS STUDIES

Several earlier studies (Baker and Langston, 1987; Langston and Blum, 1977, Ichinose et al., 2003) have examined the source parameters and ground motion characteristics of historical intraslab earthquakes in the Washington and Oregon region of the Cascadia Subduction Zone (Figure 6). The South Puget Sound earthquake of 1939 (M~5.8), for example, is the earliest documented intraslab event to occur in the region. The Puget Sound earthquake of 1946 (reported M~5.8) has also been reported in some

catalogs as an intraslab event. However, Stover and Coffman (1993) proposed that the 1946 event was actually a crustal event (~18 km depth) of smaller magnitude (~5.3).

The Olympia earthquake of 1949 is currently the largest event to have occurred in the region within the last 100 years. Baker and Langston (1987) investigated source parameters of the 1949 Olympia earthquake using long-period body waves and strong ground motions. They determined that the event occurred at ~54 km depth with a strike-slip focal mechanism and eastward rupture propagation. I re-examine this event, and, since Baker and Langston (1987) focused primarily on seismograms recorded in Europe, I use additional teleseismic seismograms from stations located south and west of the earthquake. I also incorporate regional seismograms that I compare to records of a 2001 earthquake that occurred near Nisqually, Washington in order to understand the similarities and differences between the two events.

Langston and Blum (1977) investigated the 1965 South Seattle earthquake. They inverted World-Wide Standardized Seismic Network (WWSSN) seismograms recorded at teleseismic distances to determine the point source parameters. They found the South Seattle event to have occurred at approximately 63 km depth with a normal faulting mechanism. Langston and Blum (1977) also performed a simultaneous determination of the crustal and upper-mantle structure. I also re-investigate this event in light of the 2001 Nisqually earthquake in order to gain better insight to the rupture process and how it impacts the ground shaking in the region.

Ichinose et al. (2003) estimated ground motions expected from a repeat of the 1965 South Seattle intraslab earthquake. They created a slip model for the 1965 event that contained two small asperities with dimensions of 4 and 8 km^2. These were located

~2 km up-dip and ~4 km south of the hypocenter. Ichinose et al. (2003) estimated the maximum slip of the first asperity to be 2 meters, and the second to be 2.8 meters, leading to a new $M_w = 6.63$.

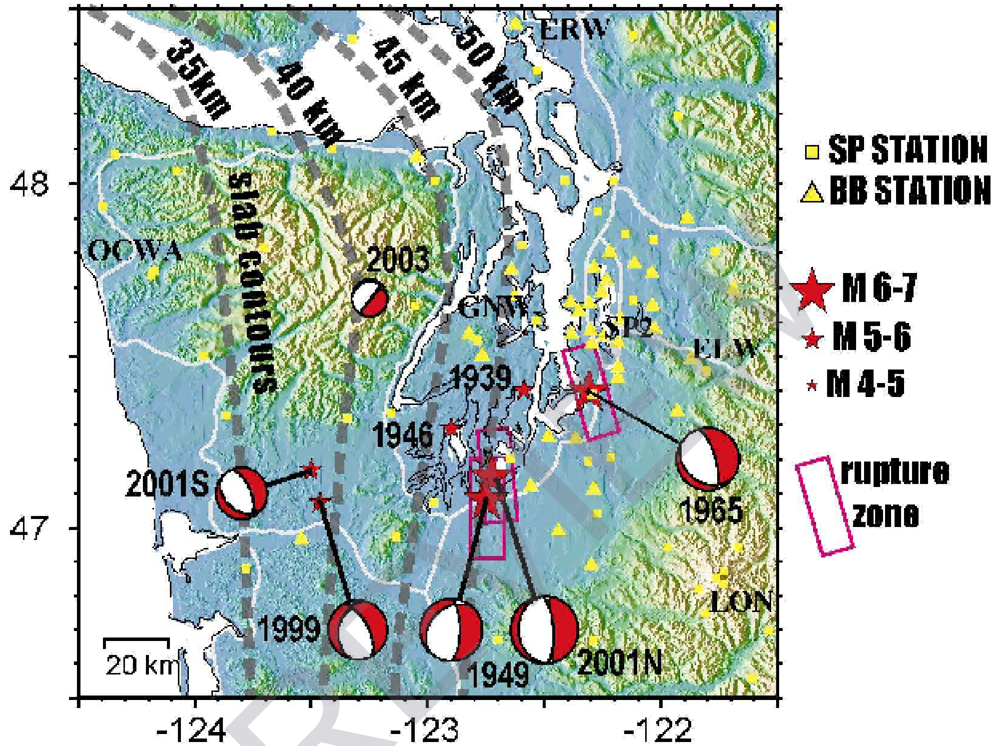

Figure 6: Focal mechanisms for CSZ slab events. Also shown are the rupture zones associated with the 1949, 1965, and 2001 events. Dashed structure contours show the top of the subducted Juan de Fuca plate. From Ichinose et al. (2003).