

Geophysical and geomorphological signatures of accretionary wedge faulting at the Cascadia
subduction zone

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Abstract

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Harold J. Tobin

Earth and Space Sciences

For thousands of years, people on Earth have been living with earthquakes and tsunamis – in both harmony and destruction. Millions of people living along the active western margin of the North American continent are at risk of potentially devastating earthquakes and tsunamis. As geoscientists, we must do more than simply increase our understanding of the hazards posed to society by active tectonic margins – we must also effectively communicate our scientific findings with the general public and work together with communities to adapt to coastal hazards and change. Here I present my dissertation research that applies a range of geophysical and geomorphological analysis methods to modern high-resolution geophysical datasets of the offshore Cascadia accretionary wedge to better understand earthquake and tsunami hazards at the Cascadia subduction zone. In Chapters 1-3, I find that accretionary wedge faults leave a distinct

geophysical and geomorphic signature within the subsurface and at the seafloor. My work provides new insights into the tectonic evolution of the Cascadia margin and the likelihood for future fault rupture behavior and tsunamigenesis. In Chapter 1, using modern seismic reflection and multibeam bathymetric datasets of varying resolutions, I find that there is no evidence for an active margin-spanning megasplay fault at the Cascadia subduction zone. Instead, I find that out-of-sequence accretionary wedge splay faulting is highly variable and segmented along strike, consistent with the segmentation of other physical and mechanical properties at the Cascadia subduction margin. Building from regional fault mapping completed in Chapter 1, in Chapter 2, I use ultra-high-resolution sub-bottom seismic and multibeam bathymetric data to map the Albatross fault system, a system of en echelon Holocene-active right-lateral strike-slip faults spanning 45 kilometers from 45-46°N offshore Oregon. Applying a Riedel shear model, I propose that oblique plate convergence at the central Cascadia subduction zone is accommodated through distributed shearing on multiple conjugate strike-slip faults within the accretionary wedge. In Chapter 3, I apply subaerial topographic analysis tools to submarine topography of the offshore Cascadia accretionary wedge. I find that the longitudinal profiles of submarine channels respond to active subsurface faulting characterized in Chapters 1 and 2. This finding enables me to improve upon and extend previous fault mapping based on the morphologic expression of faulting in submarine channels and at the seafloor. To conclude, in Chapter 4, I share my experience applying the Riverways Model to engage with the Quileute Tribal School and the Quileute Tribe of La Push, Washington through the Quileute Culture & geoScience Exchange Program. I explore how this work contributes to increasing coastal community resilience to earthquakes and tsunamis through building educational partnerships between scientific and Indigenous communities and creating place-based and culturally sustaining K-12 geoscience

curriculum. Overall, through my dissertation work, I find that we can become more resilient as a society when we break down barriers (e.g., cultural, geographical, institutional) between scientists and the broader community. It is my mission, through this dissertation and in my career ahead, to continue working towards this goal; recognizing that one person has the power to influence the actions of others towards protecting life along Earth's active tectonic margins.

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–Frank Herbert

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Preface

“Science does not exist in isolation. Science exists at the crossroads between nature and spirit.”

– *Lyanda Lynn Haupt*

My idea of what science is has transformed throughout the course of my PhD. Before starting graduate school, I held a more “westernized” idea of what science is. I thought to do good science, we must objectively create new knowledge through controlled observation, experimentation, and analysis, independent from spirituality, emotionality, and the overall human condition. From my experiences in graduate school, I learned that science is more than the objective pursuit of knowledge. Science is a human endeavor that is inherently subjective and flawed – just as we humans are. In working with the Quileute Tribal School and the UW Riverways program over the last four years, I learned about Indigenous science and how it can co-exist with Western science to create new knowledge rooted in place, relationship, and reciprocity – with outcomes that often far better serve real people and communities. Over the last six years, I’ve done things that have forced me way outside my comfort zone, and in being uncomfortable, I’ve grown more than I ever thought possible. My life path has taken me in a way I never could have imagined when I started my PhD, and I am coming away from this whole experience with relationships that will last a lifetime. I thought I would mostly learn new things about the Earth during my PhD, but instead I learned more about myself as a person and the kind of scientist I want to be. I will carry these lessons with me for the rest of my life.

Introduction

Subduction zone earthquakes and tsunamis are some of the world's most deadly and damaging natural hazards. Recent great earthquake and tsunami events at subduction zones, including the 2004 Sumatra and 2011 Japan events, have resulted in a catastrophic loss of human life and infrastructure (Athukorala & Resosudarmo, 2005; Kajitani et al., 2013; Nakahara & Ichikawa, 2013; Telford & Cosgrave, 2006). Historically, subduction zone earthquakes have exhibited significant variability in rupture characteristics including magnitude, fault slip, and tsunamigenesis (Satake & Atwater, 2007; Wirth et al., 2022).

The last great Cascadia megathrust earthquake (~M9) and tsunami occurred in the year 1700 (Atwater et al., 2005; Satake et al., 2003). This event is well-documented by Native American oral histories (e.g., Ludwin et al., 2005), Japanese historical records (e.g., Atwater et al., 2005; Ludwin et al., 2007), ghost forests (e.g., Atwater, 1992; Dziak et al., 2021), and tsunami deposits (e.g., Garrison-Laney & Miller, 2017). With an average estimated recurrence rate of ~200-500 years (Goldfinger et al., 2003, 2012), another great earthquake is likely to occur at the Cascadia subduction zone in the near future.

The next Cascadia subduction zone megathrust earthquake and tsunami poses a significant hazard to people living in the Pacific Northwest region of North America as well as along the Pacific Rim (Gomberg et al., 2017). Slip on splay faults during Cascadia megathrust earthquakes, where slip branches from the megathrust fault up onto faults within the accretionary wedge, has the potential to significantly increase vertical seafloor displacement and tsunami size, posing an enhanced tsunami hazard to coastal communities in the Pacific Northwest (Gao et al., 2018; Geist & Yoshioka, 1996; Lotto et al., 2019; Priest et al., 2009; Sypus, 2019; Witter et al.,

2013). However, little is known about which faults in the Cascadia accretionary wedge are currently active and most likely to slip in the next megathrust earthquake (K. Wang & Tréhu, 2016). Further investigation of the interplay between accretionary wedge evolution and fault behavior is required to understand potential variability in megathrust earthquakes and tsunamis at the Cascadia subduction zone and how this variability influences earthquake and tsunami hazard (Watt & Brothers, 2020).

In this dissertation I explore the interplay between accretionary wedge structure, faulting, and submarine channel morphology through analysis of complementary geophysical datasets using different approaches and methodologies from structural geology, tectonic geomorphology, and marine geophysics. In doing so, my work increases our overall understanding of faulting at the Cascadia accretionary wedge, and helps to inform at-risk communities in the Pacific Northwest region about potential sources of hazards related to the patterns and characteristics of fault rupture during the next Cascadia subduction zone earthquake through collaboration with the Cascadia CoPes Hub (e.g., Ruggiero et al., 2023) and the U.S. Geological Survey. My dissertation research primarily uses modern high-resolution geophysical datasets to answer my research questions, including ultra-long-offset multi-channel seismic reflection data from the Cascadia Seismic Imaging Experiment 2021 (CASIE21) survey, near-surface sparker and sub-bottom seismic reflection data (SBP29), and high-resolution multibeam bathymetry compilations (15- to 30-meter grid resolution). I then share how I led a team of UW students to transform my scientific research outcomes into culturally sustaining and place-based K-12 geoscience curricula using the Riverways Model for building educational partnerships. I conclude by sharing lessons learned from my experience leading the Quileute Culture and geoScience Exchange program. My dissertation chapters and associated research questions include:

Chapter 1: No evidence for margin-spanning megasplay fault at the Cascadia Subduction Zone

- What does modern ultra-long-offset multi-channel seismic reflection data reveal about structure and fault activity within the Cascadia accretionary wedge?
- Do these geophysical datasets provide evidence for an active margin-spanning megasplay fault at the Cascadia Subduction Zone as previously suggested?

Chapter 2: Distributed shearing in accretionary wedge accommodates oblique convergence at the Cascadia Subduction Zone

- What new information does ultra-high-resolution seismic and bathymetry data reveal about accretionary wedge fault activity and structure?
- How is shearing due to oblique plate convergence at the Cascadia subduction zone accommodated within the Cascadia accretionary wedge?

Chapter 3: Geomorphologic signature of active faulting in Cascadia's submarine channels

- Can we apply subaerial topographic analysis tools to submarine channel topography?
- Is geomorphic analysis of submarine channel morphology consistent with independent subsurface geophysical observations of accretionary wedge structure and fault activity?
- What new insights does submarine channel morphology provide about accretionary wedge structure and fault activity?

Chapter 4: The Riverways Model: Culture and science exchange with the Quileute Tribal School

- What are good ways to build educational partnerships with rural and tribal communities?
- How do we create culturally sustaining and place-based K-12 geoscience curricula in partnership with communities?

1. **Chapter 1:** No evidence for margin-spanning megasplay fault at the Cascadia Subduction Zone

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Abstract

It has been previously proposed that a megasplay fault within the Cascadia accretionary wedge, spanning from offshore Vancouver Island to Oregon, has the potential to slip during a future Cascadia subduction zone earthquake. This hypothetical fault has major implications for tsunami size and arrival times and is included in disaster-planning scenarios currently in use in the region. This hypothesis is evaluated in this study using CASIE21 deep-penetrating and U.S. Geological Survey high-resolution seismic reflection profiles. We map changes in wedge structural style and seismic character to identify the inner-outer wedge transition zone where a megasplay fault has been previously hypothesized to exist and evaluate evidence for active faulting within this zone. Our results indicate that there is not an active, through-going megasplay fault in Cascadia, but instead, the structure and activity of faulting at the inner-outer wedge transition zone is highly variable and segmented along strike, consistent with the segmentation of other physical and mechanical properties in Cascadia. Wedge sedimentation, plate dip, and subducting topography are proposed to play a major role in controlling megasplay fault development and evolution. Incorporating updated megasplay fault location, geometry, and activity into modeling of Cascadia earthquakes and tsunamis could help better constrain associated hazards.

1.1 Introduction

Slip on splay faults during Cascadia megathrust earthquakes has the potential to significantly increase vertical seafloor displacement and tsunami size, posing an enhanced tsunami hazard to coastal communities in the Pacific Northwest (Gao et al., 2018; Geist & Yoshioka, 1996; Lotto et al., 2019; Priest et al., 2009; Sypus, 2019; Witter et al., 2013). However, little is known about which splay faults in the Cascadia accretionary wedge are currently active and have the potential to slip in the next megathrust earthquake (e.g., Wang and Tréhu, 2016). Stress barriers in the accretionary wedge created by major contrasts in wedge lithology and strength can promote splay fault rupture (Byrne et al., 1993; Wendt et al., 2009). Splay fault rupture at stress barriers has been observed in recent large megathrust earthquakes, including the 1964 Alaska Mw 9.2 (Haeussler et al., 2015; Liberty et al., 2013; Plafker, 1969), 1944 Tonankai Mw 8.2 (G. F. Moore et al., 2007; Park et al., 2002), and 2004 Sumatra Mw 9.2 (Sibuet et al., 2007), and is considered to have significantly contributed to tsunami generation (Baba & Cummins, 2005; Cummins & Kaneda, 2000; Plafker, 1965).

It has been previously hypothesized that there is an active megasplay fault system in Cascadia spanning the margin from Vancouver Island to Oregon that is coincident with a major stress barrier in the accretionary wedge where there is a change in wedge lithology and strength (e.g., Witter et al., 2013; Watt and Brothers, 2020) (**Fig. 1**). A megasplay fault, as defined by previous work, is a persistent, large, out-of-sequence thrust fault or fault system within the accretionary wedge of a subduction zone that merges with the main megathrust fault at depth while also branching up to the seafloor (e.g., Tobin and Kinoshita, 2006; Moore et al., 2007). Analysis of early seismic imaging of the Cascadia subduction zone identified out-of-sequence, megasplay-style faults in the accretionary wedge branching from the megathrust fault up to the

seafloor, cutting across the multiple sedimentary units that make up the Cascadia accretionary wedge and focused at a major lithologic boundary in the wedge (Snively, 1987; Goldfinger, 1994; Goldfinger *et al.*, 1997). The age of offshore accretionary wedge complexes was previously inferred from bedrock outcrops on the western Olympic Peninsula and industry boreholes on the continental shelf (McNeill *et al.*, 1997; Palmer & Lingley, 1989). Watt and Brothers (2020) furthered analysis of offshore wedge lithology and faulting by inferring the boundary between the older, stronger Miocene wedge and younger, weaker Pleistocene accretionary wedge (i.e., dynamic backstop; **Fig. 1**) based on morphologic breaks in wedge surface slope interpreted from seafloor bathymetry. They found that the dynamic backstop exists along the hypothesized megasplay fault from Witter *et al.* (2013). However, they specify that this fault at the dynamic backstop requires further evaluation with modern multibeam bathymetry and high-resolution seismic reflection imaging at different scales to resolve how deep fault structure connects to near-surface fault deformation, indicating megasplay fault activity within the late Pleistocene to Holocene periods.

Studies modeling megathrust earthquakes and tsunamis at the Cascadia subduction zone often include a scenario with margin-wide rupture on this hypothetical megasplay fault (**Fig. 1**) (Gao *et al.*, 2018; Lotto *et al.*, 2019; Priest *et al.*, 2009; Sypus, 2019; Witter *et al.*, 2013). In these studies, scenarios including megasplay fault rupture exhibit significantly higher tsunami wave heights and run-ups and shorter tsunami arrival times compared to scenarios modeling only megathrust fault rupture. The hypothesized megasplay fault is generalized as a continuous along-strike, seaward-verging thrust fault structure dipping landward at about 30° and merging with the megathrust at depths less than ~20 km (Gao *et al.*, 2018; Priest *et al.*, 2009; Witter *et al.*, 2013). Although this megasplay fault geometry is the most commonly used, other geometries and

locations for this fault have been tested (Aslam et al., 2021; Gao et al., 2018). Due to relatively poor data quality and limited spatial coverage of legacy geophysical experiments, many of these studies emphasize that the geometry, location, and activity of the hypothesized fault is not conclusive and further structural analysis of this fault is needed to determine its existence and likelihood of rupture in future earthquakes. Despite this, the megasplay fault scenario as described has been consistently included in modern hazard assessments due to the potential for this fault to significantly contribute to tsunamigenesis in a future Cascadia earthquake (K. Wang & Tréhu, 2016), as demonstrated at other subduction zones.

In this study, we use 2D seismic reflection data from the CAscadia Seismic Imaging Experiment 2021 (CASIE21) (Carbotte et al., 2021) to evaluate the hypothesis for a megasplay fault at Cascadia. Using CASIE21 seismic profiles, we characterize the nature of the transition between the inner and outer domains of the Cascadia accretionary wedge. Our analysis focuses on differences in structural style and seismic character between the inner and outer wedge domains, defining the spatial extent of the “inner-outer wedge transition zone” (IOWTZ) in Cascadia. Then, we evaluate evidence for the presence of a megasplay fault structure at the IOWTZ. Evidence for an active, margin-spanning megasplay fault system is investigated by linking observations of fault structure, activity, and continuity along strike at or near the IOWTZ.

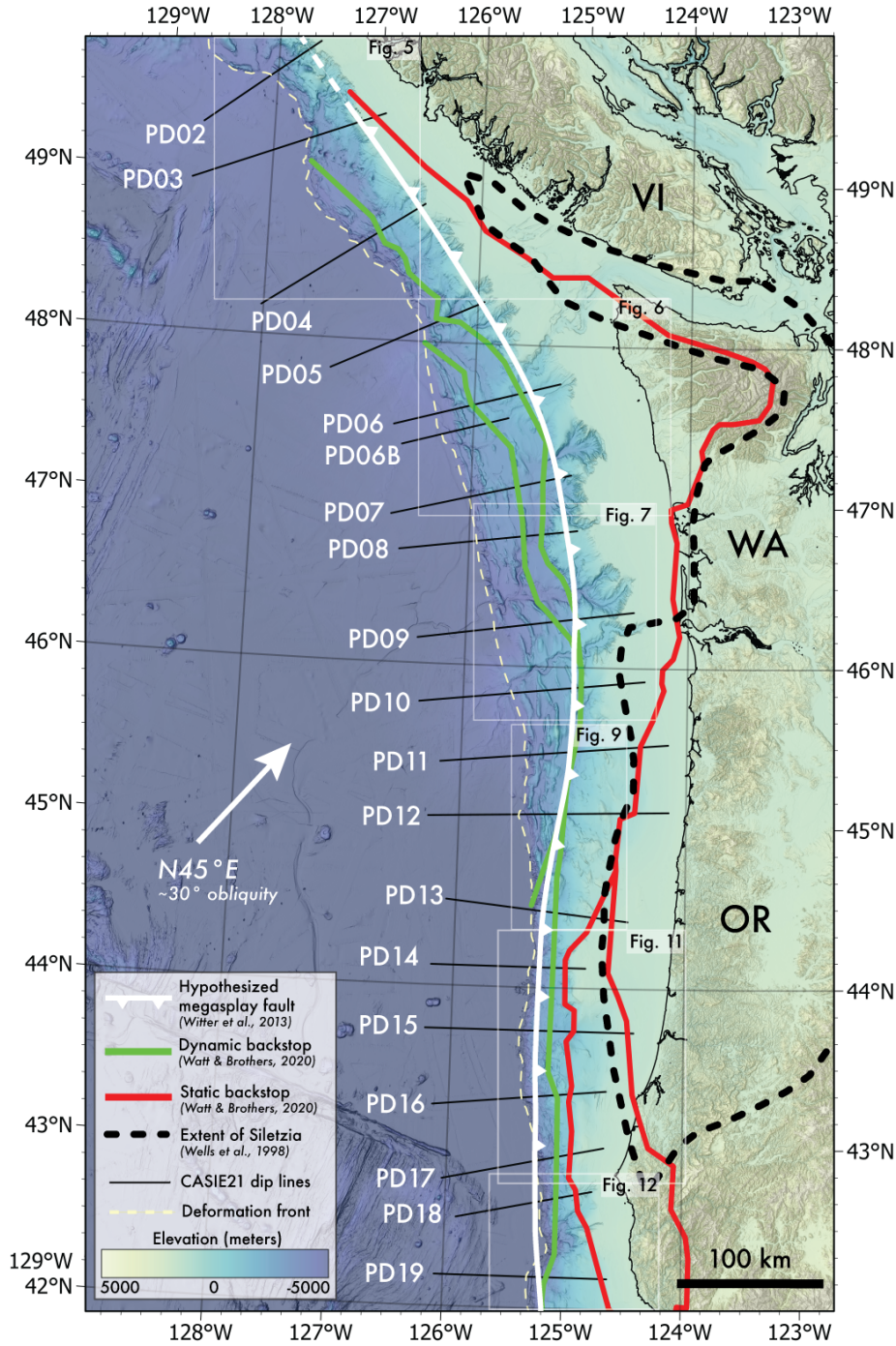


Figure 1. Elevation map of GMRT bathymetry compilation (Ryan et al., 2009) in meters for the region of the offshore Cascadia Subduction Zone overlain with the location of the hypothesized megasplay fault system from Witter et al. (2013), dynamic and static backstops (Watt and Brothers, 2020), Siletzia extent (Wells et al., 1998), CASIE21 dip lines (PD02 to PD19), and approximate deformation front location. Subduction vector and obliquity angle indicated on map (McCaffrey et al., 2007).

1.2 Data and Methods

1.2.1 Terminology

There is a clear agreement among previous studies that a major structural boundary exists within the Cascadia accretionary wedge between older and younger wedge terranes offshore the northern region (Vancouver Island, Washington, northern Oregon) of the Cascadia margin (Adam et al., 2004; Davis & Hyndman, 1989; Flueh et al., 1998; Hyndman et al., 1990; Mann & Snavely, 1984; McNeill et al., 2000a; P. D. Snavely, 1987; Silver, 1972; Watt & Brothers, 2020; Webb, 2017). Because terminology used to describe this boundary is ambiguous, we define the terms and criteria used in this study. We choose to not use the term “backstop” because it implies information about wedge strength and deformation. For example, the term “dynamic backstop” has been used to describe an actively deforming backstop where older accreted materials are still deforming as new material is accreted to the wedge (Heidrun Kopp & Kukowski, 2003; Watt & Brothers, 2020). Conversely, the term “static backstop” has been used to describe a backstop that is no longer actively deforming between the accretionary wedge and crystalline, continental backstops (Silver *et al.*, 1985; Byrne *et al.*, 1993, Kopp and Kukowski, 2003; Watt and Brothers, 2020). Instead, we use the term “inner wedge” to describe the older (inferred Miocene) accretionary wedge complex; and the term “outer wedge” to describe the younger (inferred Pleistocene) accretionary wedge complex. Our use of these terms deviates from morphological uses of the terms in which the boundary between the inner and outer wedge is defined by the outer arc high. This terminology allows for our analysis of wedge structure to be independent from surface morphology and active deformation.

1.2.2 *Geophysical Datasets*

To characterize the transition between the inner and outer wedge domains of the Cascadia accretionary wedge, we use ultra-long offset seismic reflection images from CASIE21, which capture subsurface structure to depths greater than 10 km. CASIE21 utilized the R/V Marcus G. Langseth to complete the first modern, regional-scale seismic reflection imaging survey of the offshore Cascadia subduction zone (Carbotte et al., 2021, 2023). In the CASIE21 survey, we collected 2-D multi-channel seismic (MCS) reflection and multibeam bathymetric data along 18 primary dip lines, 7 strike lines, and several turning lines, from Vancouver Island to southern Oregon (**Fig. 1**). Dip lines are interpreted in this study because they provide a cross-sectional view of accretionary wedge structure. All seismic profiles in this study are presented with the seaward direction (west) to the left and the landward direction (east) on the right. Data acquisition was carried out with a 12-15 km-long streamer and a 36-airgun array with a maximum volume of 6600 cubic inches. CASIE21 MCS data were processed by ION Geophysical to produce pre-stack depth migrated (PSDM) MCS reflection profiles. Processed seismic lines are available on the Marine Geoscience Data System (MGDS) hosted by the Lamont-Doherty Earth Observatory of Columbia University (refer to Data and Code Availability Statement). Since the CASIE21 seismic data were acquired and processed with consistent workflows and parameters, this allows for direct comparison of seismic imaging features between lines. Analysis of CASIE21 seismic profiles is supplemented with 50m gridded bathymetry from the Global Multi-Resolution Topographic (GMRT) compilation (Ryan et al., 2009) and, where available, 30-m gridded U.S. Geological Survey (USGS) bathymetry (Dartnell et al., 2021, 2023) to evaluate the geomorphic expression of faulting related to the IOWTZ and connect the surface expression across 2D seismic profiles. Complementary and higher resolution

sparker multi-channel seismic reflection data collected with the R/V Rachel Carson in 2019 (Balster-Gee et al., 2023) by the USGS is interpreted to evaluate near surface (i.e., upper ~1 km of the subsurface) evidence of fault activity within the IOWTZ and inner wedge domains. Joint interpretation of seismic reflection data at multiple scales of resolution allows us to more effectively connect deeper fault structure imaged by CASIE21 to near surface fault activity imaged within the USGS sparker seismic data. A complementary study by Ledeczi et al. (2024) provides a thorough evaluation of late Quaternary evidence for fault activity within the outer wedge domain using sparker seismic data. Through joint analysis of different geophysical datasets with multiple scales of resolution, this study refines the location and nature of the IOWTZ in the Cascadia accretionary wedge and evaluate evidence for an active, margin-spanning megasplay fault system in the vicinity of the IOWTZ in Cascadia.

1.2.3 Methods for mapping accretionary wedge domains

To locate the IOWTZ in the Cascadia accretionary wedge, we identify regional-scale changes in the overall structural style and seismic character of the wedge captured in CASIE21 dip profiles using *Kingdom Suite* software (refer to Data and Code Availability Statement).

a. Structural style

Structural style is an observation of the dominant mode of subsurface deformation in a region due to a common tectonic origin (e.g., Harding and Lowell, 1979). Changes in the structural style of accretionary wedges provides insight into the history of wedge development and evolution (Breen et al., 1986; Cook et al., 2014; Flinch et al., 2003; Richter et al., 2007). Fault vergence, fault dip, thrust spacing, and faulting type from the CASIE21 data are used to characterize regional-scale trends in structural style in both the along-dip and along-strike direction. For

example, in CASIE21 line PD04, the outer wedge domain is identified based on its structural style characterized by wide seaward verging, fault-propagation fold style thrust faulting (**Fig. 2A**). The inner wedge domain is identified based on its structural style characterized by closely spaced, imbricated thrust sheets dominated by seaward vergence (**Fig. 2A**). The IOWTZ is characterized as a zone between the inner and outer wedge with a gradational change in the observed structural style of the wedge with mixed vergence thrust faulting (**Fig. 2A**).

b. Seismic character

Seismic character reflects the cumulative expression of subsurface physical and chemical properties and is inherently linked to both subsurface structural complexity and the presence and migration of subsurface fluids and gas (Berndt et al., 2004; Jurado & Comas, 1992; M. W. Lee et al., 1994; Løseth et al., 2009; J. C. Moore et al., 1985; J. C. Moore & Vrolijk, 1992). Changes in seismic character are identified primarily by changes in reflector coherency, which is a measure of the spatial continuity of seismic reflectors that depends on the level of scattering and attenuation of seismic energy in the subsurface (Li et al., 2021). We develop and employ a qualitative scale for seismic character ranging from “coherent” to “incoherent” (**Fig. 2C**). Decreasing seismic coherency has been inferred to represent increasing structural complexity of accretionary complexes (Cowan, 1985; Moore *et al.*, 1985). For example, in CASIE21 line PD04, the seismic character of the incoming sediment is coherent, the seismic character of the outer wedge is mostly coherent to semi-coherent seismic character, the seismic character of the IOWTZ is semi-coherent to mostly incoherent, and the seismic character of the inner wedge is mostly incoherent to incoherent. This demonstrates a gradational decrease in seismic coherency across the IOWTZ (**Fig. 2B**). Additionally, throughout the entire accretionary wedge, there is a loss in seismic coherency with depth due to seismic attenuation and scattering (**Fig. 2B**).

Together with our characterization of structural style, this example using CASIE21 line PD04 demonstrates how seismic character is linked with increasing structural complexity of the Cascadia accretionary wedge moving landward from the deformation front.

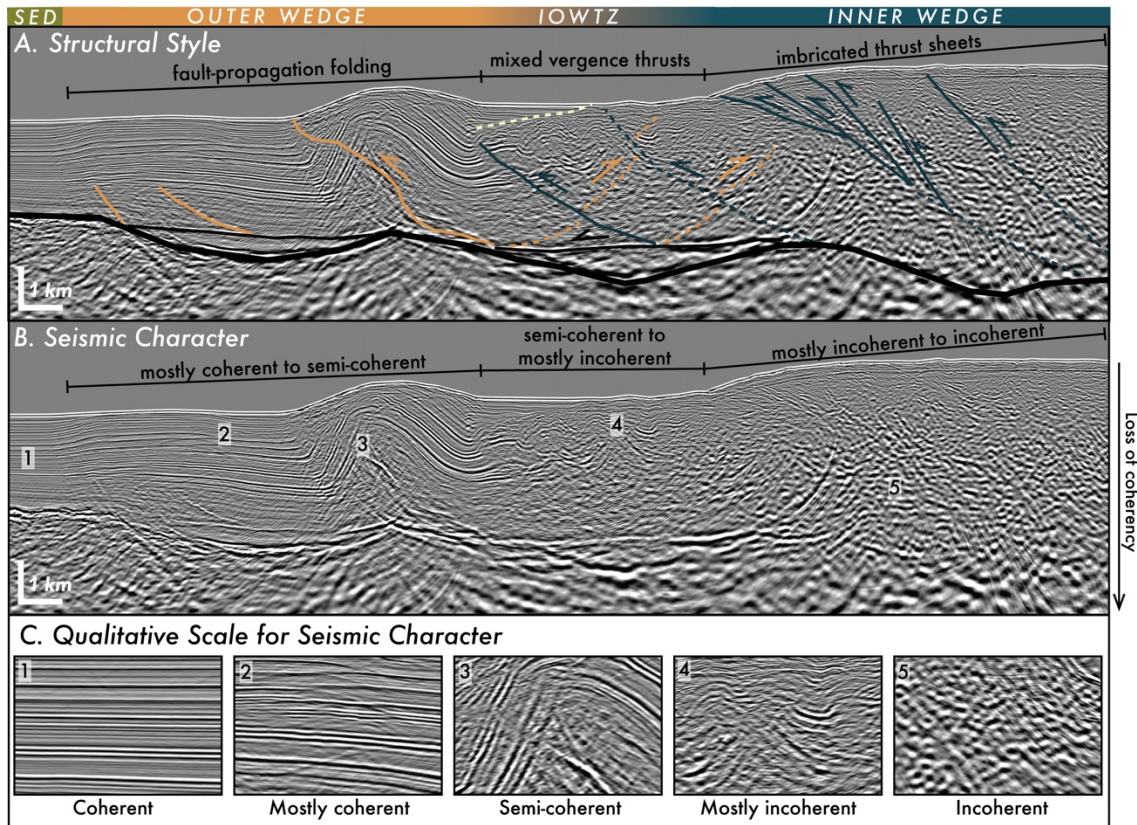


Figure 2. Structural style and seismic character methods. **A-B.** Example figures demonstrating methods for evaluating changes in (A) structural style and (B) seismic character of the Cascadia accretionary wedge using pre-stack depth migrated CASIE21 seismic profile PD04 (no vertical exaggeration) to delineate outer and inner wedge domains and the inner-outer wedge transition zone (IOWTZ). Also note seismic coherency decreases with depth in addition to in the along dip direction. (C) Seismic sections (~3x zoom) from PD04 profile demonstrating qualitative scale used for evaluating seismic character based on reflector coherency.

1.2.4 Methods for evaluating megasplay fault activity

Evidence for megasplay fault activity at the IOWTZ is evaluated for each of the identified along-strike segments and compared with the location and structure of the previously hypothesized megasplay fault. Evidence for megasplay fault activity is classified into three

categories: positive, negative or inconclusive. A classification of positive evidence indicates that a megasplay fault structure is observed at the IOWTZ and there is sufficient evidence to demonstrate recent fault activity. In this study, the same definition is used for “active” as that described in Ledeczi et al. (2024), where faults that either deform or offset inferred late Quaternary sedimentary horizons are classified as active. A classification of negative evidence indicates that a megasplay fault structure is observed at the IOWTZ in CASIE21 seismic profiles, but near surface observations from USGS sparker seismic profiles and available bathymetry provide conclusive evidence of no recent fault activity. A classification of inconclusive indicates that a megasplay fault structure is observed in the given location; however, there is either a lack of near surface observations in that location or fault activity is ambiguous based on all existing data. In some locations along strike, a megasplay fault structure may not exist at the IOWTZ, neither active nor inactive.

1.3 Results

The spatial extent of the inner and outer wedge domains and the IOWTZ of the Cascadia accretionary wedge is mapped based on changes in structural style and seismic character observed in CASIE21 seismic profiles (**Fig. 3, 4**). The landward extent of the inner wedge domain (**Fig. 3**) is bounded by the seaward-most boundary of the combined Siletzia terrane from Wells et al. (1998) and the static backstop from Watt and Brothers (2020) (**Fig. 1**). We also document the approximate extent of wedge top sedimentary cover and incoming sediments (**Fig. 4**). Interpretations of plate boundary geometry and megathrust decollement used to guide our analysis of upper plate structures are consistent with or simplified from Carbotte et al. (2024). Based on changes in accretionary wedge structure and faulting, the wedge is classified into five

along-strike segments: Northern Vancouver Island (~49.2-49.6°N; PD02), Central Vancouver Island (~48.3-49.2°N; PD03-04), Washington & Northern Oregon (~44.2-48.3°N; PD05-13), Central Oregon (~42.6-44.2°N; PD14-17), and Southern Oregon (~42-42.6°N; PD18-19) (**Fig. 3, 4, Table 1**). The Washington & Northern Oregon segment is further subdivided into three subsegments: Olympic (PD06-PD07), Astoria (PD08-PD09), Tillamook (PD10-PD12). In some locations, segment boundaries in accretionary wedge structure exhibit more spatially gradational changes in structure, and hence, are described as along-strike transition zones (ATZ) instead of distinct along-strike boundaries.

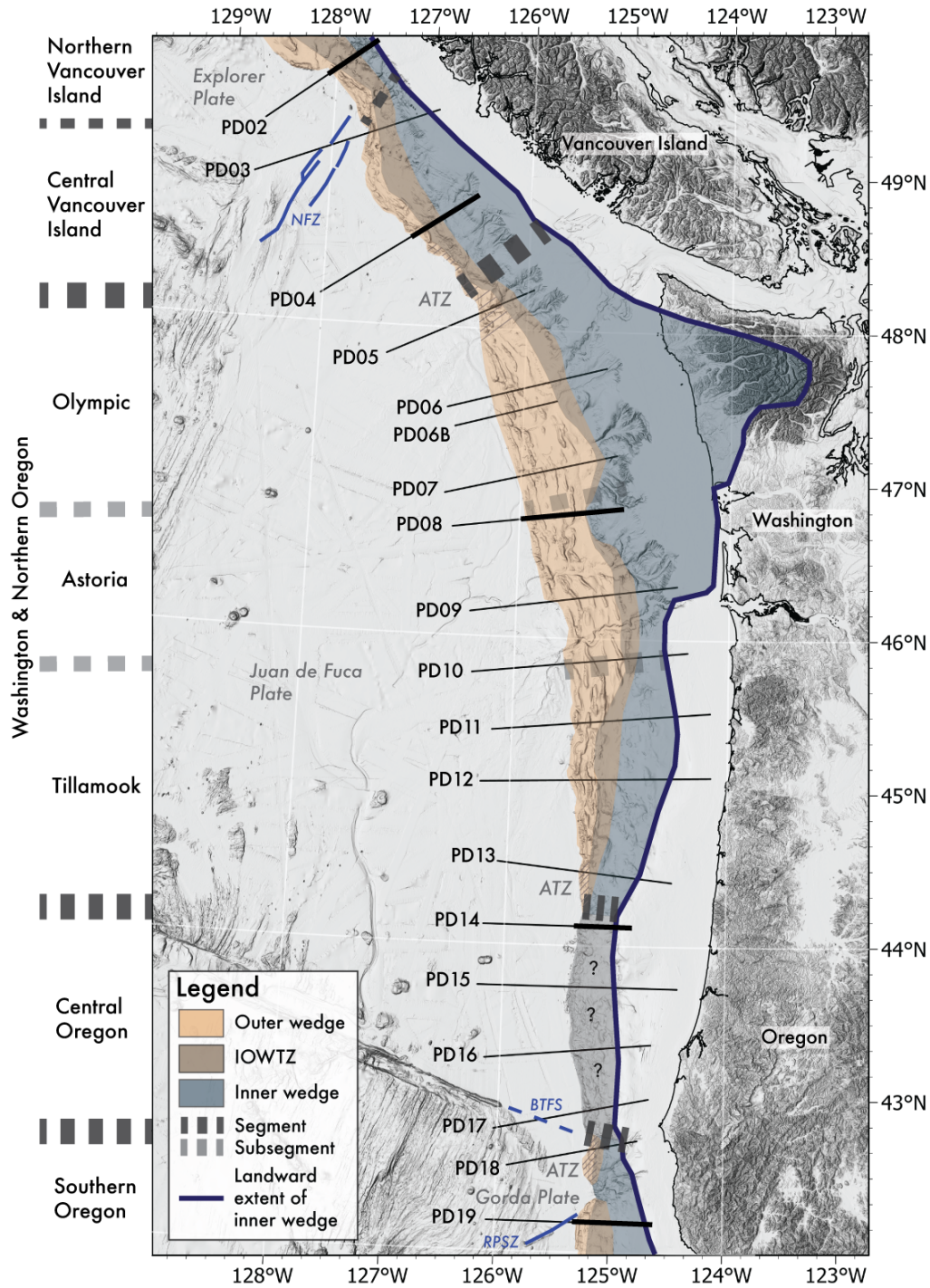


Figure 3. Hillshaded map of GMRT bathymetry compilation with results for spatial extent of outer wedge, inner wedge, and inner-outer wedge transition zone (IOWTZ). Grey hatching of the outer wedge domain indicates the extent of along-strike transition zones (ATZ). Along-strike segment and subsegment boundaries drawn with dark grey and light grey dashed lines, respectively (with line width corresponding to locational certainty of the boundary), landward extent of inner wedge drawn with thick blue line, CASIE21 dip lines drawn with fine black lines,

and extent of seismic profiles presented in Figure 4 drawn with thicker black lines. Grey shading of the wedge with question marks indicates no outer wedge or IOWTZ domains can be identified. Blue lines show the location of relevant structures on the incoming plate. The grey domain with a question mark indicates no inner, outer, or IOWTZ domains can be identified. NFZ is Nootka Fault Zone, BTFS is Blanco Transform Fault System, RPSZ is Rogue Propagator Shear Zone.

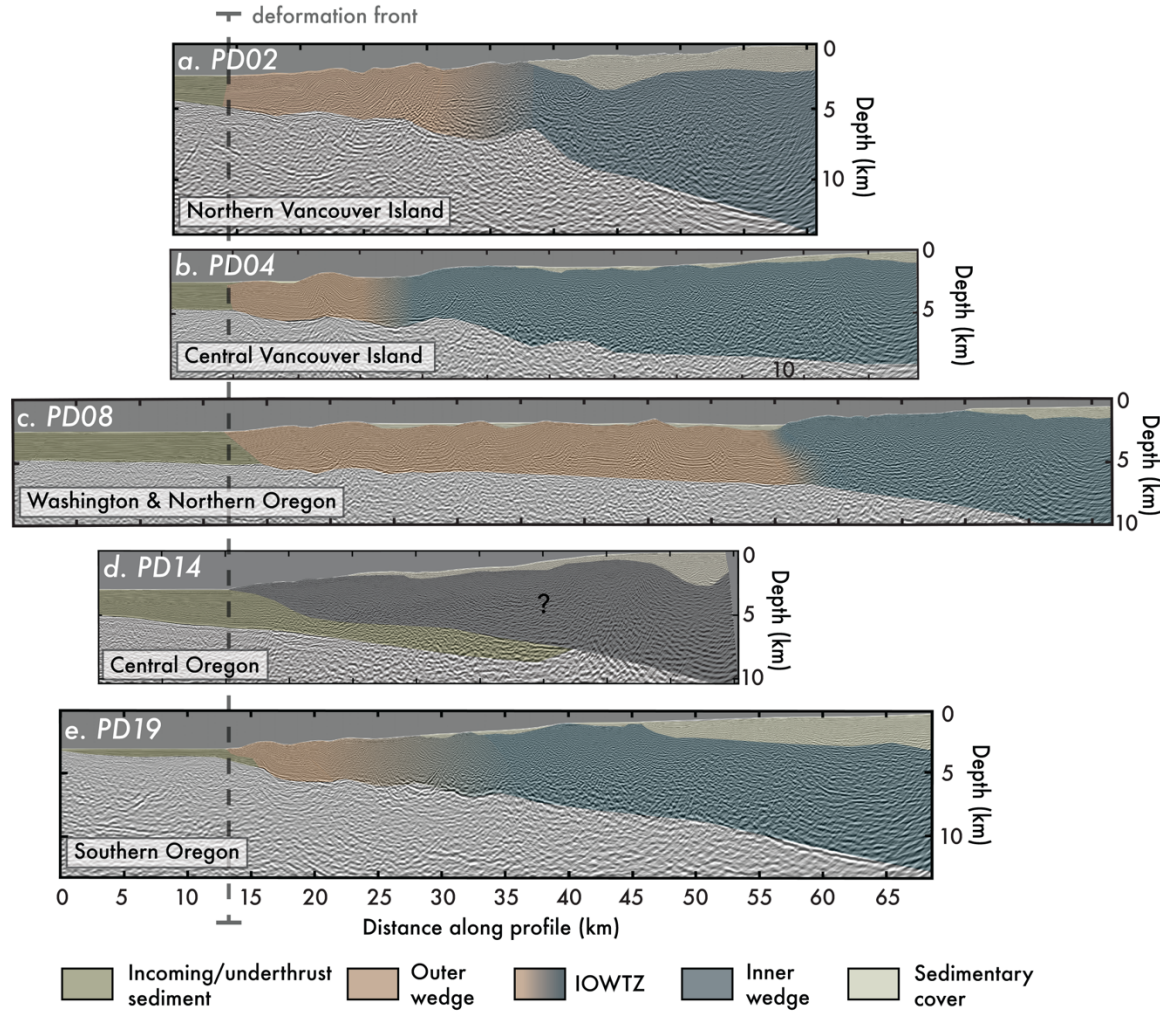


Figure 4. Representative examples of CASIE21 seismic profiles from each along-strike segment showing wedge structural domains. **a-e.** Overlain with semi-transparent masks delineating the interpreted incoming/underthrust sediment (green), outer wedge (orange), inner wedge (blue), IOWTZ (orange-blue gradient), sedimentary cover (yellow), and downgoing igneous basement crust of the Juan de Fuca plate (white). The grey domain with a question mark indicates no inner, outer, or IOWTZ domains can be identified. Extent of CASIE21 seismic profiles is indicated by thick black lines in Figure 3. Plate boundary and decollement interpretations simplified from Carbotte et al. (2024).

1.3.1 Northern Vancouver Island (~49.2-49.6°N)

The Northern Vancouver Island segment is situated at the northern terminus of the Cascadia subduction zone (**Fig. 3**). This segment of the accretionary wedge, which appears to be indented landward, has been previously interpreted as a structural transition (Watt and Brothers, 2020) corresponding with the location where the NFZ intersects the margin (Hutchinson et al., 2023; Rohr et al., 2018) (**Fig. 5a**). CASIE21 line PD02 images the ~7 km wide IOWTZ in this segment and captures drastically different wedge structure compared to that of Central Vancouver Island segment in lines PD03 and PD04 (**Fig. 5b-g**). This is expected given that PD02 captures the upper-plate structure atop the more steeply dipping Explorer Plate (Carbotte et al., 2024). The outer wedge in PD02 is dominated by imbricated, landward-verging fault-propagation fold style thrust sheets with mostly coherent reflectivity (**Fig. 5b**). The plate hinge identified by Carbotte et al. (2024), where the dip of the downgoing plate abruptly steepens, is located near the seaward end of the IOWTZ within the outer wedge domain (**Fig. 5b**). The inner wedge in PD02 exhibits incoherent reflectivity and has an overlying sedimentary sequence that thickens landward from the IOWTZ. Characterizing structure within the IOWTZ zone is difficult due to mostly incoherent reflectivity; however, there is evidence for landward-dipping reflectors with a linear pattern (i.e., seismic lineations) that may represent potential seaward-verging megasplay faults at the IOWTZ. It is unclear whether these seismic lineations reach the near surface due to poor coverage in our available bathymetry and the highly channelized seafloor in this location. Local basement topography was observed in the downgoing Juan de Fuca plate by Shuck *et al.* (2023) and Carbotte et al. (2024) at the IOWTZ and was interpreted as a tear in the downgoing slab (**Fig. 5b**). The observed landward-dipping seismic lineations of the IOWTZ appear to sole near the top of this topographic structure (**Fig. 5b**). Based on a lack of coherent reflectivity at the

IOWTZ in PD02, we cannot confidently determine whether an active out-of-sequence megasplay fault system exists in this location.

1.3.2 Central Vancouver Island (~48.3-49.2°N)

Both CASIE21 lines PD03 and PD04 exhibit similar overall wedge structural style and seismic character (**Fig. 5e, g**). In both lines, the outer wedge consists of a single major seaward-verging fault-bend fold style thrust sheet that accretes all or nearly all of the incoming sediment section to the wedge. The seismic character of the outer wedge is mostly-coherent with well-imaged, continuous reflectors offset by the frontal thrust fault. The inner wedge captured by PD03 and PD04 exhibits mostly-incoherent to incoherent reflectivity with closely spaced, dominantly seaward-verging thrust fault structures and landward dipping seismic lineations. The IOWTZ is characterized by a zone of doubly-verging thrust faults. Seaward-verging thrust faults of the inner wedge domain deform landward-verging thrust faults of the outer wedge domain. Landward of this change in fault vergence adjacent to the IOWTZ, inner wedge faults in both seismic profiles have a clear expression at the seafloor observable in both the seismic and bathymetric data (**Fig. 5c,d,f**). PD03 has a wider IOWTZ where individual inner wedge faults appear to disturb and tilt overlying sediments and deform the seafloor between 10 and 30 km distance along the seismic section (**Fig. 5c-e**; white triangles). In some locations, these faults also exhibit distinct fault plane reflections with reverse polarity (**Fig. 5d**). PD04 has a narrower zone of faulting between 20 and 30 km distance along the seismic section where deformation is more focused (**Fig. 5f-g**; white triangles). In PD04, faults at the IOWTZ are locally associated with both a steeper wedge slope and lack of overlying sediment cover (**Fig. 5f**). These faults are classified as megasplay faults because inner wedge faults appear to deform younger outer wedge

material, providing evidence for out-of-sequence fault activation in this zone, and because these faults coincide with the boundary between the coherent and incoherent seismic character of the wedge. Additionally, these faults also show evidence of surface expression at the seafloor in the GMRT 50-m bathymetry (**Fig. 5a**) while connecting with the megathrust fault at depth (**Fig. 5e,g**). The coherence of seismic reflectors decreases with depth, particularly in line PD04 between 25-30 km along the seismic section, making it difficult to identify the exact points in the subsurface at which faults sole into the megathrust fault (**Fig. 5g**). The trace of these megasplay faults in the bathymetry is discontinuous, however the faults all generally trend in the same direction and extend over ~50 km along strike (**Fig. 5a**). This system of megasplay faults at the IOWTZ is located on average ~10-30 km southwest of the previously proposed megasplay fault trace of Witter et al. (2013) (**Fig. 5a**). The plate hinge identified by Carbotte et al. (2024) coincides with this megasplay fault system in PD04 (**Fig. 5g**; green star). However, in PD03, the plate hinge is not associated with the identified megasplay fault system and is instead located further east beneath a major slope break coincident with the location of the previously hypothesized megasplay fault by Witter et al. (2013) (**Fig. 5e**; green star). Further acquisition and analysis of higher resolution seismic and bathymetric data is needed in this segment to determine the recency of megasplay fault activity; therefore, the evidence for activity of this megasplay fault system captured in PD03 and PD04 is classified as inconclusive.

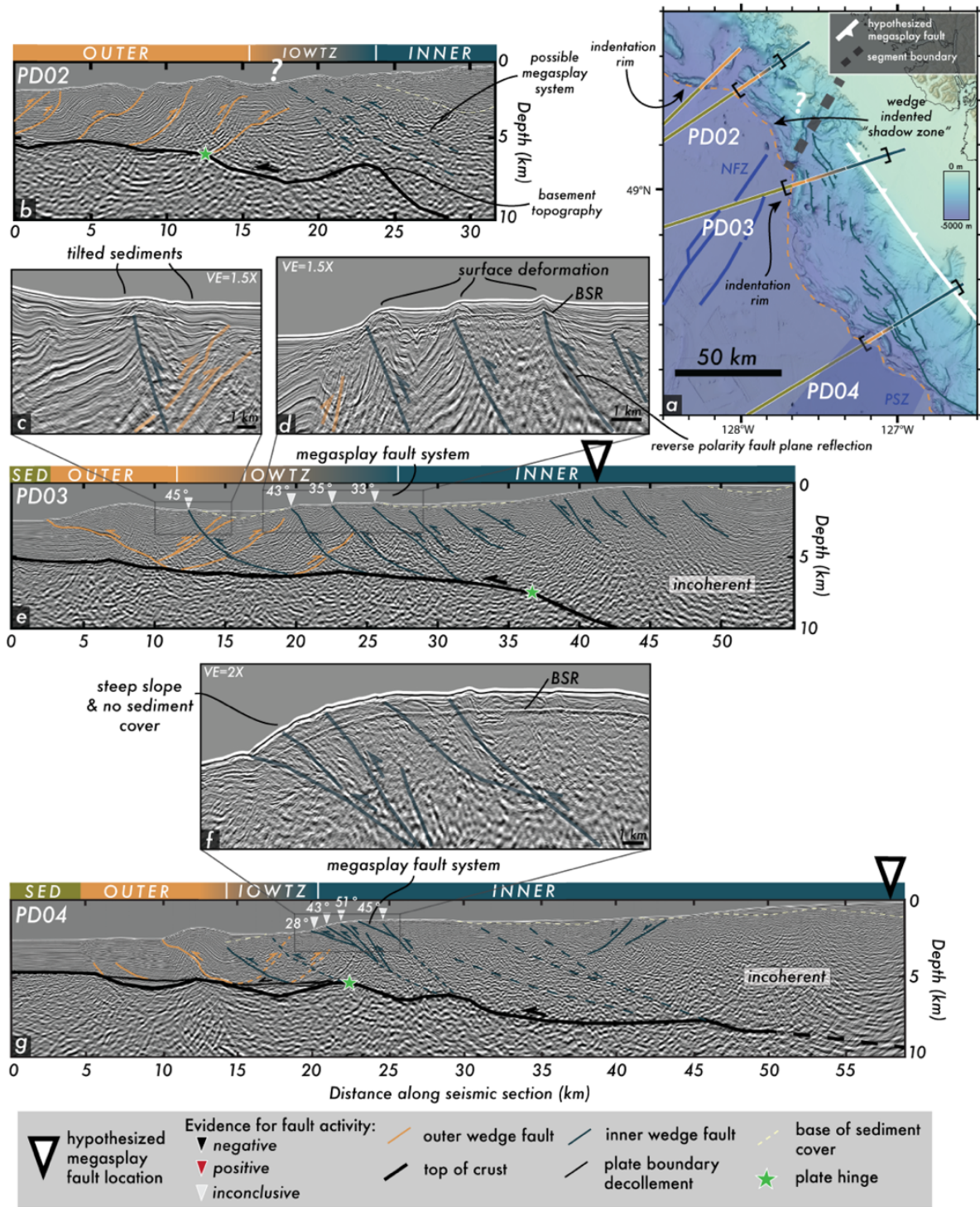


Figure 5. The Northern and Central Vancouver Island segments. a. Map of GMRT bathymetry with locations of corresponding CASIE21 seismic images, segment boundaries, and megasplay fault location hypothesized by Witter et al. (2013). Seismic image extent is indicated on the map by black brackets. Fine blue lines in the map correspond with megasplay faults of the inner wedge domain as interpreted in seismic images. Thick blue lines show the location of the Nootka

Fault Zone (Rohr et al., 2018). b-g. Orange color represents the outer wedge, blue color represents inner wedge, orange-blue gradient represents inner-outer wedge transition zone (IOWTZ), and green color represents incoming sediment section. Dotted lines represent less certain fault interpretations. Simplified top of crust, plate boundary decollement, and plate hinge interpretation is from Carbotte et al. (2024). Previously hypothesized splay fault location is from Witter et al. (2013). Smaller triangles in the seismic sections indicate the position of interpreted megasplay faults at the IOWTZ and are color-coded by evidence for fault activity. No vertical exaggeration of seismic images. Bottom-simulating reflector (BSR) is indicated on seismic images.

1.3.3 Washington & Northern Oregon (~44.2-48.3°N)

The Washington & Northern Oregon segment, imaged by CASIE21 profiles PD05-PD13, is defined by the extent of the landward vergence zone and is the longest of the identified segments, spanning ~400 km along strike (**Fig. 3, Table 1**). This segment exhibits a widening and then narrowing of the outer wedge domain at the northern and southern ends of this segment, with the widest point near line PD07 spanning ~65 km between the deformation front and the beginning of the IOWTZ (**Fig. 3**). The structural style of the outer wedge domain in this segment is characterized by landward-dominated mixed vergence thrust faulting (**Fig. 4c**). This segment exhibits the most internal variation in accretionary wedge structure of all the identified segments, especially at the IOWTZ. Based on this, this segment is further subdivided into three subsegments (Olympic, Astoria, Tillamook; **Fig. 3**). PD05 and PD13 capture ATZs where wedge structure and faulting exhibits gradational changes across segment boundaries, and hence, these profiles contain structural features in common with adjacent segments and subsegments.

a. Olympic Subsegment (PD05, PD06, PD07)

PD05 is located within an ATZ where key structural features are present from both adjacent segments (**Fig. 3, Table 1**), including landward-verging outer wedge thrust faults, typical of the Washington & Northern Oregon segment, and a megasplay fault system reaching

near the surface, typical of the Central Vancouver Island segment. The IOWTZ in line PD05 is characterized by a zone of mixed vergence where landward-verging thrust faults of the outer wedge domain overlap with seaward-verging faults of the inner wedge domain (**Fig. 6c**). A decrease in the coherency of seismic character from semi-coherent to mostly incoherent occurs across the IOWTZ. Adjacent to the IOWTZ, a series of seaward-verging inner wedge thrust faults dipping at $\sim 33^\circ$ sole near the megathrust fault at depth (**Fig. 6c**). At the surface, these faults coincide with a slope break in the bathymetry and tilted wedge top sediments (**Fig. 6b**). At depth, the faults correspond with a steepening of the downgoing plate dip (i.e., plate hinge), and an along-dip shallowing of the plate boundary decollement (Carbotte et al., 2024) (**Fig. 6c**). Therefore, these inner wedge faults are interpreted as a system of megasplay faults associated with the IOWTZ. The near surface expression of this megasplay fault system is disrupted by a deep seafloor channel that cuts across the accretionary wedge in this location (**Fig. 6a**); therefore, evidence for activity of these megasplay faults at the IOWTZ in PD05 is classified as inconclusive. Nevertheless, these faults should be considered as candidate active megasplay faults at the IOWTZ and a potential focus for more detailed near-surface investigations to evaluate deformation of wedge top sediments. PD05 does not intersect the trace of the Witter et al. (2013) megasplay fault; however, the IOWTZ has been identified within the extent of the seismic profile and there is no clear surface expression of faulting in the GMRT bathymetry at the location of the Witter et al. (2013) splay fault trace that would suggest a megasplay fault exists at that location (**Fig. 6a**).

In line PD06, the IOWTZ is buried by a 1-2 km thick layer of undeformed sediment (**Fig. 6d**). No faults are mapped at the IOWTZ in this location by a recent sparker investigation of near surface splay fault activity (Ledeczi et al., 2024). However, at depth, 2-3 seaward-verging inner

wedge thrust faults dipping at 30° and 42° are observed to offset folded strata of outer wedge thrust sheets at the IOWTZ between 7 to 20km distance along the seismic section (**Fig. 6d-e**). The IOWTZ also corresponds with a local shallowing of the plate boundary decollement (Carbotte et al., 2024) inferred to cut across the base of these inner wedge thrust faults (**Fig 6e**). These faults are interpreted as megasplay faults due to their apparent out-of-sequence reactivation because they appear to have deformed more recently accreted outer wedge material but are now no longer active as evidenced by undeformed overlying sediment (**Fig. 6d**). Within the inner wedge at ~25km along the seismic section, there is a pair of conjugate faults that are also buried by ~1km of undeformed sediment (**Fig. 6e**). This thick layer of undeformed sediment cover atop the wedge indicates a lack of recent activity on megasplay faults and other inner wedge splays in the location of PD06. Without information on sedimentation rate, we cannot estimate when these faults were last active; however, it is likely on the order of tens (if not hundreds) of thousands of years. This result is inconsistent with the hypothesis for active megasplay fault in this location.

Three isolated fault structures between PD06 and PD07 captured only in the bathymetry at the location of the mapped IOWTZ are expressed at the seafloor just south of the Quillayute submarine channel (**Fig. 6a**). The westernmost fault of the three faults has been classified as Quaternary active by Ledeczi et al. (2024). These faults are short in length, isolated to a small area, do not appear to plausibly connect to surrounding structures captured in adjacent CASIE21 seismic profiles, and do not appear to offset adjacent submarine channels. Further MCS surveying is needed in this location to determine the deeper structure of these faults and whether they are connected to the megathrust fault at depth.

In line PD07, a single seaward-verging thrust fault steeply dipping at 47° within the IOWTZ represents a candidate megasplay fault (**Fig. 6g**). This fault is located ~5 km west of the megasplay fault trace from Witter et al. (2013). The location of this fault at the IOWTZ corresponds with a steepening of the downgoing plate dip (Carbotte et al., 2024) and an increase in wedge surface slope (i.e., wedge taper angle) (**Fig. 6g**). This fault offsets folded strata within the hanging wall of a landward-verging thrust sheet of the outer wedge domain (**Fig. 6f**). However, the fault is partially buried by a ~1-km thick layer of sediment at the seafloor (**Fig. 6f**), indicating a lack of recent activity. This result is consistent with Ledeczi et al. (2024) who also found no evidence for late Quaternary activity on this fault in their analysis of sparker seismic data. Therefore, evidence for recent activity on this megasplay fault structure at the IOWTZ is concluded as negative.

There is no evidence to suggest there is a continuous, active megasplay fault system in the Olympic subsegment imaged by CASIE21 lines PD05-PD07 as previously suggested by Witter et al. (2013). In PD05, subsurface structures indicate a megasplay fault system is likely present at the IOWTZ; however, evidence for recent activity of this fault system is inconclusive. Megasplay faults identified within lines PD06 and PD07 of the Olympic subsegment are buried by up to 2 kilometers of undeformed sediment, exhibit a discontinuous surface expression, and cannot be plausibly connected to the megasplay fault system identified in PD05. Overall, fault structure at the IOWTZ varies substantially from PD05 to PD07 and no active megasplay faults can be connected along-strike through this region based on similarities in fault surface expression and subsurface fault structure at the IOWTZ (**Fig. 6**).

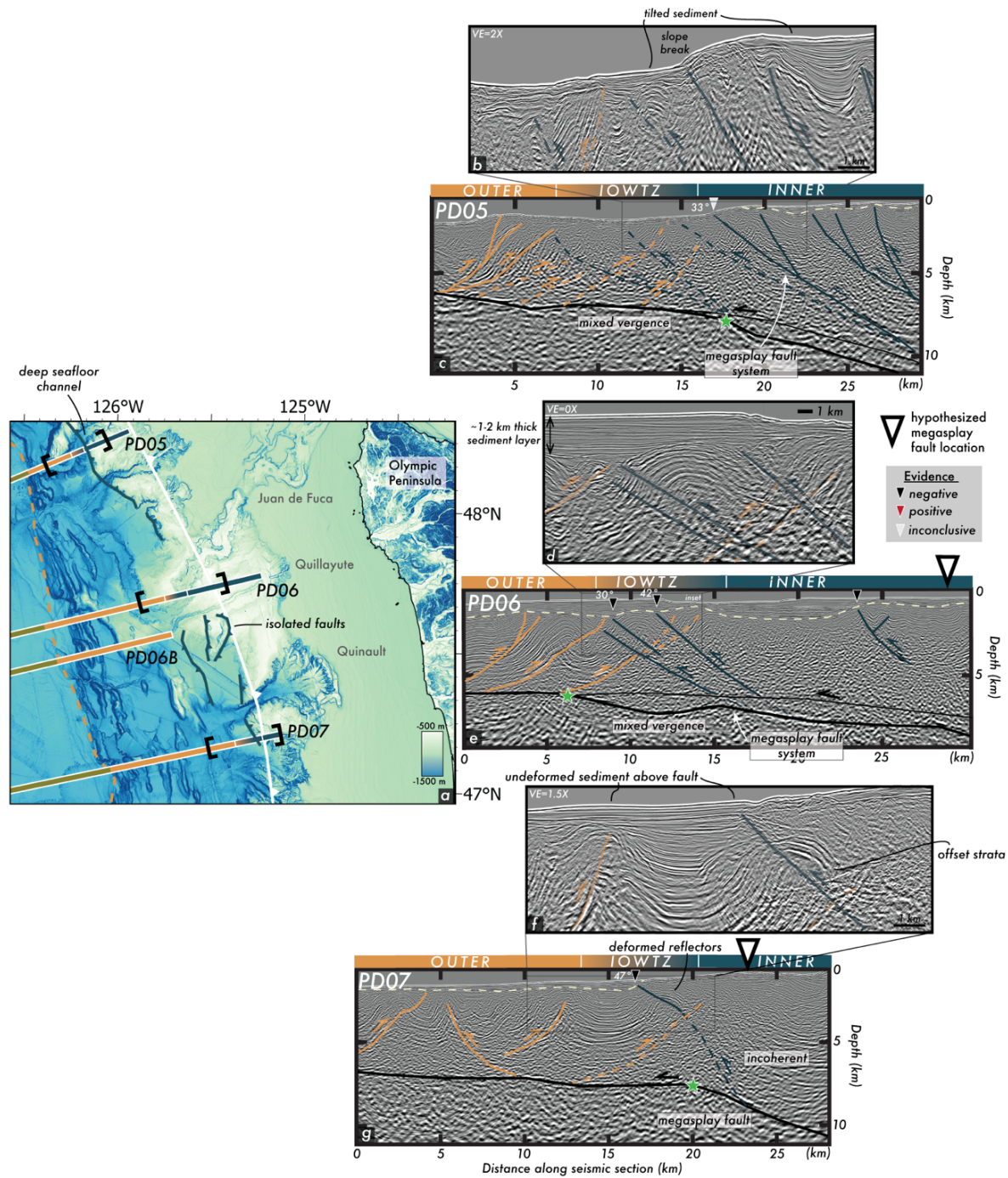


Figure 6. Olympic subsegment of Washington and Northern Oregon segment. Symbology is the same as Fig. 5. **a.** Map of 30-m USGS bathymetry. **b-g.** Seismic panels from CASIE21 seismic lines PD05, PD06, and PD07 showing deep and shallow fault structure.

b. Astoria Subsegment (PD08, PD09, PD10)

PD08 captures the best evidence for an active megasplay fault system at the IOWTZ within the Washington & Northern Oregon segment. The IOWTZ captured in PD08 is less of a zone, and instead a sharp boundary between the inner and outer wedge domains (**Fig. 7a-b**). A seaward-verging thrust fault system dipping at $\sim 28^\circ$ is present at this inner-outer wedge boundary and merges with the megathrust fault at depth while also extending up to the seafloor (**Fig. 7b**). At the seafloor, this fault system is expressed as two distinct fault scarps in the USGS 30-m bathymetry (**Fig. 8c**). At depth, this megasplay fault structure exhibits a highly deformed zone with mostly incoherent reflectivity, representing a well-developed fault system with numerous branching fault strands (**Fig. 8b**). The surface trace of these faults extends ~ 50 km along strike and is co-located with large seafloor slope failures identified by Hill et al. (2022). This megasplay fault system is located ~ 20 km west of the previously hypothesized splay fault system (**Fig. 7a**). This fault system does not appear to connect with structures further north in PD07, primarily because of a lack of evidence in the bathymetry due to the extensive seafloor erosion by the Grays submarine channel between PD07 and PD08 (**Fig. 7a**). This fault is also coincident with an unusual, convex-outward boundary between the inner and outer wedge domains (**Fig. 8a**) as well as with a relatively undeformed zone with extremely flat wedge taper seaward of the fault system within the outer wedge domain (**Fig. 7b, 8b**). Submarine channels Grays and Guide appear to be routed to the north and south around this major morphologic feature (**Fig. 8a**). Near surface evidence for late Quaternary activity on this fault system from nearby sparker data remains inconclusive because the steep slope associated with this structure that acts as a sediment bypass, preventing sedimentation of the slope (Ledeczi et al., 2024).

Therefore, activity on this megasplay fault system is likely, but activity is currently inconclusive based on available evidence.

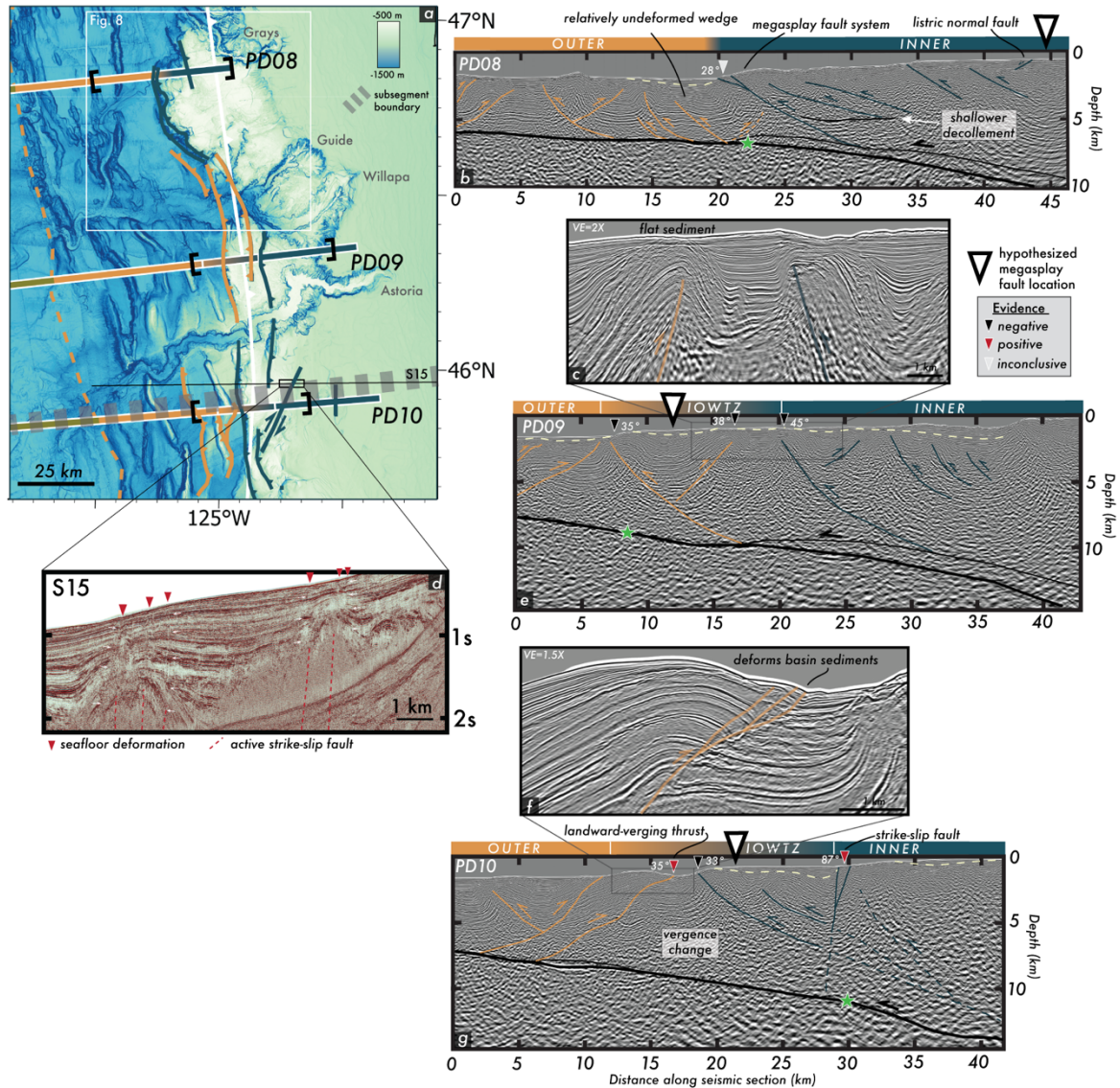


Figure 7. Astoria subsegment of Washington & Northern Oregon segment, including the Astoria-Tillamook subsegment boundary. Symbology is the same as Fig. 5. **a.** Map of 30-m USGS bathymetry. Continental shelf shown in light green color. White inset box shows the region of Fig. 8. Subsegment boundary shown by grey dashed line. **b-g.** Seismic panels of CASIE21 seismic lines PD08, PD09, and PD10 and USGS sparker seismic line S15 showing accretionary wedge structure and near surface fault deformation.

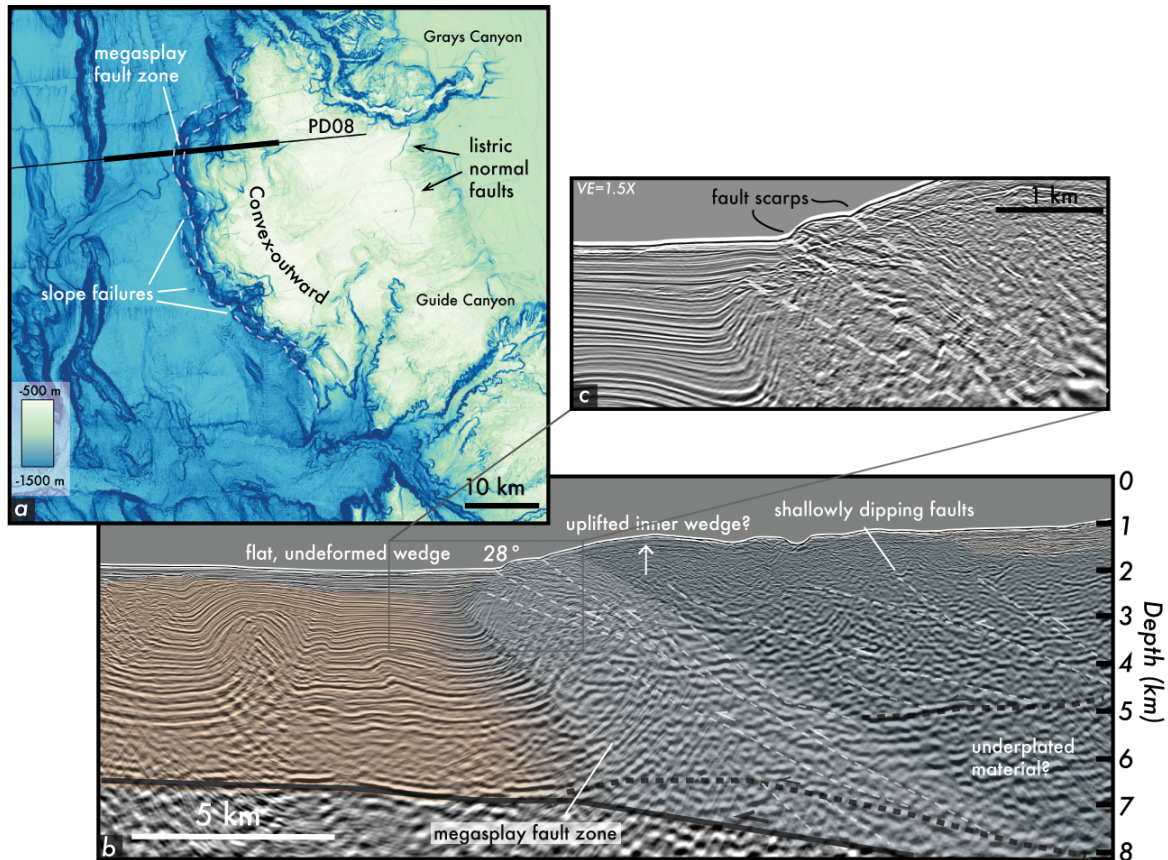


Figure 8. IOWTZ megasplay fault system captured by CASIE21 line PD08 of Astoria subsegment. **a.** Detailed map of USGS 30-m bathymetry. Continental shelf shown in light green color. Thicker black on PD08 line shows the extent of the seismic image shown in this figure. White dashed lines on the map indicate the surface trace of the megasplay fault interpreted at depth. White shaded area between the outer (orange) and inner (blue) wedge domains indicates our proposed megasplay fault zone. No vertical exaggeration on seismic image.

PD09 crosses a similar slope break and increase in the seafloor elevation that can be traced south in the bathymetry across the Guide and Willapa submarine channels from the potentially active megasplay fault system identified in PD08 (Fig. 7a,e). This break in the seafloor corresponds with a seaward-verging thrust fault within the IOWTZ that has a similar structural style to faults within the outer wedge domain. This fault is dipping at 35° and soles into the megathrust fault at depth (Fig. 7e). This structure is classified as a megasplay fault due to its apparent out-of-sequence activity and apparent connectivity with the megasplay fault

system identified in PD08. However, unlike the megasplay fault system identified in PD08, there is conclusive evidence from sparker seismic data that this megasplay fault in PD09 is not recently active based on a lack of deformation in overlying sediments (Ledeczi et al., 2024). Two additional thrust faults within the IOWTZ are identified; however, these faults exhibit no expression at the seafloor and are also blanketed by a layer of undeformed sediments (**Fig. 7c,e**; black triangles).

PD10 is located at the Astoria-Tillamook subsegment boundary defined by where a megasplay fault structure is no longer observed, neither active nor inactive. Instead, a system of active right-lateral strike-slip faults and a landward verging thrust fault are observed at the IOWTZ (**Fig. 7g**). Thrust fault vergence at the IOWTZ in PD10 changes from dominantly landward within the outer wedge domain to seaward within the inner wedge domain. A landward-verging thrust fault in the IOWTZ dipping at 35° is observed to reach the surface and deform wedge top basin sediments while also connecting with the megathrust at depth (**Fig. 7f-g**). Consistent with these observations, Ledeczi et al. (2024) found this fault to exhibit evidence for late Quaternary activity in sparker data. Landward of this fault, a seaward-verging inner wedge thrust fault dipping at 33° is observed at the IOWTZ near the megasplay fault trace hypothesized by Witter et al. (2013). This fault is associated with a slope break in the seafloor (**Fig. 7g**; black triangle) and appears to reach the surface; however, it is found to be conclusively not active based on near surface observations of basin sediments (Ledeczi et al., 2024). Additionally, it is unclear where this fault soles in the subsurface due to a lack of coherent reflectivity at depth (**Fig. 7g**). At the boundary between the IOWTZ and the inner wedge domain, an active right-lateral strike slip fault system is present and extends ~25 km along strike. This strike-slip fault is dipping at 87° and crosscuts two adjacent inactive seaward-verging thrust

faults (**Fig. 7g**; red triangle). This fault is associated with a more gradual increase in seafloor elevation and is roughly co-located with the plate hinge from Carbotte et al. (2024) (**Fig. 7g**; green star). At the seafloor, this fault exhibits evidence for deformation of near surface sediments captured in sparker seismic line S15 just to the north of line PD10 (**Fig. 7a,d**). This provides positive evidence for late Quaternary activity on this strike-slip fault at the IOWTZ. Both active faults identified within the IOWTZ captured by PD10 do not exhibit typical megasplay fault structure, suggesting that a more complex style of wedge deformation is occurring at the IOWTZ in this location and an overall change in faulting style at the IOWTZ at the Astoria-Tillamook subsegment boundary.

Within the Astoria subsegment captured by CASIE21 lines PD08 and PD09, a seaward-verging megasplay fault system is associated with the IOWTZ. This fault system is prominently expressed at the seafloor and continuous along strike (**Fig. 7a, 13**). However, this fault system is observed to have either negative or inconclusive evidence for recent activity. In PD10, at the Astoria-Tillamook subsegment boundary, CASIE21 and sparker seismic data provide evidence that both a landward-verging thrust fault and a strike-slip fault system are active at the IOWTZ. Overall, faulting at the IOWTZ in this region varies greatly over relatively short along strike distances (on the order of tens of kilometers) and evolves from dominantly thrust faulting to strike-slip faulting at the Astoria-Tillamook subsegment boundary. Megasplay faults in this region may be locally active at the structure identified in PD08; however, more high-resolution geophysical observations are needed to confirm recency of activity on this fault.

c. Tillamook Subsegment (PD11, PD12, PD13)

At the beginning of the IOWTZ captured by PD11, a landward-verging thrust fault, dipping at 34° , shows evidence for late Quaternary activity (**Fig. 9a,c**; red triangle)(Ledeczi et al., 2024). Landward of this fault, an active strike-slip fault system is present within the IOWTZ between 30 to 35km distance along the profile (**Fig. 9a,c**; red triangle). CASIE21 line PD11 and sparker line S19 are roughly co-located, allowing for comparison of this strike-slip fault system in both seismic profiles of differing resolutions (**Fig. 9a**). In sparker line S19, seafloor sediments are deformed by two high-angle subsurface faults with opposing dips (**Fig. 9b**). This surficial deformation corresponds with a positive (transpressional) flower structure that is linked to this strike-slip fault system in PD11 (**Fig. 9c**). Landward of this flower structure, there is a near-vertical truncation of deep basin sediments associated with the IOWTZ at depth and an almost complete loss of coherence landward of this strike-slip fault system (**Fig. 9c**). Within the inner wedge, there is faint evidence for seaward-verging thrust faults that corresponds with mostly buried ridges at the surface; however, the lack of seismic coherence prevents detailed interpretation of these structures (**Fig. 9c**).

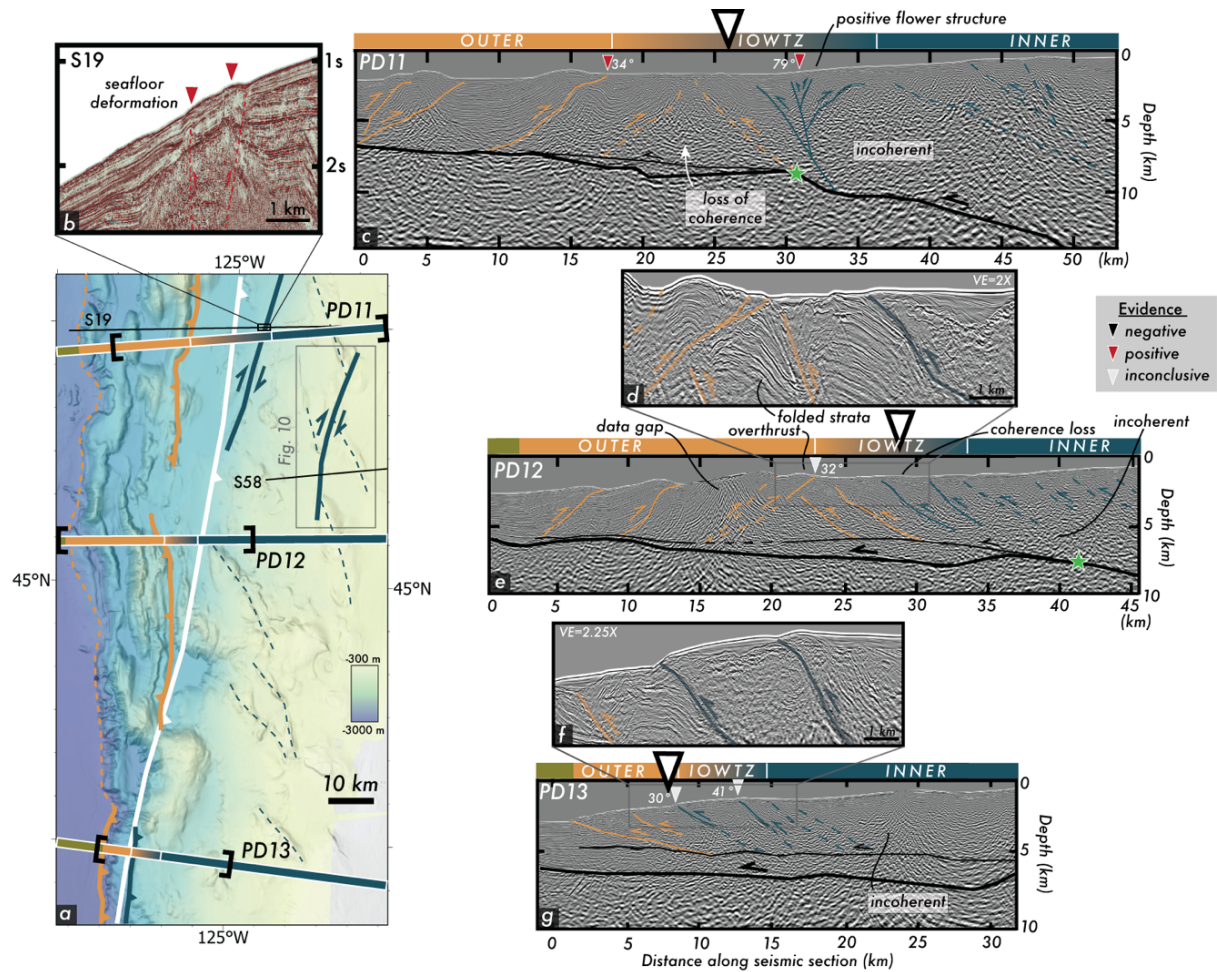


Figure 9. Tillamook subsegment of the Washington & Northern Oregon segment captured by PD11 to PD13 and USGS sparker seismic lines S19 and S58. Symbology is the same as Fig. 5. **a.** Map of 30-m USGS bathymetry showing seismic line locations and extent of wedge domains. Grey inset box shows region of Fig. 10. **b-g.** CASIE21 seismic lines PD11, PD12, and PD13 and USGS sparker seismic line S19.

Between CASIE21 lines PD11 and PD12 and within the inner wedge domain near the IOWTZ, another strike-slip fault system is present (**Fig. 9a**). This fault trends in the same direction as the two active strike-slip faults imaged in PD10, PD11 and S19. A distinct, and apparently young, seafloor scarp in the USGS 30-m bathymetry at this location offsets older seafloor ridges in a right-lateral sense of motion (**Fig. 10b**). Based on this observation, this fault system and the adjacent strike-slip faults captured in PD10 and PD11 likely comprise a larger-scale system of active right-lateral strike-slip faults in this region. Sparker line S58 captures the

main strand of this active strike-slip fault. In the subsurface, a near-vertical strike-slip fault deforms the seafloor where the primary fault scarp is observed in the bathymetry (**Fig. 10a-b**; large red arrow). This fault is associated with multiple subsidiary normal faults that offset basin sediments adjacent to this structure (**Fig. 10a**, small red arrows). One of these normal faults exhibits significant offset of a buried and inactive ridge. The presence of normal faults surrounding the main fault strand indicate a negative (transtensional) flower structure in this location, as opposed to the positive flower structure observed in PD11 (**Fig. 9c**).

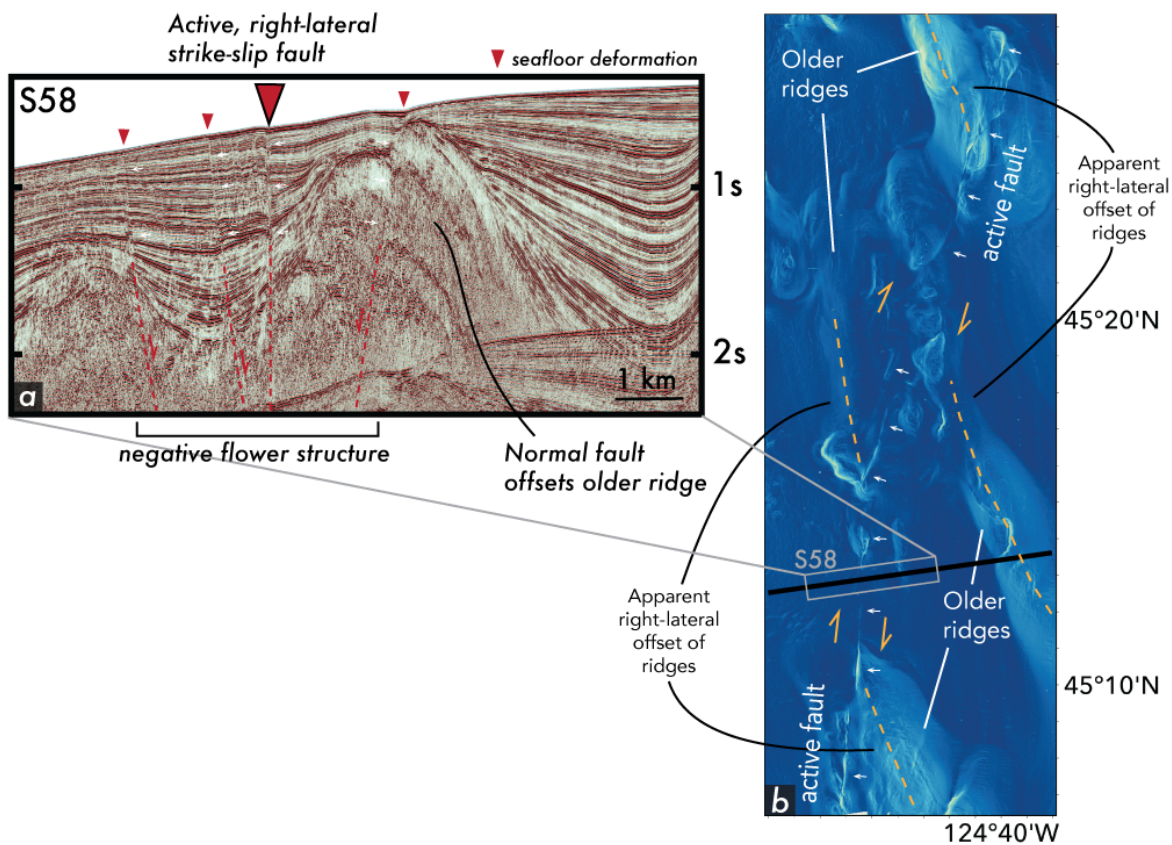


Figure 10. Active right-lateral strike-slip fault of the Tillamook subsegment. **a.** USGS sparker seismic line S58 showing evidence for an active right-lateral strike-slip fault. Surface displacements from subsidiary normal faults shown by small red arrows and are associated with subsurface fault denoted by red dotted lines. Large red arrow with black outline indicates the primary strike-slip fault scarp identified in the bathymetry. **b.** Multi-directional hillshade map created using USGS 30-m bathymetry showing younger fault scarp at seafloor (traced by small white arrows) cutting across older seafloor ridge structures. Lighter colors represent steeper slopes; darker colors represent shallower slopes. Fault trace accentuated by hillshaded map. Map extent denoted in Figure 9.

In PD12, thrust faults sole into a shallower decollement above the top of crust (**Fig. 9e**) (Carbotte et al., 2024). A change in thrust fault vergence from landward to seaward defines the beginning of the IOWTZ. There is no evidence for a seaward-verging megasplay fault structure at the IOWTZ in PD12, and instead there is an out-of-sequence landward-verging fault, dipping at 32° , that is overthrust onto a seaward-verging thrust fault at the IOWTZ (**Fig. 9e**). This fault cuts across folded strata of this seaward-verging thrust and appears to disturb sediments near the seafloor (**Fig. 9d**). There is a data gap in PD12, so interpretation of deeper fault structure in this location is based on information from surrounding seismic lines. It is inconclusive whether this overthrust landward-verging fault remains active at present (**Fig. 9e**; white triangle). Within the IOWTZ between 22km to 35km, four thrust sheets exhibit similar structure and vergence (**Fig. 9e**). However, the reflectivity of the strata comprising the two seaward-most outer wedge thrust sheets is more coherent than the reflectivity of the two landward-most inner wedge thrust sheets. This transition in subsurface seismic character defines the extent of the IOWTZ. A similar pattern occurs in PD13, where thrust sheets exhibit similar structural vergence, but different seismic character expressed as decreasing reflectivity moving landward across the profile (**Fig. 9g**). This enables the delineation of an outer wedge domain in PD13 without a major transition in structural style. In PD13, there is also an abrupt termination of the underthrust sediment section at ~ 30 km along the seismic section (**Fig. 9g**) attributed to a possible subducted seamount atop the downgoing Juan de Fuca plate (Carbotte et al., 2024). This pattern in PD12 and PD13, along with the presence of subducted seamounts near the southern end of the Washington & Northern Oregon segment, reflects the narrowing of the outer wedge domain and IOWTZ at the boundary of the Central Oregon segment and corresponds with the interpreted ATZ (**Fig. 3**). In PD13, two breaks in the seafloor within the IOWTZ are associated

with two seaward-verging inner wedge thrust faults at depth (**Fig. 9f-g**; white triangles). These faults are potential megasplay fault structures; however, it is inconclusive whether these faults are active.

From CASIE21 line PD11 to PD13, the IOWTZ is roughly co-located with the proposed Witter et al. (2013) megasplay fault trace (**Fig. 9a**). However, fault structure, including fault type, fault vergence, and fault activity, within the IOWTZ is highly variable across these three seismic profiles. South of PD10 and within the Tillamook subsegment, there is a system of active right-lateral strike-slip faults at the IOWTZ along with an active landward-verging splay fault, but no seaward-verging megasplay fault structure is present. PD13 captures an ATZ where structure of the accretionary wedge features both an identifiable outer wedge domain characteristic of the Washington & Northern Oregon segment, but also an underthrust sediment section characteristic of the Central Oregon segment. This result reflects similar overarching conclusions from our analysis of the Washington & Northern Oregon segment that splay fault structure at the IOWTZ cannot be described by a single, active seaward-verging thrust fault that spans continuously along strike, as previously hypothesized.

1.3.4 Central Oregon (~42.6-44.2°N)

The Central Oregon segment is captured by CASIE21 lines PD14-PD17 (**Fig. 11a**). ATZs are captured by PD13 and PD18 at either end of this segment where there are key structural features in common with adjacent wedge segments to the north and south (**Fig. 3**). The Central Oregon segment is uniquely characterized by a lack of an identifiable outer wedge domain based on changes in structural style and seismic character of the wedge (**Fig. 11b, Table 1**). Instead, the entire accretionary wedge in this segment resembles the inner wedge domain as observed in other segments. Other key structural features of this segment include evidence for underthrust

sediment, a shallower plate boundary decollement, and pervasive wedge-top slope failures (**Fig. 11**).

CASIE21 line PD14 represents the dominant structural style and seismic character within this segment (**Fig. 11b**). It is difficult to interpret subsurface structure in this profile due to the lack of coherent reflectivity, with seismic character ranging from semi-coherent near the toe of the wedge to mostly incoherent near the static backstop. The structural style is consistent throughout the accretionary wedge domain where seaward-verging thrust faults sole into a shallow plate boundary decollement with sediment underthrust beneath (Carbotte et al., 2024). The accretionary wedge in this segment is juxtaposed against the static backstop (Watt and Brothers, 2020) where the seismic character is incoherent and faults cannot be interpreted (**Fig. 11b**; light gray region). Bathymetric evidence does not provide evidence for continuous, major structural trends at the seafloor that can be traced along strike and linked to observed subsurface fault structure (**Fig. 11a**). Instead, the seafloor in this segment is chaotic, likely due to extensive slope failures in this region (e.g., Hill *et al.*, 2022) that potentially disrupt the near-surface expression of wedge faulting (**Fig. 11a,b**). Fault structures identified in adjacent segments do not extend into this segment based on wedge structure and seafloor morphology.

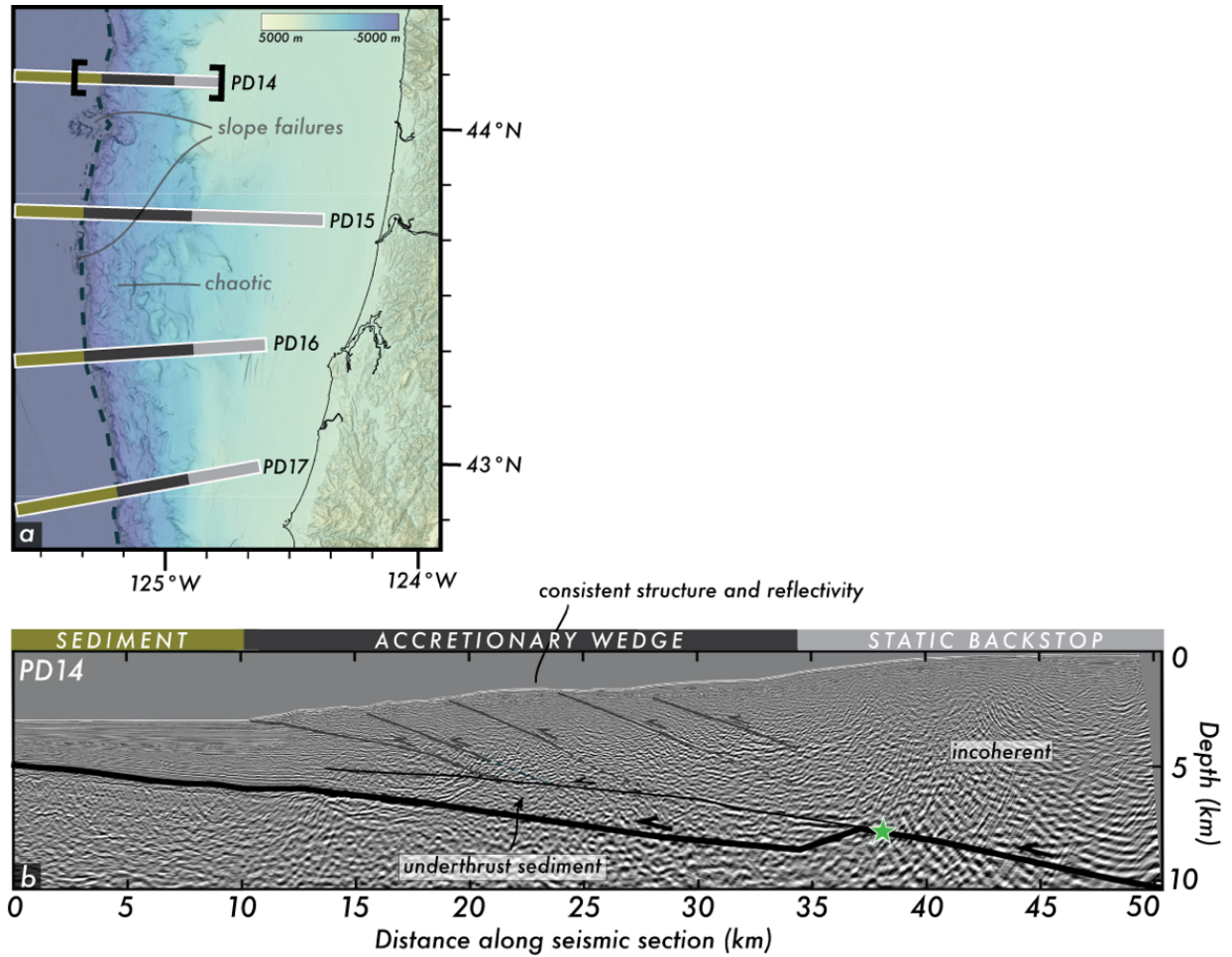


Figure 11. Central Oregon segment. **a.** Map of GMRT 50-m bathymetry showing location of line PD14. Symbology is the same as Fig. 5. **b.** CASIE21 seismic line PD14 with static backstop extent from Watt and Brothers (2020). Interpretation of underthrust sediment, plate hinge, and upper megathrust decollement from Carbotte et al. (2024).

1.3.5 Southern Oregon (~42-42.6°N)

The Southern Oregon segment is characterized by the re-emergence of an observable outer wedge domain (**Fig. 12**). The boundary between Central and Southern Oregon segments also appears to correspond with the projected trace of the Blanco Transform Fault System (**Fig. 3**; BTFS). The Southern Oregon segment exhibits an indentation of the wedge between lines PD18 and PD19 corresponding with the Rogue Propagator Shear Zone (RPSZ)(**Fig. 12a**). North of this indentation in PD18, there is a narrow, ~5 km wide outer wedge composed of two imbricated

seaward-verging thrust faults with mostly coherent reflectivity (**Fig. 12c**). Similar to faulting in the Central Oregon segment, these two outer wedge thrust faults are interpreted to sole into a shallower plate boundary decollement with sediment underthrust beneath (Carbotte et al., 2024). The IOWTZ in PD18 is ~7 km wide and composed of a single seaward-verging thrust sheet with mostly incoherent reflectivity (**Fig. 12c**). Within the inner wedge domain of PD18 it is difficult to interpret subsurface structure due to incoherent reflectivity. Some shallow fault structures are well-imaged; however, it is unclear how these structures sole into the subsurface. South of the wedge indentation, PD19 also exhibits a narrow ~5 km wide outer wedge characterized by 2-3 seaward-verging thrust sheets with coherent reflectivity that accrete the incoming sediment section (**Fig. 12e**). This differs from PD18 where sediment underthrusts beneath the outer wedge domain. The IOWTZ in PD19 is ~15 km wide and characterized by a structural gradient from mixed-verging thrust faulting to dominantly seaward-verging thrust faulting to the east. The observed structural gradient is accompanied by a gradient in the seismic character of the subsurface from mostly coherent to mostly incoherent reflectivity. The inner wedge domain in PD19 is characterized by incoherent reflectivity, which results in difficulty in interpreting subsurface structure at greater depths.

PD18 captures a prominent seafloor ridge associated with a seaward-verging thrust fault at the IOWTZ with a dip of 29° (**Fig. 12c**). This fault appears to be inactive because it is buried by a basin of apparently flat-lying sediments and is associated with a seafloor slope failure (**Fig. 12b**). Therefore, its activity is classified as inconclusive due to a lack of higher resolution seismic imaging at this location (**Fig. 12c**). However, an adjacent outer wedge fault appears to tilt basin sediments and may be recently active, but this fault requires further investigation with near surface data (**Fig. 12b**). Other IOWTZ and inner faults imaged in PD18 are interpreted near

the surface, but it is not clear if these faults are connected to the megathrust fault at depth due to a lack of coherent reflectivity (**Fig. 12c**).

In PD19, a landward-verging thrust fault at the IOWTZ is dipping at 38° (**Fig. 12e**). This fault appears to be overthrust onto an adjacent seaward-verging thrust fault, similar to the overthrust fault observed at the IOWTZ in PD12. This fault is a candidate out-of-sequence splay fault at the IOWTZ due to its apparent re-activation at the IOWTZ, connectivity with the megathrust fault at depth, and possible uplift of the seafloor (**Fig. 12d**). However, evidence for recent activity of this fault is inconclusive based on available data. Additionally, the length of this fault is only ~ 15 km and it is not connected to faulting north of the RPSZ based on its surface expression in the bathymetry and structural similarities with nearby faults in PD18 (**Fig. 12a**).

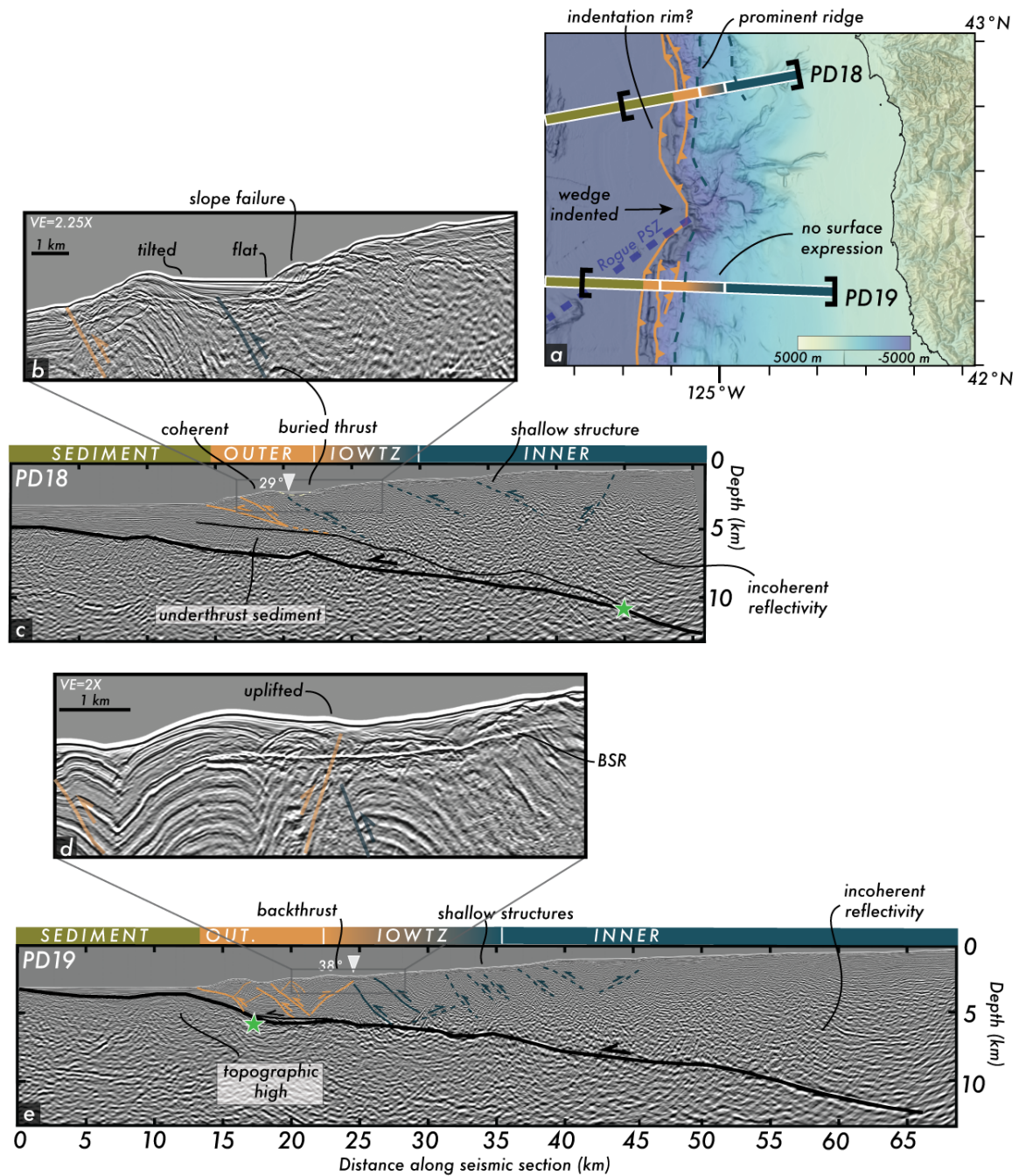


Figure 12. Southern Oregon segment. Symbolism is the same as Figure 5. **a.** Map of GMRT 50-m bathymetry showing locations of lines PD18 and PD19. **b-c.** CASIE21 seismic lines PD18 and PD19.

1.3.6 *Summary of Results*

Observations of IOWTZ structure, megasplay fault activity, outer wedge thrust fault vergence, and other key wedge structural features are used to define wedge segment boundaries (**Table 1**). Across the Northern and Central Vancouver Island segmentation boundary, thrust fault vergence of the outer wedge domain changes abruptly from landward to seaward, which appears to closely align with the Nootka Fault Zone (NFZ) (Rohr et al., 2018) (**Fig. 3, 4, 5**). A megasplay fault system is present along the Central Vancouver Island segment and has a prominent but discontinuous surface expression (**Fig. 5**). Between the Central Vancouver Island and Washington & Northern Oregon segments, the location of the segmentation boundary is uncertain due to a lack of seismic imaging between PD04 and PD05 (**Fig. 3**). This boundary may be gradational in nature due to the apparent lack of a major bounding structure, and therefore this area is defined as an ATZ at the segment boundary. The Washington & Northern Oregon segment is broadly defined by the extent of the wide outer wedge landward vergence zone that tapers at the northern and southern ends of the segment (**Fig. 3, 4, 6-9**). This segment is subdivided into three subsegments: Olympic (PD06-PD07), Astoria (PD08-PD09), Tillamook (PD10-PD12) based on transitions in faulting style and activity at the IOWTZ (**Table 1**). At the southern end of the Washington & Northern Oregon segment, there is an ATZ in PD13 where there is an outer wedge domain and underthrust sediment beneath the wedge, both key structural features of adjacent segments (**Fig. 9**). In the Central Oregon segment, no clear inner or outer wedge domains can be identified within the wedge (**Fig. 11**). Instead, there is a consistent structural style and seismic character throughout the entire accretionary wedge distinctly characterized by underthrust sediment and extensive wedge-top slope failures. In the Southern Oregon segment, a narrow outer wedge domain and corresponding IOWTZ re-emerges that is aligned with the

projected location of the Blanco Transform Fault System (BTFS) (Ren et al., 2023) and this segment is dissected by the Rogue Propagator Shear Zone (RPSZ)(**Fig. 3, 12**). An ATZ is defined between the BTFS and RPSZ at the location of PD18 in which underthrust sediment and a clear outer wedge domain is observed, which are key features of both the adjacent Central and Southern Oregon segments (**Table 1**). Overall, there are observable changes in wedge structure and faulting over relatively short along-strike distances (10s of kms), which enables clear delineation of regional-scale segmentation boundaries within the Cascadia accretionary wedge.

Segment name and latitudinal extent		CASIE21 lines	IOWTZ structure	Megasplay fault activity	Outer wedge thrust fault vergence	Key wedge structural features
Northern Vancouver Island (~49.2-49.6°N)		PD02	Relatively undeformed, possible megasplay structure	N/A	Landward	Landward vergence, possible slab tear
Central Vancouver Island (~48.3-49.2°N)		PD03-04	Megasplay fault system with prominent but discontinuous surface expression	Inconclusive	Seaward	Near-identical frontal thrust structure, megasplay faults
Washington & Northern Oregon (~44.2-48.3°N)	Olympic (48.3-47°N)	PD06-07	Megasplay faults buried by 1-2 km thick sediment	Negative	Landward-dominated mixed	Extensive and wide landward vergence zone
	Astoria (47-45.8°N)	PD08-09	Megasplay fault with prominent and continuous surface expression	Inconclusive to negative		
	Tillamook (45.8-44.2°N)	PD10-12	Active strike-slip and splay faults present at or near IOWTZ	N/A		
Central Oregon (~42.6-44.2°N)		PD14-17	N/A	N/A	N/A	Underthrust sediment, wedge-top slope failures, no outer wedge/IOWTZ domain
Southern Oregon (~42-42.6°N)		PD18-19	Possible megasplay fault structures	Inconclusive	Seaward-dominated mixed	Re-emergent outer wedge/IOWTZ domains

Table 1. Structural features used to define each along-strike accretionary wedge segment and subsegment. “N/A” indicates category is “not applicable” for given segment.

1.4 Discussion

1.4.1 Impact of wedge sedimentation on megasplay fault structural evolution and activity

Sedimentation onto the Cascadia accretionary wedge during the Pleistocene likely plays a major role in the wedge structural evolution and modern-day wedge structure. We suggest that variations in sedimentation onto the wedge along strike significantly contribute to the apparent segmentation of megasplay fault development and activity at the IOWTZ.

The rapid growth of the outer wedge domain in the Washington & Northern Oregon segment is thought to have begun at roughly 1.5 Ma during the early Pleistocene when large quantities of glacial sediment were deposited onto the offshore accretionary wedge (Flueh et al., 1998). Due to lower sea levels during Pleistocene glaciation, sediments were able to bypass the continental shelf, flow into submarine channels, and deposit directly atop the Cascadia accretionary wedge (J. Clark et al., 2014; Klotsko et al., 2021). This process formed the Astoria and Nitinat sedimentary fans which blanket the outer wedge region for the Washington & Northern Oregon segment (Underwood, 2002).

During the Miocene, prior to glacial sedimentation, we hypothesize that the wedge was in steady-state deformation, maintaining critical taper through sediment subduction and the addition of incoming sediment through accretion via seaward verging thrust faults and underplating (Dahlen, 1990)(**Fig. 13a**). It has been suggested that rapid outward growth of the wedge likely occurred in response to heavy influx of sediment resulting from glacial sedimentation of the central Cascadia region beginning in the Pleistocene (Adam et al., 2004; Simpson, 2010). This growth formed the modern-day inner-outer wedge boundary (i.e., IOWTZ) between the older, more deformed Miocene wedge and the younger, less deformed Pleistocene wedge (**Fig. 13b**). The rapid addition of new material to the wedge would result in the overall deformational style

of the wedge to transition from a steady-state to wedge-taper disequilibrium. The presence of disequilibrium structures during heavy sedimentation is predicted by mechanical models, which includes observations of buried structures, reduced wedge surface slopes, widespread wedge top basins, and increased thrust spacing (Simpson, 2010). We observe many of these disequilibrium features throughout the outer wedge domain of the Washington & Northern Oregon segment (**Fig. 3, 6-9**). Numerical models also show that when a stress barrier is present in the wedge, megathrust rupture tends to propagate up splay faults at this barrier (Wendt et al., 2009). The formation of the boundary between the inner and outer wedge during the Pleistocene created a major stress barrier in the wedge between the younger, less deformed, and therefore, weaker Pleistocene wedge and older, more deformed, and therefore, stronger Miocene wedge. This is likely the mechanism for the development of out-of-sequence megasplay faults at the IOWTZ throughout the Washington & Northern Oregon segment (**Fig. 13c**), despite the lack of evidence for recent activity on these faults (**Fig. 14**).

The rate and location of syntectonic sedimentation of accretionary wedges directly affects out-of-sequence megasplay fault evolution and activity (Mannu et al., 2016; Simpson, 2010; Strasser et al., 2009). Numerical models and real-world observations from these studies show that rapid sedimentation on the wedge can bury and deactivate out-of-sequence megasplay faults. Evidence that megasplay faults were once active is observed at the IOWTZ in PD06, PD07, PD09, and PD10 (**Figs. 6-7**); however, these megasplay fault structures are now buried by undeformed sediment and do not show evidence for late Quaternary activity (**Fig. 13d**). Deactivation of out-of-sequence faults due to high sedimentation rates has also been observed within Alaska, Makran, and Nankai accretionary wedges (e.g., Strasser et al., 2009, Mannu et al., 2016). The location of the potentially active megasplay fault structure at the IOWTZ captured by

PD08 may have experienced lower sedimentation rates than surrounding areas, resulting in sustained activity and uplift of this megasplay fault structure (**Fig. 13e**). Numerical models by Simpson (2010) and Mannu et al. (2016), along with observations from the Nankai accretionary wedge by Strasser et al. (2009), show that higher sedimentation rates correlate with faster seaward migration of the deformation front, and therefore, a more rapid growth of the outer wedge and reduced activity on out-of-sequence thrusts (**Fig. 13d**). Since the outer wedge in PD08 is narrower compared to the outer wedge to the north and south, this provides further evidence that sedimentation rates may have been lower in this location. Additionally, the active domain of the outer wedge, as defined by Ledeczi et al. (2024), also appears to narrow in the vicinity of PD08, supporting the conclusion for decreased frontal accretion in this location, with a preference for uplift on the identified out-of-sequence megasplay fault system (**Fig. 8**).

Submarine channels also appear to be routed around the convex-outward, bathymetric high corresponding with this megasplay fault system in PD08 (**Fig. 8, 14**). This indicates that the rate of megasplay fault uplift likely exceeds the rate of channel incision in this location, effectively routing sediments away from this structural high and further reducing sedimentation rates and sediment burial of this structure. The routing of sediment away from this structural high may have created a deformation-sedimentation feedback loop (McArthur et al., 2021; Noda et al., 2020) that promotes continued uplift on this fault. These findings showcase an important interplay between the surface processes of submarine channels, sedimentation rates, and fault-related uplift rates that controls whether an out-of-sequence fault remains active or becomes inactive. However, it is important to note that the mechanical response of the wedge to sedimentation is not immediate, and that response time depends on sedimentation rate (e.g., Mannu et al., 2016). This is a particularly important consideration in determining whether faults

are still deforming based on observations of modern-day wedge structure, as wedge deformation requires time to respond to sedimentation or a lack thereof. In PD11 and PD12, the outer wedge is narrow compared to areas further north and there is no evidence for a megasplay fault structure in this region (**Fig. 9**). This suggests that a megasplay fault did not activate in this region because of lower relative sedimentation rates that resulted in a narrower outer wedge. Due to the narrow outer wedge in this region, there is consequently a less effective stress barrier created between the inner and outer wedge, inhibiting the activation of out-of-sequence faulting at the IOWTZ.

Other regions of the Cascadia margin did not experience the same levels of glacial sediment deposition as compared to Washington & Northern Oregon segment; therefore, a wide outer wedge did not form in these regions. In the Northern & Central Vancouver Island segments captured by PD03 and PD04, a narrow outer wedge is observed. This narrow wedge is not sufficient in creating a stress barrier necessary that would promote megasplay fault rupture. Similarly, in the Central Oregon segment, clear inner or outer wedge domains cannot be distinguished based on seismic character and structural style (**Fig. 11**). This indicates that there was only modest accretion of sediments during the Pleistocene in this region and hence no stress barrier was created between the inner and outer wedge that would result in the development of an out-of-sequence megasplay fault system as observed in the Washington & Northern Oregon segment. The wedge in this segment likely resembles the Miocene wedge prior to accretion of the wide outer wedge domain in the Washington & Northern Oregon segment during the Pleistocene and may be akin to the modern-day inner wedge of adjacent regions. This conclusion is further supported by the similarity in structure between the modern wedge of the Central Oregon segment and the inner wedge domain of other segments along strike, which is

characterized by a series of imbricated, seaward-verging thrust faults and mostly incoherent seismic character.

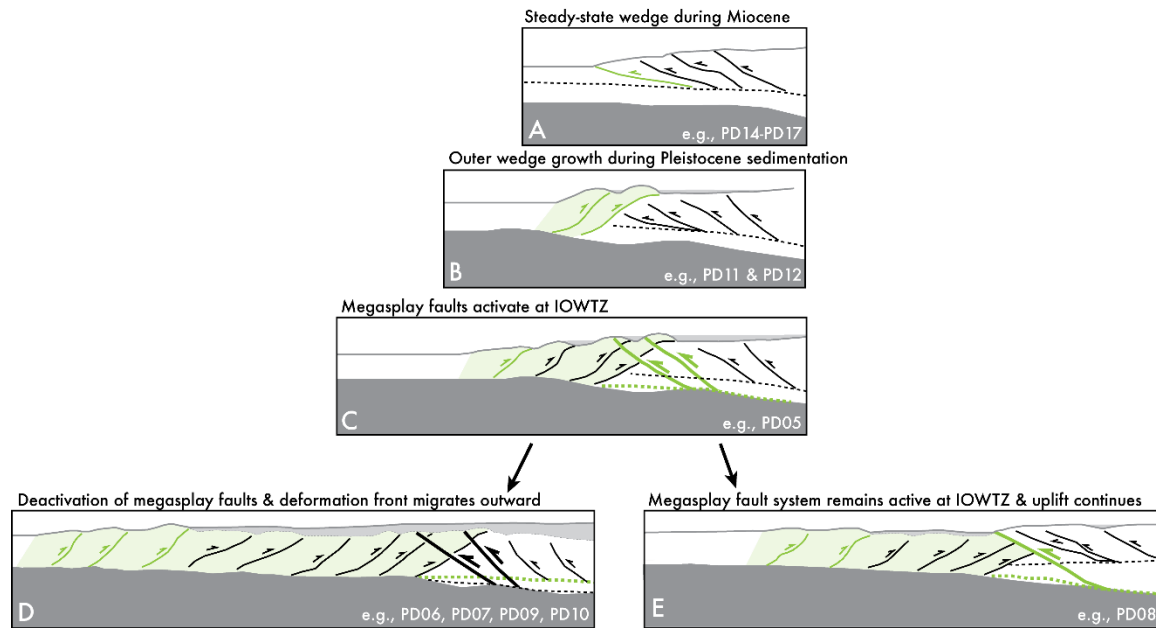


Figure 13. Schematic figure showing a simplified representation of the development and evolution of megasplay faulting in Cascadia. **A-E.** Simplified diagrams based on observed accretionary wedge illustrating the hypothesis for how megasplay faulting would develop and remain active or become inactive due to sedimentation. Green lines represent active structures, and black lines represent inactive structures. White domains represent the inner wedge, and green domains represent the outer wedge. Seismic lines that were used to develop the diagrams are noted in the lower left corner of each picture. Bolded lines show megasplay faults. Dotted lines represent decollements above top of crust. Solid gray represents the Juan de Fuca plate.

1.4.2 Influence of subducting topography on accretionary wedge evolution

We suggest that the development of an outer wedge domain and activation of megasplay faults at the IOWTZ in the Northern and Central Vancouver Island segments and the Southern Oregon segment may be controlled by subducting topography on the downgoing plate. Analogue

sandbox experiments show that seamount subduction can result in the outward growth of the wedge and development of out-of-sequence thrust faults between the older and younger wedge domains (Dominguez et al., 2000). The subduction of local topography offshore the Vancouver Island and Southern Oregon regions associated with propagator wakes and shear zones on the downgoing plate (Carbotte et al., 2024; Hutchinson et al., 2023; Nedimović et al., 2009; Wilson, 2002) may provide a mechanism for the outward growth of the wedge in these regions that does not require the same levels of glacial sedimentation as suggested for the formation of the wide outer wedge domain in the Washington & Northern Oregon segment. Dominguez et al. (2000) show out-of-sequence faults are observed to form in the older, more cohesive domain of the wedge. As predicted by Dominguez et al. (2000), out-of-sequence megasplay faulting associated with subducting topography, observed in PD03 and PD04, primarily occurs within the more cohesive inner wedge domain at the IOWTZ (**Fig. 5**). In PD04, the development of out-of-sequence, megasplay faults at the IOWTZ is co-located with rough subducting topography of a propagator shear zone (**Fig. 5c**). In PD03, although significant topography is not observed on the downgoing plate at the IOWTZ (**Fig. 5b**), this line is located along the indentation rim of the “shadow zone” that likely formed due to subducting topography captured in PD02 (**Fig. 5a**). Modeling of seamount subduction from Dominguez et al. (2000) shows that the rim of the shadow zone will also exhibit out-of-sequence megasplay fault activation at the IOWTZ in addition to the location where the local topography itself is being subducted. There is not sufficient seismic and bathymetric evidence to conclusively determine whether there is active megasplay faulting in PD02; however, out-of-sequence splay faulting is likely present in this area and evolving in response to the regional subduction of the topography. Similar to how the

wedge responds to sedimentation loads, the wedge structure may require time to respond to the subduction of lower plate topography.

At the Southern Oregon segment, topography associated with the RPSZ is subducting beneath the wedge (Carbotte et al., 2024; Chaytor et al., 2004). It is also important to consider that, at longer topographic wavelengths, the more buoyant crust of the Gorda plate is subducting in this region along with shorter wavelength topography associated with the RPSZ. In the Southern Oregon segment, the re-emergence of an outer wedge domain and an ATZ is observed in PD18 that defines the segment boundary between Central and Southern Oregon (**Fig. 3, 12**). Subducting topography is not associated with the formation of the outer wedge domain in PD18 (**Fig. 12b**), but the formation of the outer wedge in PD18 could be due to a similar “indentation rim” process as suggested for PD03 (**Fig. 5**). This formation may also be due to longer wavelength topography associated with the Gorda plate. The local re-emergence of an outer wedge domain might also be due to a gradational response in wedge structural style across a major segmentation boundary in the wedge at the ATZ in the region of PD18. In PD19, a major topographic high is observed at the deformation front which appears to be in an initial stage of subduction beneath the wedge (**Fig. 12c**). Dominguez et al. (2000) show that in addition to the development of an outer wedge prominent backthrusts will also develop at this early stage of seamount subduction. In PD19, a landward verging backthrust dipping at 38° is observed (**Fig. 12c**; white arrow), consistent with this prediction. Dominguez et al. (2000) find that major out-of-sequence thrust faults due to subduction of topography do not appear to develop until later stages of seamount subduction. This could demonstrate how subducting topography in this location may have been sufficient to spur the development of an outer wedge domain and backthrusts, but not yet have led to the full activation and development of megasplay fault

structures as is observed in the Central Vancouver Island segment. This could indicate that out-of-sequence faults may develop in this location in the future over the course of outer wedge development and seamount subduction on a longer timescale.

1.4.3 Linking accretionary wedge structure with margin segmentation

Variability in accretionary wedge structure and morphology at convergent plate boundaries has been linked to segmentation of lower plate structure and megathrust fault behavior (Cook et al., 2014; H. Kopp, 2013; McNeill & Henstock, 2014). Here we aim to link our observations of accretionary wedge structure and megasplay fault activity at the IOWTZ to prior observations for segmentation of the Cascadia subduction zone based on subducting plate structure (Carbotte et al., 2024) and morphotectonic variability (Watt and Brothers, 2020).

At the Nootka Fault Zone, Carbotte et al. (2024) found that the downgoing plate is deeper and more steeply dipping compared to surroundings. To the east of the Nootka Fault Zone, they observe a relatively shallower downgoing plate dip near the deformation front, delineating a clear segmentation boundary in lower plate structure. This segmentation in lower plate structure at the Nootka Fault Zone was previously linked to a structural and morphologic transition in the accretionary wedge, with a sharp bend observed in the overall trend of the deformation front (Watt and Brothers, 2020). This fault-controlled segmentation boundary is linked to a clear transition in outer wedge structural style from dominantly landward-verging thrust faulting in the Northern Vancouver Island segment to mixed-seaward-verging thrust faulting in the Central Vancouver Island segment (**Fig. 5, Table 1**). Additionally, megasplay fault structures observed at the IOWTZ in CASIE21 lines PD03 and PD04 do not connect across this segmentation boundary (**Fig. 14**).

At $\sim 47^\circ\text{N}$, and the boundary between the Olympic and Astoria subsegments, the North and South Nitinat strike-slip faults cross the deformation front and are expressed in both the upper and lower plate (Goldfinger et al., 1997) (**Fig. 14**). Using CASIE21 seismic profiles, Carbotte et al. (2024) find these faults to extend across the margin beneath the continental shelf where the fault system offsets basement rock by over 1 km. These faults are found to be coincident with a seaward step in the Siletz terrane and a local seaward step in the location of the dynamic backstop from Watt and Brothers (2020) (refer to “dynamic backstop” in **Fig. 1**). At the location where these faults cut across the wedge, there is evidence in CASIE21 line PD08 for a potentially active megasplay fault zone associated with a sharp and distinctively convex-outward boundary between the inner and outer wedge domains (**Fig. 8**). The location of this fault system is associated with an increase in seafloor elevation, a steepening of the downgoing plate dip (refer to “plate hinge” in **Fig. 8**), and a shallowing of the plate boundary decollement (**Fig. 8**). We propose that subducting topography in the lower plate related to the North and South Nitinat strike-slip faults is linked to the localized activity and uplift of this megasplay fault structure at the IOWTZ. This hypothesis is further supported by the presence of active listric normal faults in the upper slope of the margin in this region (**Fig. 7b, 8a**) (McNeill et al., 1997; Watt & Brothers, 2020) that could potentially be the result of extensional collapse within the hanging wall of the megasplay fault system due to subducting topography and associated fault uplift. A similar process has been observed at the Hikurangi subduction zone where relief on the subducted Pacific plate has been linked to out-of-sequence activity of the Lachlan thrust fault system and subsequent development of listric normal faults (Barnes et al., 2002).

Shallowly dipping inner wedge thrust faults appear to sole into a shallower decollement within the hanging wall of the proposed megasplay fault system (**Fig. 8b**). This further implies that

preferential uplift has occurred on this megasplay fault structure at the IOWTZ and that uplifted inner wedge material has been underplated to the base of the wedge (**Fig. 13e**). An alternative explanation could be that these shallowly dipping faults developed within the upper plate along an upper-level decollement. However, these faults are not associated with significant topography at the seafloor that would suggest that this occurred (**Fig. 8b**). A similar process to that proposed for PD08 has also been observed at the north Ecuador-south Colombia subduction margin where sediment underplating to the base of the inner wedge is associated with out-of-sequence activation of splay faults at the inner-outer wedge boundary and broad uplift of the inner wedge domain through slip on this splay fault system over multiple earthquake cycles (Collot et al., 2008).

Between 46.5°N and 44.5°N, there is a marked change in the lower plate geometry characterized by a steepening of the downgoing plate dip (Carbotte et al., 2024). The width of the outer wedge narrows southward through this region, starting near the boundary between Watt and Brothers (2020) morphotectonic regions 2&3 and the Willapa Canyon Fault Zone, until the boundary between the Washington & Northern Oregon and Central Oregon segments. South of this apparent segmentation boundary, starting at PD10, faulting style at the IOWTZ is observed to change from compressional to transform moving south along the margin (**Fig. 7, 14**). This change in faulting style at the IOWTZ defines the Tillamook subsegment boundary from PD10-12 within this segment (**Table 1**). South of PD10, a megasplay fault style structure is not present at the IOWTZ. At the location of the Wecoma Fault and the secondary morphotectonic segment boundary from Watt and Brothers (2020)(**Fig. 13**; purple dotted line), the outer wedge domain increasingly narrows and thrust fault vergence changes from dominantly landward-verging to seaward-verging and strike slip-fault activity appears to cease through this region until the ATZ

captured by PD13 (**Fig. 3, 7, 14, Table 1**). This may illustrate a potential mechanical trade-off between margin-parallel and margin-perpendicular strike-slip faults in the accommodation of shear strain related to oblique convergence in this region. Overall, we suggest that segmentation due to lower plate faults likely exerts a primary control on megasplay and other out-of-sequence splay fault activity within the accretionary wedge of this region and overall wedge morphology.

In some locations along the margin, the IOWTZ corresponds with the position of a gradual to sharp increase in the dip of the downgoing Juan de Fuca plate, or plate hinge (**Figs. 5-9, 11, 12**). In particular, for CASIE21 lines where active out-of-sequence faulting is observed within the IOWTZ, the plate hinge is located near the base of these faults (e.g., PD08, PD10, PD11). This spatial relationship suggests that variations in accretionary wedge structure and geology are directly related to variations in the dip of the downgoing plate. However, the underlying processes controlling this proposed relationship are yet to be determined. Carbotte et al. (2024) suggests that, due to the weak, warm and hence buoyant nature of the Juan de Fuca plate related to its relatively young age, lower plate bending may be more sensitive to change in the strength and density of the overlying plate such as the transition from the younger outer to older inner wedge domains. Accretionary wedge faulting likely also responds to changes in the dip of the downgoing plate because the change in plate dip could effectively act as a stress barrier to the propagation of megathrust slip towards the trench. Recent numerical modeling of megathrust fault ruptures has shown that fault dip and curvature are primary controls on rupture propagation and segmentation as well as earthquake recurrence rates (Biemiller et al., 2024). Therefore, the observed change in plate dip and high curvature at the plate hinge location could potentially promote megasplay fault activation at the IOWTZ.

1.4.4 Re-evaluation of splay fault rupture scenarios for Cascadia and implications for future hazard modeling

Prior to this study, it had been widely proposed (or assumed) that an active megasplay fault exists at the IOWTZ in Cascadia spanning continuously from Vancouver Island to Oregon (e.g., Priest *et al.*, 2009; Witter *et al.*, 2013; Gao *et al.*, 2018; Lotto *et al.*, 2019; Sypus, 2019). Earthquake and tsunami hazard assessments developed from simulated rupture on this hypothetical fault, specifically the L1 splay fault scenario, have been routinely included in models underlying numerous hazard assessments for the Cascadia region (e.g., Lee, 2017; Morkner, 2019; Dolcimascolo *et al.*, 2022; Bernard, 2023; La Selle *et al.*, 2024). Using new CASIE21 MCS and USGS sparker seismic profiles along with GMRT 50-m and USGS 30-m bathymetry compilations, the IOWTZ between the inner and outer wedge domains was located and fault structure was analyzed in this zone from Vancouver Island to Oregon. Results indicate there is not sufficient evidence to support the hypothesis for an active, through-going megasplay fault system at the IOWTZ along the Cascadia subduction zone margin spanning the region between latitudes 44° and 50°N. Instead, megasplay fault structure and activity in Cascadia is highly variable and segmented along strike. Furthermore, positive or inconclusive evidence of a recently active major out-of-sequence splay fault is only present in a few isolated regions along strike at the IOWTZ (**Fig. 14**). This has major implications for the likelihood of the L1 and other megasplay scenarios as a significant tsunami source (e.g., Witter *et al.*, 2013).

Synthesizing our results, a map of simplified megasplay fault structure and activity at or near the IOWTZ is presented, focused on the region of the previously proposed active, margin-spanning megasplay fault from Witter *et al.* (2013) (**Fig. 14**). Through joint analysis of multiple marine geophysical datasets, most megasplay fault structures at the IOWTZ are discovered to

either have inconclusive or negative evidence for recent activity. Therefore, it is unlikely that the L1 scenario represents plausible future Cascadia megathrust earthquakes, except in some strike-limited locations. This result demonstrates how more comprehensive, high-resolution seismic surveying and seafloor mapping of the Cascadia accretionary wedge can help clarify how faults connect through space between seismic lines and characterize the expression of active faulting at the seafloor. More comprehensive surveying and mapping could ultimately improve our understanding of which faults have slipped in past Cascadia earthquakes and which faults might slip in future earthquakes. Such work is crucial for accurately quantifying tsunami hazard and risk along the Pacific Northwest coast.

Incorporating the segmented nature of accretionary wedge splay faulting at the IOWTZ into modeling efforts could help quantify earthquake and tsunami hazards at the Cascadia subduction zone. Regional scenarios could include different styles and locations of splay fault rupture. In the Central Vancouver Island segment between latitudes 48° and 49.5°N , megasplay fault rupture on a system of seaward-verging thrust faults with an average dip of $\sim 40^{\circ}$ is likely at the IOWTZ in addition to frontal thrust rupture (**Fig. 5, 14**). In the Washington & Northern Oregon segment, rupture on multiple splay faults at the toe of the wedge near the deformation front should be primarily examined based on evidence for late Quaternary activity of splay faults (Ledeczi et al., 2024). Localized scenarios could also be modeled, including rupture on an isolated seaward-verging megasplay fault dipping at $\sim 30^{\circ}$ as identified in CASIE21 line PD08 in the region offshore Grays Harbor, Washington between 46.5° and 47°N (**Fig. 7, 8, 14**), or rupture on the system of active right-lateral strike-slip faults identified in CASIE21 lines PD10, PD11, and PD12 between 45° and 46°N spanning roughly from Seaside to Newport, Oregon (**Fig. 9, 14**).

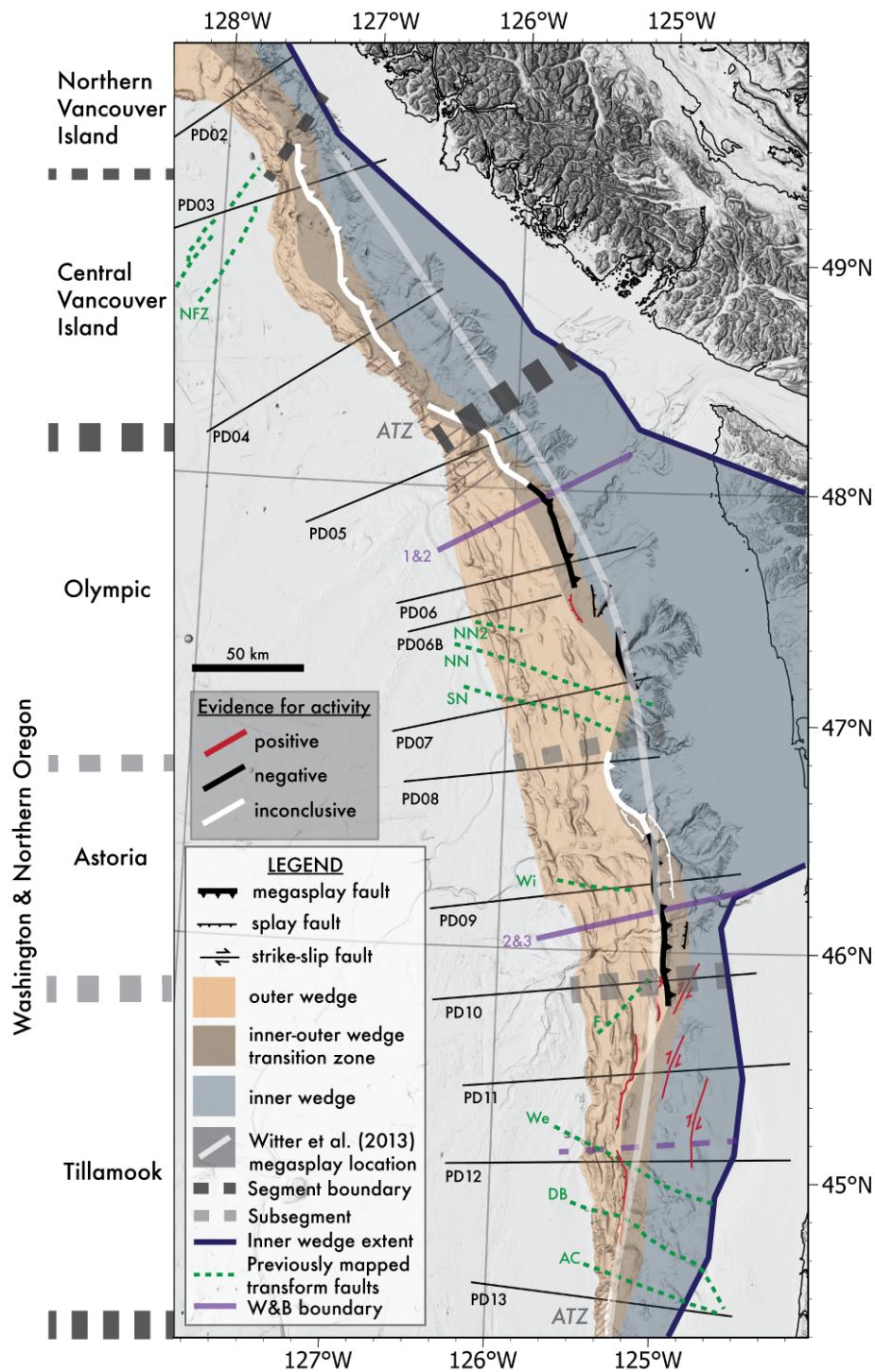


Figure 14. Map showing extent of inner (blue) and outer (orange) wedge domains in the accretionary wedge and the transition zone (blueish orange) between these domains as determined using CASIE21 seismic reflection images. These domains correspond with domains

identified in seismic cross-sections shown in Figure 3. Splay faults at the IOWTZ are shown. Bold faults represent megasplay faults in this zone and non-bolded faults represent splay faults. Strike slip faults are represented with dotted lines. Different colors represent our analysis of fault activity: red indicates faults with positive evidence of late Quaternary activity, black indicates faults with negative evidence of late Quaternary activity, and white indicates inconclusive evidence for late Quaternary activity given our analysis of current datasets (this study and Ledeczi et al., 2024).

1.5 Conclusions

Overall, although megasplay fault structures exist and may be locally active at the IOWTZ in a few locations along strike, we find that there is not sufficient evidence supporting the previously proposed hypothesis for an active, margin-spanning megasplay fault system in Cascadia (e.g., Witter et al., 2013). Instead, the structure and activity of faulting at the IOWTZ is highly variable and segmented along-strike, consistent with the segmentation of other physical and mechanical properties at the Cascadia subduction zone (Adam et al., 2004; Booth-Rea et al., 2008; Carbotte et al., 2024; Han et al., 2018; Underwood, 2002; Walton et al., 2021; Watt & Brothers, 2020). Megasplay fault formation and segmentation is controlled by numerous factors, including margin lithology and strength, wedge sedimentation, sediment accretion, subducting topography, and changes in downgoing plate dip. The substantial variations in megasplay fault structure and activity along-strike presented in this study have important implications for earthquake and tsunami hazard at the Cascadia subduction zone. Through our comprehensive analysis of the CASIE21 and USGS sparker seismic reflection profiles along with the best available resolution of bathymetry, we conclude:

There is no evidence to support the previously proposed hypothesis for an active, margin-spanning megasplay fault system at the IOWTZ in Cascadia.

Megasplay fault structures exist but are only locally active at the IOWTZ at a few, relatively isolated locations along strike.

Sedimentation onto the wedge surface likely plays a primary role in megasplay fault activation (or lack thereof) and evolution at the Cascadia subduction zone, while subducting topography may also influence out-of-sequence faulting in specific, relatively localized regions.

Downgoing plate dip is linked to regional-scale variations in upper-plate architecture, with increasing downgoing plate dip appearing to correspond with the position of the IOWTZ in many locations along strike as identified in CASIE21 seismic profiles.

Future modeling studies for Cascadia could incorporate megasplay fault location, geometry, and activity as presented in this study.

2. **Chapter 2:** Distributed Shearing in Accretionary Wedge

Accommodates Oblique Convergence at the Cascadia Subduction Zone

Submitted as: Lucas, M. C., Beeson, J., Watt, J. T., Ledeczi, A. M., Orange, D., Tobin, H. J.

Distributed shearing in accretionary wedge accommodates oblique convergence at the Cascadia subduction zone. Geophysics, Geochemistry, Geosystems (G-Cubed), February 2026 (in review).

Abstract

Shear strain resulting from oblique subduction is commonly accommodated along trench-parallel strike-slip fault systems, a relationship documented in numerous oblique subduction zones worldwide. However, we have a limited understanding of how these strike-slip fault systems initiate, localize, and evolve through time, primarily due to the challenge of identifying such tectonic features, especially in offshore settings. Furthermore, where a major trench-parallel strike-slip fault is not present, but oblique convergence occurs, it still remains unclear how shear strain is accommodated. At some subduction margins, such as the Cascadia subduction zone, it has been proposed that, instead, strike-slip faults oriented sub-perpendicular to the trench work to accommodate shear strain due to oblique convergence from clockwise block rotation. Here we present new observations from recent high-resolution seismic reflection and multibeam bathymetry surveys that reveal an active, trench-parallel strike-slip fault system within the Cascadia accretionary wedge, hereafter the Albatross Fault System. The Albatross Fault System is localized along the outer arc high between major lithologic terrane boundaries within the

accretionary wedge. Seep clustering along the fault trace suggests the fault zone acts as a conduit for fluid flow to the seafloor from depth. Close proximity of the Albatross Fault to the trench implies plate interface slip occurs subparallel to the subduction margin. Evidence of Holocene deformation along this fault system suggests that a portion of the oblique component of shear strain due to convergence at the Cascadia margin, and is accommodated through distributed Riedel-type shearing along multiple strike-slip faults of different orientations and slip sense.

2.1 Introduction

2.1.1 Accommodation of oblique convergence at subduction margins

Trench-parallel shear strain due to oblique plate convergence at subduction zones is typically modeled by strain partitioning among strike-slip faults within the upper plate (Fitch, 1972). Well-known examples of major trench-parallel strike-slip fault systems at oblique subduction zones include the Sumatran Fault (Sieh & Natawidjaja, 2000), the Atacama Fault (Brown et al., 1993), the Southwest Kuril forearc sliver (Kimura, 1986), the Lesser Antilles (Bénâtre et al., 2025), among others. These strike-slip fault systems tend to develop at subduction zones where there is a high angle of oblique convergence (greater than 25-30°) (Beck, 1983; Platt, 1993). The formation of trench-parallel fault systems creates a distinct forearc sliver that is bounded by the fault and the main subduction thrust (Jarrard, 1986). Trench-parallel strike-slip fault systems host lateral slip in the direction consistent with the shear component of oblique plate convergence, which can vary along strike and modulate forearc structure (McCaffrey, 1992). Analogue and numerical modeling has shown that the degree of convergence obliquity and backstop geometry controls the development, localization and evolution of trench-parallel strike-slip faulting (Beck et al., 1993; Wang, 1996). However, some oblique subduction

zones do not exhibit trench-parallel strike slip faulting as predicted by these models, and the degree of subduction obliquity is not directly predictive of forearc sliver faulting (Morell et al., 2025). Consequently, the mechanism for shear strain accommodation and partitioning at these oblique subduction margins remains poorly understood. Here, we advance our understanding of how shear strain is accommodated in Cascadia, an oblique subduction margin (with obliquity $>20^\circ$) where no major trench-parallel strike slip fault system has been identified.

2.1.2 Oblique subduction at the Cascadia margin

The Cascadia subduction zone (**Fig. 1a**) is an example of an oblique subduction zone that lacks a major trench-parallel strike slip fault system. At Cascadia, the Juan de Fuca and North American tectonic plates are converging at a rate of 30-40 mm/year (DeMets et al., 2010; Fig 1a, white arrow) with an obliquity angle that varies substantially along strike (McCaffrey et al., 2007) from 0° to greater than 45° (e.g., Wang et al., 1997; Morell et al., 2025). Modeling of the stress field at the margin predicts a major component of trench-parallel shear due to oblique subduction along the margin until convergence becomes mostly compressional at a prominent westward bend in the deformation front at 48°N (Wang, 1997, Morell et al., 2025; Fig 1a, “bend”). Offshore northern California, numerous trench-parallel strike-slip faults within the upper plate have been shown to participate in strain partitioning due to complex plate kinematics at the Mendocino Triple Junction (McCrory, 2000; Nuyen & Schmidt, 2022). However, north of 42°N in central Cascadia, no active trench-parallel strike-slip faulting has been observed. Instead, it is widely accepted that oblique convergence in central Cascadia ($44\text{-}48^\circ\text{N}$) is accommodated by a series of WNW left-lateral strike-slip faults within the upper plate that are sub-perpendicular to the trench (**Fig. 1a**; Appelgate et al., 1992; Goldfinger, 1994; Goldfinger et al., 1997). Goldfinger et al. (1997) applies a Riedel shearing model to their structural map of the

offshore Washington and Oregon margin and categorize identified WNW left-lateral faults as antithetic R' shears. They also find that there is limited evidence for the existence of distinct trench-parallel faults, such as R and P shears, although they do observe a zone of folding at the edge of the Siletzia terrane that could suggest trench-parallel dextral shearing at depth. Overall, the study concludes that oblique subduction in central Cascadia is almost entirely accommodated by clockwise rotation of blocks bounded by margin-perpendicular WNW left-lateral strike-slip faults.

Deformation and faulting have been documented in our study region within central Cascadia (**Fig. 1a**). Earlier work by Snively (1987) identified the Fulmar fault (**Fig. 1a**; purple dashed line), a N-S system of right-lateral strike slip faults running parallel to the trench, spanning from 43-45°N offshore central Cascadia and measuring a total estimated cumulative offset of 200 km. These observations would be consistent with modeling predictions for trench-parallel accommodation of shear strain (e.g., Wang, 1997, Morell et al., 2025), however, Snively (1987) concluded that the majority of slip on the Fulmar Fault occurred from the late middle Eocene to the late Eocene and that the fault is no longer active based on interpretation of undeformed Quaternary sediments overlying the fault system. Subsequent studies, however, found limited evidence of deformed Quaternary sediments near the fault at the edge of the Siletzia terrane (Tréhu et al., 1995; Witter et al., 2003; Goldfinger et al., 2023), alternatively suggesting the Fulmar Fault is still active. While the activity of this fault has yet to be examined systematically using modern high-resolution marine geophysical datasets, observations of basinal growth strata surrounding two prominent structural highs offshore central-northern Oregon suggest the outer arc high uplifted in the early-mid Pliocene (McNeill et al., 2000; Watt & Brothers, 2020), indicating more recent deformation of this region. McNeill et al. (2000)

hypothesize that the outer arc high could represent a structural boundary against which the mid-Pliocene to Pleistocene wedge was accreted, as well as a stress boundary where principal stress direction changes from convergence-normal to arc-parallel. The outer arc high also coincides with the location of the Fulmar Fault (**Fig. 1a**), further indicating a persistent boundary in both wedge structure and stress localization at this location (Watt & Brothers, 2020).

2.1.3 Study motivation and overview

Recent work by Lucas et al. (2025) used new seismic and bathymetric datasets to identify the Albatross fault system, a system of en echelon right-lateral strike-slip faults spanning between 45-46°N that trend parallel to the trench (**Fig. 1a-c**). This fault system is located primarily within the inner wedge domain between the outer wedge and the crystalline continental backstop. These preliminary findings indicating the presence of a potentially Holocene-active fault system motivated the acquisition of higher resolution marine geophysical data during expedition SR2414 along the seafloor fault scarp (**Fig. 1c**, black arrows). Through joint interpretation of our newly compiled 15-meter multibeam bathymetry grid along with new high-frequency *Kongsberg* sub-bottom profiler (SBP29), USGS sparker, and CASIE21 multi-channel seismic images in the region of the Albatross fault system, we map seafloor morphology and subsurface structure associated with the fault system in unprecedented detail (**Fig. 1b-c**). These new geophysical datasets reveal evidence for Holocene deformation across the fault, which helps us understand how the Albatross fault system accommodates shear strain due to oblique convergence at the Cascadia subduction zone.

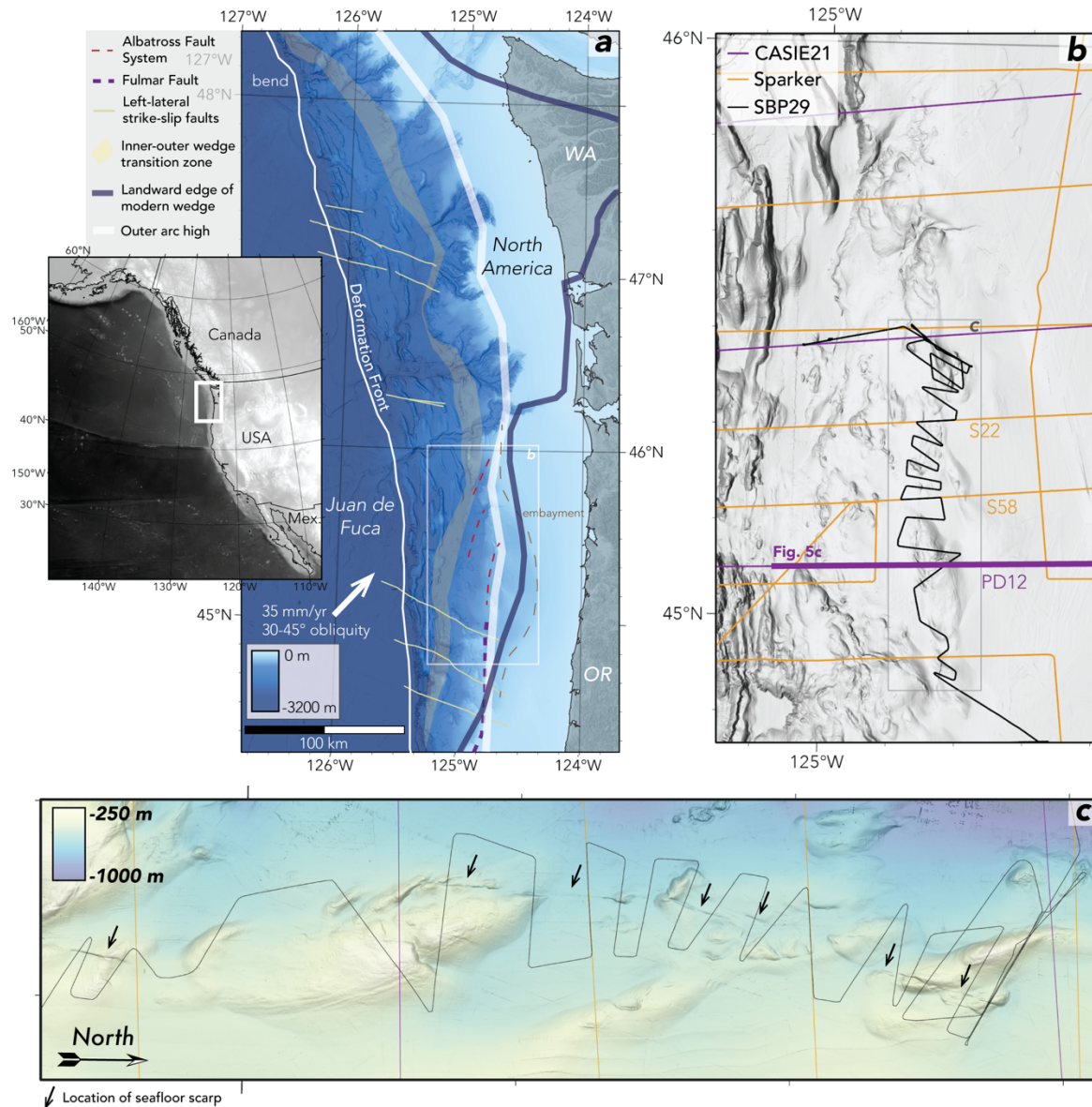


Figure 1. Tectonic setting & new geophysical data. **a.** GMRT 50-m bathymetry offshore Washington and Oregon with global inset for reference (Ryan et al., 2009). Thick blue lines indicate landward edge of modern Cascadia accretionary wedge; light yellow shaded regions indicate inner-outer wedge transition zone (IOWTZ) (Lucas et al., 2025); thin white line indicates deformation front; thick white line indicates outer arc high (Watt & Brothers, 2020). Yellow lines indicate WNW-trending left-lateral strike slip faults (Goldfinger, 1994; Goldfinger et al., 1997); thick purple dashed line indicates Fulmar fault location (Snively, 1987). Juan de Fuca–North American plate convergence rate from DeMets et al. (2010). **b.** Hillshaded USGS 30-meter bathymetry (J. Beeson et al., 2025; Dartnell et al., 2021, 2023) with line locations from CASIE21 (MGL2104), USGS sparker, and SBP29 (SR2414) seismic surveys in the study region. **c.** Detailed map of SR2414 survey line locations across the prominent scarp of the Albatross fault system. Black arrows point to the location of the scarp at the seafloor.

2.2 Data and Methods

2.2.1 Marine geophysical data acquisition and processing

For this investigation, we integrate newly acquired 15-m bathymetry and SBP29 data with existing sparker and crustal-scale seismic data to map and characterize faulting at the Albatross fault system. SBP29 seismic reflection data (e.g., Holland et al., 2025; Orange et al., 2021) was acquired via the *R/V Sally Ride* research vessel using the *Kongsberg* hull-mounted SBP29 system with a frequency range that linearly sweeps down from 9000 to 2000 Hz. We used a pulse length of 100ms with a ping interval calculated based on water depth, and a source power of 215dB with the full-array of the SBP29 system employed for transmitting and receiving of instrument pings. The data spans the upper 100 meters of the subsurface, providing high resolution seismic reflection imaging of stratigraphic and structural geometries near the surface, including Quaternary to Holocene age sediments. In post-acquisition, we applied a time-variable gain to the SBP29 data to strengthen deeper reflections. To supplement near-surface SBP29 imaging, we use 8 primary dip lines of sparker seismic data acquired by the U.S. Geological Survey (Balster-Gee et al., 2023) to map fault structure in the upper 1 km of the subsurface. We also evaluate 4 primary dip lines of ultra-long offset multi-channel seismic (MCS) data from the CAscadia Seismic Imaging Experiment 2021 (CASIE21) (Carbotte et al., 2021, 2023) which were post-stack depth-migrated by *ION Geophysical*. Deep seismic imaging allows us to characterize fault structure to depths greater than 10 km and evaluate fault interactions with nearby geologic terrains (e.g., Siletzia) and accretionary wedge domains such as the inner-outer wedge transition zone (**Fig. 1a**; Lucas et al., 2025). All seismic data were then viewed and analyzed using *Kingdom Suite* seismic interpretation software, and only an exemplary subset of

the analyzed seismic lines is presented in this study. Finally, we use 30-meter resolution multibeam bathymetry data (Dartnell et al., 2021, 2023, Beeson et al., 2025) to link subsurface observations from 2D seismic reflection imagery to the surface expression of faulting at the seafloor. During SR2414, multibeam bathymetry, backscatter, and water column data were acquired over the main strand of the Albatross fault system via the *R/V Sally Ride* using the hull-mounted 12kHz 1°x2° EM124 system. Using this new data, we compiled a new 15-meter resolution bathymetry grid using *Qimera*, *Fledermaus*, and *MB-System* bathymetric processing software. By utilizing multiple types of geophysical imaging at different scales, we are able to gain a detailed spatial understanding of fault geometry and activity from the plate interface up to the seafloor.

2.2.2 *Methods for identifying evidence of Holocene fault activity*

To identify stratigraphic and structural evidence for Holocene fault activity, we infer the Pleistocene-Holocene (P-H) boundary in SBP29 profiles based on an abrupt change in the seismic character of sedimentary horizons. Poor layering of the Holocene deposits indicates clay and silt-rich sediment, while well-layered Pleistocene deposits indicate interbedded glacial deposits of sand, gravel, and clay. The sharp contact between the Pleistocene and Holocene epochs is well documented from sediment coring along the Cascadia margin, with a best-estimated age of ~12,800 cal yr B.P. (Goldfinger et al., 2012). The P-H stratigraphic boundary exhibits a sharp color and faunal change that Goldfinger et al. (2012) attributes to a loss of glacially-derived sediments to the margin. This sharp contact is consistent with our observations of the P-H boundary based on a sharp change in seismic character. Additionally, the P-H boundary identified in SBP29 data is a persistent feature across multiple seismic images at different locations along the Albatross Fault System (**Fig. 3**).

To confirm evidence for Holocene fault activity, we combine structural observations of subsurface faulting with geomorphic observations of faulting at the seafloor. Where a fault strand vertically offsets sediments of inferred Holocene age and is co-located with a discrete fault scarp at the seafloor, we confirm evidence for Holocene fault activity along the given fault strand. Based on planform geomorphic observations of horizontal fault offset, we also confirm evidence for the slip sense of the fault system.

2.3 Results

Sparker and SBP29 seismic profiles acquired over the Albatross fault system reveal shallow subsurface fault structure corresponding to fault scarps at the seafloor (**Fig. 2a, 3**). In two locations, SBP profiles (**Fig. 3a,b,d,e**) were acquired along existing sparker seismic profiles S22 and S58 (**Fig. 3c,f**), allowing for direct comparison of deeper structure imaged by sparker to shallow structure and sedimentary units imaged by SBP29.

2.3.1 *Geomorphic evidence for Holocene fault activity and slip sense*

The ~45-km-long surface trace of the main fault scarp associated with the Albatross fault system is well-defined at the seafloor in our 15-meter bathymetry compilation (**Fig. 2**). The surface expression of the Albatross fault scarp evolves along strike and exhibits planform structures that are characteristic of both releasing and restraining strike-slip fault bends, such as horse-tail splays and bend folds (**Fig. 2a**, “horse-tail splays”, “releasing bend”, “restraining bend folds”). The northern section of the fault system has multiple en echelon strands (**Fig. 2a-c**), whereas the southern section is primarily a single fault strand (**Fig. 2a,d-e**). This transition from a single fault strand to multiple fault strands occurs at the observed releasing bend in the fault

system where the strike of the fault changes abruptly from 019° to 003° (**Fig. 2c**; “fault bend”). Further south, there is a ~10-km stepover of the single fault strand to the southeast (**Fig. 2a**, “10-km fault stepover”). Within this stepover, there are three observed restraining bend folds indicating a zone of relative compression (**Fig. 2e**). The apparent opposing vergence of these folds, based on seafloor steepness, is consistent with contractional duplexing expected for an eastward stepover (heading south) in a right-lateral strike-slip fault system (e.g., Mengjia et al., 2024).

Distinct right-lateral offsets of seafloor ridges intersecting the Albatross fault system are observed in three locations along strike (**Fig. 2f, 2g, 2h**). Cumulative offsets at these locations range from 300 to 450 meters, with an average total offset of 385 meters. Fault offsets are measured by hand, and the uncertainty of these measurements is a minimum of ± 15 meters due to the resolution of the bathymetry. The northernmost offset ridge trends NNW and is offset in a right-lateral sense of motion by ~400 meters (**Fig. 2f**). Here, the Albatross fault system exhibits two major strands (**Fig. 2b**), potentially distributing fault motion onto both strands and reducing total fault offset observed at this piercing point. South of where these two fault strands coalesce, another piercing point is observed with a larger total offset of ~430 to 450 meters (**Fig. 2g**). At this piercing point, a narrow sliver of a broad seafloor ridge appears to be translated northeast with a right-lateral sense of motion. The third piercing point is observed at another NNW trending ridge with an apparent right-lateral offset of 300 to 330 meters (**Fig. 2h**). This piercing point is located at the end of the main fault strand near a large stepover and restraining bend in the fault system (**Fig. 2a,d**), possibly contributing to the reduced observed offset compared to piercing points identified further north. Overall, geomorphic observations of the Albatross fault

system are all consistent with that of a Holocene-active right-lateral strike-slip fault system trending NNE.

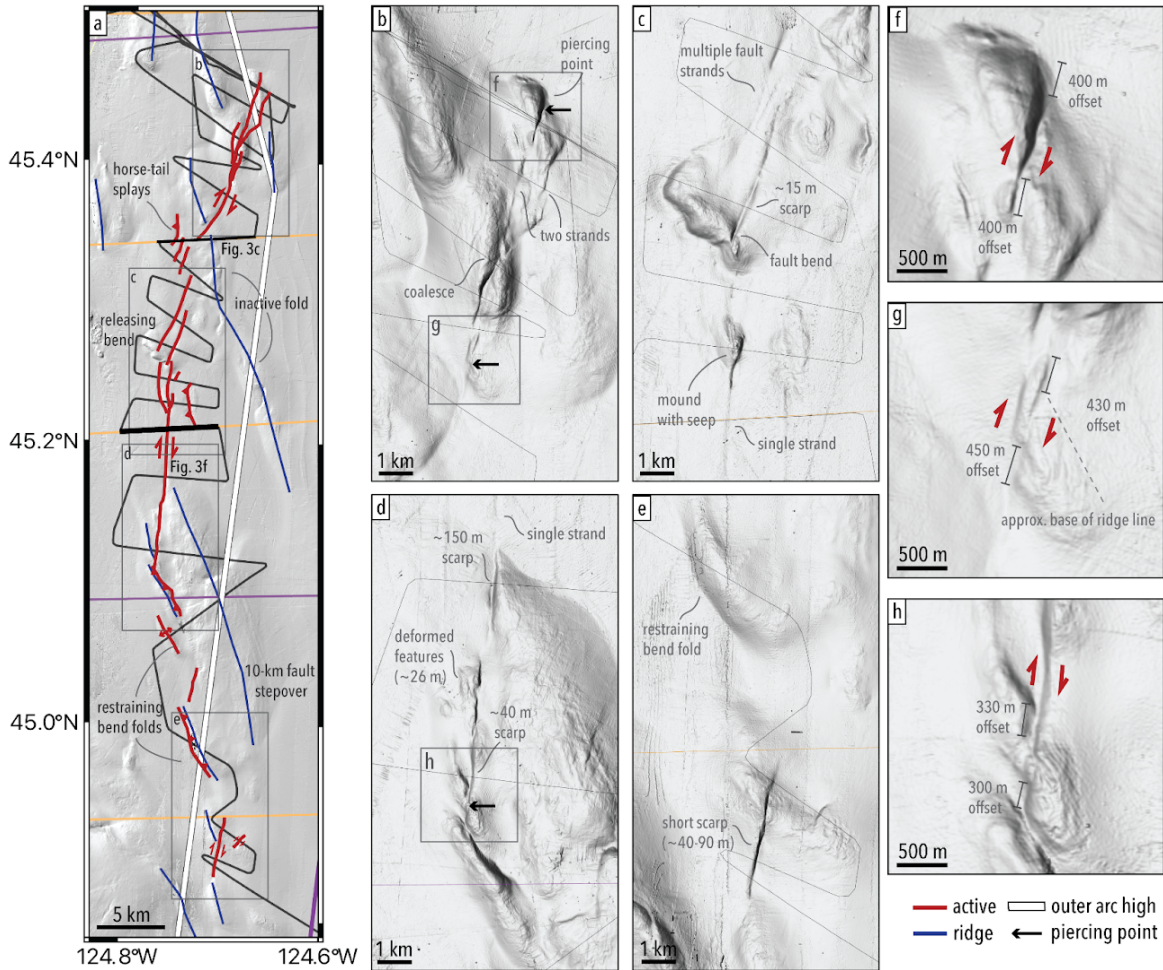


Figure 2. Hillshaded 15-meter multibeam bathymetry with interpreted structural morphology of the Albatross fault system. **a.** Structural map showing how active Albatross fault scarp (red) cuts across seafloor ridges (blue). Outer arc high (thick white line) from Watt & Brothers (2020) is roughly co-located with extent of fault scarp. **b-e.** Map insets showing detailed seafloor morphology of the fault system, vertical fault offsets, and other relevant structural features. **f-h.** Map insets of piercing points (black arrows in b. and d.) with approximately measured offsets of seafloor structural features (dark grey brackets).

2.3.2 *Structural evidence for Holocene fault activity*

North of the major fault bend (**Fig. 2c**), sparker line S22 images a ~1-km-wide fault zone with numerous horse-tail style fault splays associated with near-vertical discontinuities in subsurface sedimentary packages that also exhibit apparent normal offset (**Fig. 3a,c**, “multiple fault strands”). Above these faults, we observe growth strata packages within the accommodation spaces created by relative vertical motion on parallel fault strands (**Fig. 3a**, “growth strata”). Although the P-H boundary is less clear at this specific location (**Fig. 3a**, “P-H?”), we infer the growth strata to be Holocene sediment. Adjacent to this fault zone, a westward-dipping blind thrust fault exhibits folded and tilted sedimentary packages that are truncated unconformably by overlying sediment layers (**Fig. 3a,c**; “reactivated blind thrust?”, “folded packages”). Sediment layers overlying this unconformity (**Fig. 3a**, yellow dashed line) are well-imaged by SBP29 and appear to be eroded at the surface near the crest of the anticline of the blind thrust (**Fig. 3a**, “unconformity”, “eroded”). Here, we observe the shallowest strata are tilted (**Fig. 3a**, “tilted”) along with a 15-meter fault scarp at the ocean floor, indicating that either this small fault-cored anticline is actively growing or that this structure has been reactivated by the Albatross fault system. Across a small data gap in S22, a major anticline (**Fig. 3b**; “inactive anticline”) is draped by sediments that do not thin towards the structure, indicating the anticline is not actively uplifting. Based on tilting and thinning of deeper sedimentary packages below an identified unconformity (**Fig. 3b**; yellow dashed line), this anticline likely developed prior to the activation of the Albatross fault system (**Fig. 3b-c**), possibly during the early-mid Pliocene as suggested by McNeill et al. (2000).

South of the fault bend, sparker line S58 (see **Fig. 2a**) images a near vertical fault that displaces the P-H horizon and forms a ~3-meter scarp at the ocean floor (**Fig. 3d**). The Holocene

sediment within the footwall is slightly thicker than the hanging wall, showing growth strata characteristics that are indicative of recent faulting. Surrounding this primary fault strand, we observe subsidiary, apparent normal fault structures comprising a negative flower structure, indicating relative extension in this location (**Fig. 3d-f**). To the east of the fault strand, a major subsidiary normal fault offsets a buried ridge, resembling the inactive ridge imaged in S22, and exhibits auxiliary normal faults within the hanging wall (**Fig. 3e, f**). Sediment atop these subsidiary faults exhibits growth strata of inferred Holocene sediment packages, with increasing thickness towards the main normal fault (**Fig. 3e**). This growth strata in the fault-controlled accommodation space provides further evidence for Holocene activity of the Albatross fault system.

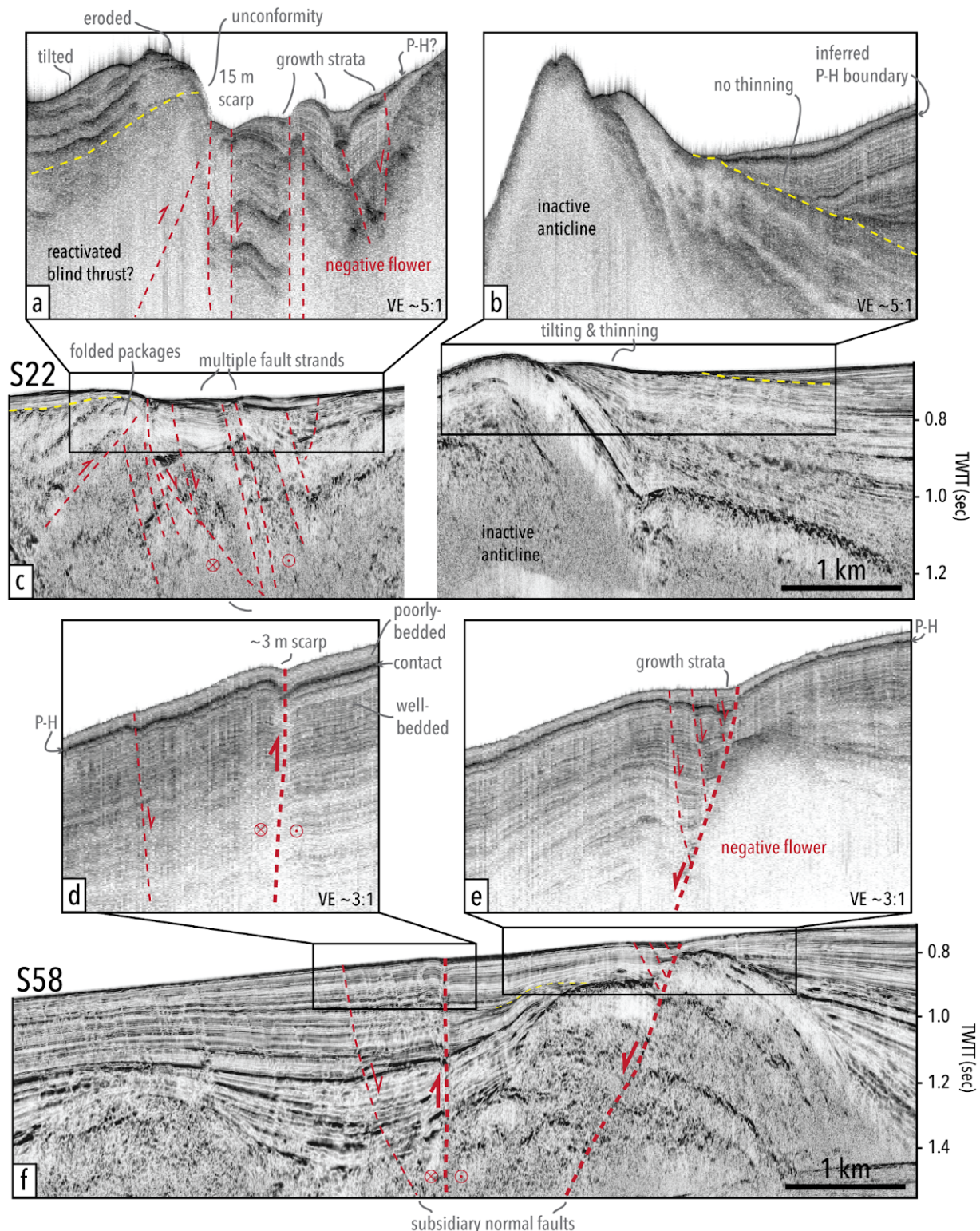


Figure 3. Sparker and SBP seismic profiles capturing subsurface structure of the Albatross fault system; line locations shown in Fig. 2a. **a-b.** SBP profiles coincident with **c.** sparker line S22. **d-e.** SBP profiles coincident with **f.** sparker line S58. Key faulting and other structural features are overlain onto seismic profiles. Yellow dashed lines indicate an unconformity. Red dashed lines indicate active fault zones, with arrows showing sense of fault motion.

2.4 Discussion

2.4.1 *Fault-controlled fluid pathways along the Albatross fault system*

Recent studies use water column acoustic backscatter data to map water column anomalies (WCAs) interpreted to be gas seeps along the Cascadia margin (Riedel et al., 2018; Merle et al., 2021; Rudebusch et al., 2023; Conrad & Rudebusch, 2023). By seep locations from Conrad & Rudebusch (2023) to the seafloor expression of the Albatross fault scarp, we find numerous seeps are located along the trace of the fault (**Fig. 4a**). Seeps also appear to follow the crest of a ~15 km-long NW trending anticline and other seafloor structures associated with the Albatross fault (**Fig. 4a**, “anticline”). Notably, no seeps are documented along the ~10-km restraining geometry stepover in the fault system (**Fig. 4a**, “stepover”) between 41.5°N and 44.95°N. New multibeam water column data collected during expedition SR2414 reveals a major seep site where a seafloor mound is bisected by right-lateral strike-slip motion of the Albatross fault with a vertical offset of ~30 meters (**Fig. 4b-c**; “seep”, “mound”). This seafloor mound occurs near a releasing bend in the fault system where the fault scarp splays out into multiple strands north of the mound (**Fig. 4a-c**, “bend”).

Evidence for seep clustering along the Albatross fault trace suggests that the fault acts as a conduit for fluid flow from depth. The transport of fluids from depth at both restraining and releasing bends in strike-slip fault systems has been documented at other locations (Cazarin et al., 2021; Hensen et al., 2022). In particular, fluid migration to the surface has been shown to be more favorable at fault releasing bends (Liu et al., 2024). Strike-slip faults have also been shown to play a role in regulating pore water pressure along the plate boundary (Tobin et al., 1993), and therefore the discovery of this fault system can work to inform our understanding of both megathrust and splay fault behavior in this region offshore Oregon. The venting of fluids at this

fault system may modulate both the mechanics of accretionary wedge deformation and megathrust fault behavior, as suggested for other subduction systems (Aylward, 2024; Watson et al., 2019). A similar process was recently proposed for the nearby Alvin Canyon fault at Pythia's Oasis where significant fluid venting occurs (Philip et al., 2023). The depth and origin of fluid venting at the Albatross fault is not known, and could have either a shallow or deep source as observed for other Cascadia seeps (Baumberger et al., 2018).

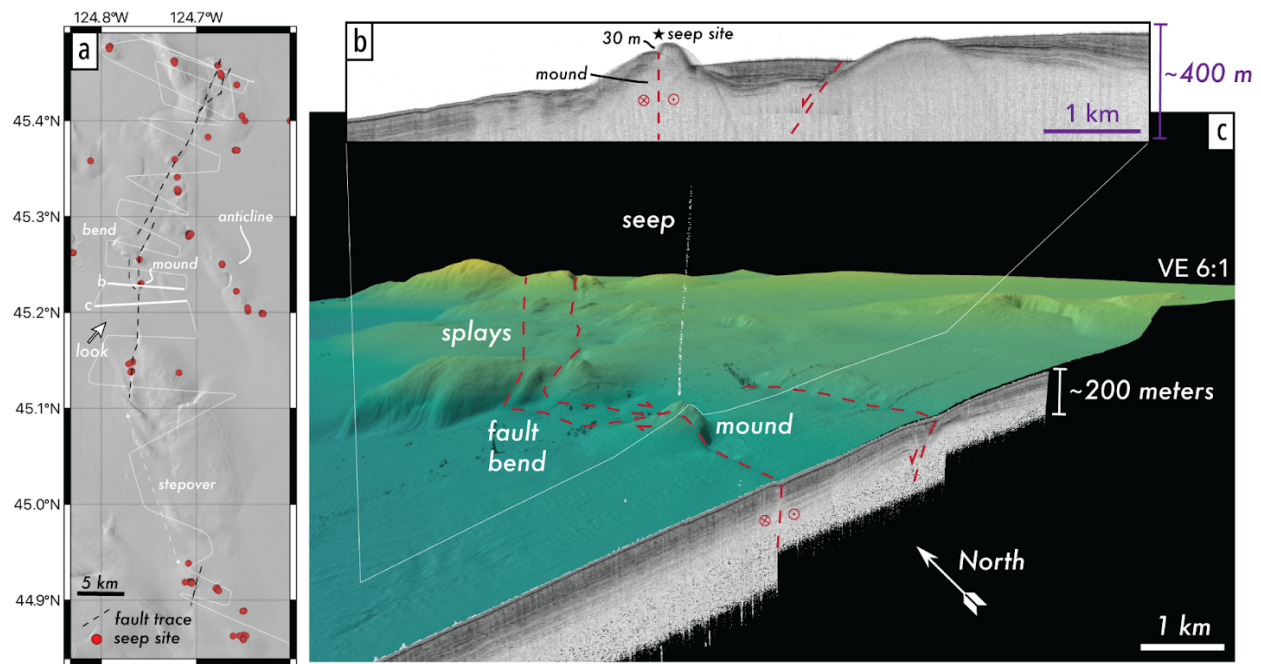


Figure 4. Water column anomalies (WCAs) interpreted to be gas seeps in the study region of the Albatross Fault System a. Hillshaded map with seep sites from Conrad & Rudebusch (2023), simplified fault trace, and look direction of 3D view in panel c. b. SBP29 image of bisected seafloor mound and associated subsurface structure. c. 3D view of 15-meter bathymetry compilation and SBP29 profile in the area of the seep site. Red dotted lines indicate simplified fault trace and linkage to subsurface fault structure. Vertical exaggeration is 6:1.

2.4.2 Deformation rates across the Albatross fault system & seismic hazard implications

Based on our measured offsets, the Albatross fault system exhibits a total fault offset ranging from 300 to 450 meters +/- 15 meters. Because the fault scarp distinctly crosscuts

seafloor structures associated with the outer arc high developed during the early-mid Pliocene (McNeill et al., 2000b), we can deduce that the Albatross fault initiated sometime after the mid Pliocene ~ 3.6 Mya. Together, this yields a minimum slip rate of the Albatross fault ranging from ~ 0.08 to 0.13 mm/year. This estimate does not exclude the possibility that the fault may have been initiated more recently, which would yield a much higher slip rate. For example, if we infer that major accretion of glacial sediments to the wedge occurred during the Pleistocene (~ 1.5 Mya) (Flueh et al., 1998; Ledeczi et al., 2024; Lucas et al., 2025) and triggered the formation of the Albatross fault system, it would then imply a fault slip rate ranging from ~ 0.2 to 0.3 mm/yr or much greater if the fault activated more recently.

At the location of the Albatross fault system ($\sim 45^\circ\text{N}$, $\sim 126^\circ\text{W}$), the Juan de Fuca plate is moving relative to North America at a rate of 35 mm/yr and an azimuth of 044.2° , yielding a north component velocity of ~ 25 mm/yr (DeMets et al., 2010; MORVEL 2010). At the same location, the Northern Oregon Coast Ranges domain of the Oregon block relative to the Juan de Fuca plate yields a north component velocity of ~ 1 mm/yr (McCaffrey et al., 2007; M05G). This implies that, at the location of the Albatross Fault System, the relative motion between Juan de Fuca and North America has a greater magnitude influence on the tectonic stress field than Oregon block rotation relative to Juan de Fuca. We hypothesize that this transition in the tectonic stress field offshore Oregon is linked to the position of the outer arc high and could effectively work to localize strain along the Albatross Fault system between the Oregon block and the Cascadia accretionary wedge. This hypothesis builds from previous work by McNeill et al. (2000), who made a similar hypothesis for the rotation of principal stress in this region based on changes in the orientation of fold trends across the wedge. A similar rotational transition in the horizontal stress orientation has been observed in the Nankai (SW Japan) accretionary wedge at a

strike-slip fault localized along the megasplay fault at inner-outer wedge transition zone (Tsuji et al., 2014). Others have suggested that book-shelf style faulting of the Gales Creek fault linked to Oregon block rotation extends offshore (Wells et al., 2020). However, the NNE orientation of the Albatross fault system is not consistent with the NW orientation of right-lateral faulting of the Gales Creek fault system, suggesting the two fault systems are not kinematically linked. This provides additional evidence that the outer arc high acts as a transitional stress boundary between Oregon block rotation and oblique subduction at the Cascadia margin.

It is plausible that the Albatross fault could either slip simultaneously with the megathrust or rupture independently. This fault system could also be triggered by megathrust rupture events, as observed at other subduction zones (e.g., Herman et al., 2023; Wiseman & Bürgmann, 2012), posing an additional risk for major aftershocks after a large Cascadia megathrust earthquake event. Modeling of the Coulomb stress field of subduction forearcs has shown that plate interface slip subparallel to the trench enhances stress on strike-slip faults closer to the trench, whereas slip perpendicular to the trench loads strike-slip faults further from the trench (ten Brink & Lin, 2004). The Albatross fault system is located ~50 km east of the Cascadia deformation front within the subduction forearc (**Fig. 2a**). The close proximity of the Albatross fault system to the trench could imply that slip on the plate interface may occur subparallel to the trench in this region, which could inform both kinematic and dynamic rupture modeling for large Cascadia megathrust earthquakes .

2.4.3 Localization of Riedel-type shears at forearc terrane boundaries

Prior to this study, Goldfinger et al. (1997) applied a Riedel-type right simple shear model to suggest that a series of WNW left-lateral strike-slip faults work together to almost

entirely accommodate oblique subduction at Cascadia through clockwise block rotation. With the discovery of the Albatross Fault System, a NNE right-lateral strike-slip fault system, we propose a new hypothesis for how oblique subduction is accommodated in central Cascadia. We argue that both the left-lateral and right-lateral faults in the region form contemporaneously, based on new high-resolution geophysical observations in the region, and that these faults work together to distribute shearing motion due to oblique convergence.

Applying the same Riedel shear model as Goldfinger et al. (1997) to our new structural map of offshore Oregon (**Fig. 5a**), with imposed dextral N-S shearing (right-lateral) given subduction obliquity of $\sim 30^\circ$, we would expect conjugate P, P', R, and R' Riedel shearing (**Fig. 5b**). The primary strand of the right-lateral Albatross fault is consistent with R shearing, whereas WNW left-lateral faults are consistent with P' shearing (**Fig. 5a**). This differs from Goldfinger et al. (1997) who identify these WNW faults as R' shears, highlighting how the addition of the Albatross fault system to structural mapping improves understanding of the framework in which distributed shearing processes are occurring in this region. It is important to note that WNW left-lateral faults originate within the subducting plate and may experience different stresses compared to faults confined to the upper plate. North of the Albatross fault, en echelon seafloor lineations that resemble R shears may represent an early stage of fault development or more distributed deformation that lacks a discrete fault scarp moving away from the main Albatross fault strand (**Fig. 5a**). We do not observe P and R' shears in our study region which could be due to a lack of high-resolution (less than 30m) seafloor imaging, shears not expressed at the wedge surface, or stress conditions not conducive for their formation. Over time, movement on the Albatross fault system may have contributed to the development of a wide forearc basin associated with an embayment of the continental shelf (e.g., Hill et al., 2022) (**Fig. 1a**,

“embayment”). The long axis of this forearc basin (**Fig. 5a**) is roughly perpendicular to the direction of extension predicted by the Riedel shear model (**Fig. 5b**). This provides further evidence that distributed Riedel shearing dominates wedge deformation in this region by producing both extensional and compressional features.

R shears of the Albatross fault system are localized within the inner wedge domain between the inner-outer wedge transition zone (Lucas et al., 2025) and the static backstop, primarily along the outer arc high (Watt and Brothers, 2020) (**Fig. 5a**). In CASIE21 line PD12, lower amplitude and chaotic seismic reflectivity associated with the Albatross fault system at the outer arc high indicates a fault damage zone (**Fig. 5c**). This damage zone may act as a conduit for fluid flow from depth and explain the abundance of seeps along the trace of the Albatross fault scarp. The presence of fluids within the fault damage zone may help to further localize shearing along the Albatross fault and promote continued development of the fault system (Wang et al., 2024). At longer time scales, the localization of Riedel shears at wedge terrane boundaries may effectively create a forearc sliver composed of the inner wedge domain and eventually allow for northward transport of this wedge terrane.

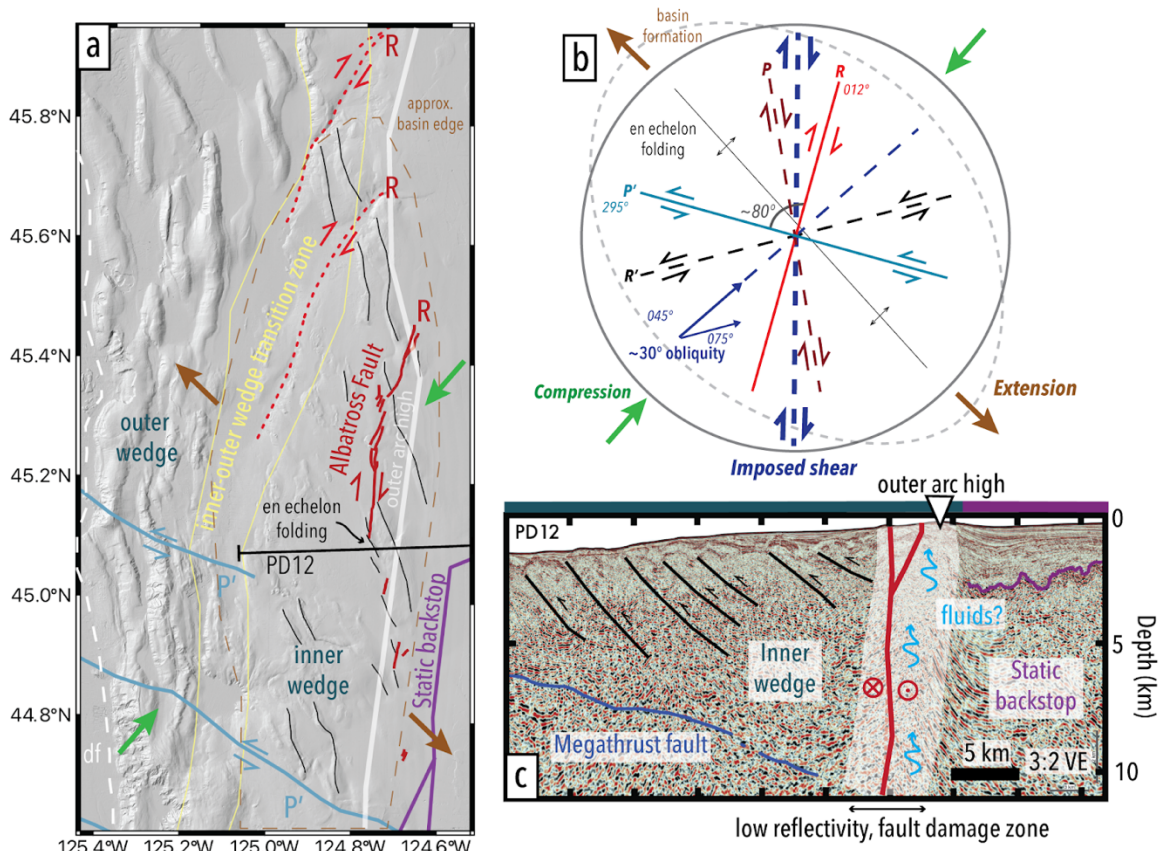


Figure 5. Application of Riedel model to new structural mapping of Cascadia accretionary wedge offshore Oregon a. Structural map in the area of the Albatross fault system, including WNW left-lateral faults from Goldfinger et al. (1997; light blue), static backstop from Watt & Brothers (2020), inner-outer wedge transition zone from Lucas et al. (2025; yellow) and the Albatross and parallel faults (this study; red). Classification of Riedel shear type by color corresponds to b. showing Riedel-type schematic with imposed right-lateral shear given 30° subduction obliquity at Cascadia. Angles indicate average fault angles measured from structural map. c. CASIE21 line PD12 showing Albatross Fault localization and potential fluid pathways at the boundary between the inner wedge and static backstop. Top of static backstop identified by Carbotte et al. (2024).

2.5 Conclusion

Prior to this study, no active margin-parallel strike-slip faults had been identified within the accretionary wedge of central Cascadia. For the first time, in this study, we use modern marine geophysical datasets collected during expedition SR2414 on *R/V Sally Ride* to map and describe the Albatross fault system, a system of en echelon right-lateral strike-slip faults within

the Cascadia accretionary wedge offshore Oregon spanning between 44.6°N and 46°N. Using SBP29 and sparker seismic reflection images along with our newly compiled 15-meter bathymetry grid, we identify structural and geomorphic evidence for Holocene activity on this fault system. We measure offsets at fault piercing points to estimate fault slip rate and to determine slip sense. The Albatross fault system occurs within the inner wedge domain near the inner-outer wedge transition zone and the static backstop. A transition in the tectonic stress field at the outer arc high in this location may help to localize strain along the Albatross fault system. The fault system is a conduit for fluid flow from depth, with the potential to drain fluid from the plate boundary fault and surrounding accretionary wedge terranes, effectively modulating subsurface fluid pressure in this region. Overall, the discovery and characterization of the Albatross fault system enables a more complete application of the Riedel shear model to the central Cascadia region. This work further supports the hypothesis for distributed accretionary wedge shearing in this region, in which numerous conjugate faults with relatively low slip rates (less than 1 mm/yr) work together as a larger-scale system to accommodate oblique subduction at Cascadia.

3. **Chapter 3:** Geomorphic signature of active faulting in Cascadia's submarine channels

In preparation for submission to *JGR: Earth Surface*; coauthors: Madeleine C. Lucas, Alyssa Iverson, Tamara Aránguiz-Rago, Anna M. Ledeczi, Jeffrey Beeson, Harold J. Tobin, Alison Duvall

Abstract

At the Cascadia subduction zone, numerous submarine channels cross the wide accretionary wedge offshore Washington and northern Oregon. This region is commonly referred to as the landward vergence zone due to widespread landward vergent splay faulting within the accretionary wedge. Submarine channels incise into numerous splay fault systems at the landward vergence zone, both active and inactive within the late Quaternary (~100,000 years BP). How subsurface fault deformation and wedge structure influences the morphology and evolution of submarine channels in Cascadia remains poorly understood and underexplored. To address this knowledge gap, this study systematically quantifies longitudinal channel profile morphology for seven major submarine channels at Cascadia (Barkley, Nitinat, Juan de Fuca, Quillayute, Quinault, Willapa, Astoria) using a suite of topographic analysis tools in *MATLAB*-based software *Topotoolbox*. We extract longitudinal channel profiles from a 30-meter resolution bathymetry grid and locate channel knickpoints using the *TopoToolbox knickpointfinder* function. We find that channel knickpoints within the active domain of the outer wedge are co-located with the trace of active splay faults at the deformation front, while there is a lack of splay fault-related knickpoints within the inactive domain. Knickpoints also occur along other seafloor features such as strike-slip faults, channel confluences, slope failures, etc., highlighting the importance of

ground-truthing geomorphic observations of accretionary wedge splay faulting with subsurface seismic constraints. We also find that major inflection points in regional-scale channel gradient correspond with the location of the inner-outer wedge transition zone, indicating longitudinal channel morphology is closely linked to heterogeneities in wedge structure and lithology. Through testing the applicability of subaerial topographic analysis tools to submarine topography, we find that, where seismic data is limited, submarine channel morphology can reveal new fault locations and their associated activity, allowing us to improve fault mapping in this region. Overall, we conclude that longitudinal submarine channel morphology is closely linked to variations in accretionary wedge fault activity and structure. This work provides new insights into channel evolution and megathrust behavior, as patterns in accretionary wedge faulting are observed to be linked to channel routing and plate coupling.

3.1 Introduction

Submarine channels are a common feature at continental margins across the globe and can provide a long-term record of margin evolution (Harris & Whiteway, 2011). At the Cascadia subduction zone, numerous submarine channels cut across the Cascadia margin, traversing from the upper continental slope through faults and folds, wedge top sediments, and other seafloor features across the deformation front to the Cascadia Basin. During sea-level lowstands, submarine channels at Cascadia were more directly connected to these onshore fluvial systems, effectively moving land-derived sediments out to the deeper ocean (Goldfinger et al., 2012; Griggs & Kulm, 1970). Today, sediment continues to erode and deposit within these channel systems by way of gravity-driven sediment transport (e.g., turbidity currents, submarine landslides, etc.), fluvial input from coastal rivers across the continental shelf (Nittrouer &

Wright, 1994), along with an array of other mechanisms (Puig et al., 2014). Simultaneously, deformation at the Cascadia subduction margin influences the evolution of submarine channels over time (Gee et al., 2007; W. H. Mitchell et al., 2021) and controls their morphologic expression at the seafloor (I. R. Clark & Cartwright, 2011). However, channel-fault interactions have yet to be systematically explored at the Cascadia margin using modern geophysical datasets and topographic analysis tools.

At the Cascadia subduction zone, which spans from Vancouver Island to northern California, the Juan de Fuca tectonic plate is colliding with and subducting beneath the North American plate (**Fig. 1a**). The Cascadia subduction zone features an extensive offshore accretionary wedge consisting of sediments and rocks that have been scraped off the downgoing Juan de Fuca plate and accreted to the North American plate margin. The widest portion of the accretionary wedge is located offshore Washington and northern Oregon, a region often referred to as the “landward vergence zone” due to the predominance of atypical landward vergent thrust faulting within the wedge in this region (**Fig. 1b**). Accretionary wedge thrust faults, also referred to as splay faults, branch from the main megathrust fault or other shallower décollement up to the seafloor, cutting through accretionary wedge material (**Fig. 1c**). Recent seismic and bathymetric geophysical surveying has enabled accretionary wedge mapping within the landward vergence zone and surrounding regions, dividing this zone into domains of active and inactive splay faulting, mapping wedge terranes and boundaries such as the inner-outer wedge transition zone (IOWTZ), and characterizing out-of-sequence faulting (**Fig. 1b-c**) (Carbotte et al., 2024; Ledeczi et al., 2024; Lucas et al., 2025; Watt & Brothers, 2020). At the IOWTZ within the Cascadia accretionary wedge, there is a major structural transition between the younger, less deformed outer wedge domain and the older, more-deformed inner wedge domain (**Fig. 1c**)

(Lucas et al., 2025). This work has enabled an improved understanding of Cascadia accretionary wedge deformation, evolution, and potential fault rupture behavior in future Cascadia megathrust earthquakes.

In this study, we explore the interplay between submarine channel morphology and accretionary wedge faulting by applying subaerial topographic analysis tools to submarine topography at the Cascadia accretionary wedge. This approach allows us to determine the distinct signature active faulting leaves within Cascadia's submarine channels. We also investigate the signature of accretionary wedge terrane boundaries within submarine channel morphology. We ground-truth our geomorphic analysis with recent geophysical observations of splay fault activity and accretionary wedge structure (Ledeczi et al., 2024; Lucas et al., 2025), which allows us to test the performance of subaerial topographic analysis tools in identifying active subsurface deformation in submarine landscapes. We then apply this new methodology to regions of the Cascadia accretionary wedge with limited to no subsurface seismic constraints, enabling us to update and improve fault mapping in the region of the landward vergence zone. From this analysis, we begin to unravel the complex coevolution of submarine channel formation, accretionary wedge deformation, and megathrust behavior.

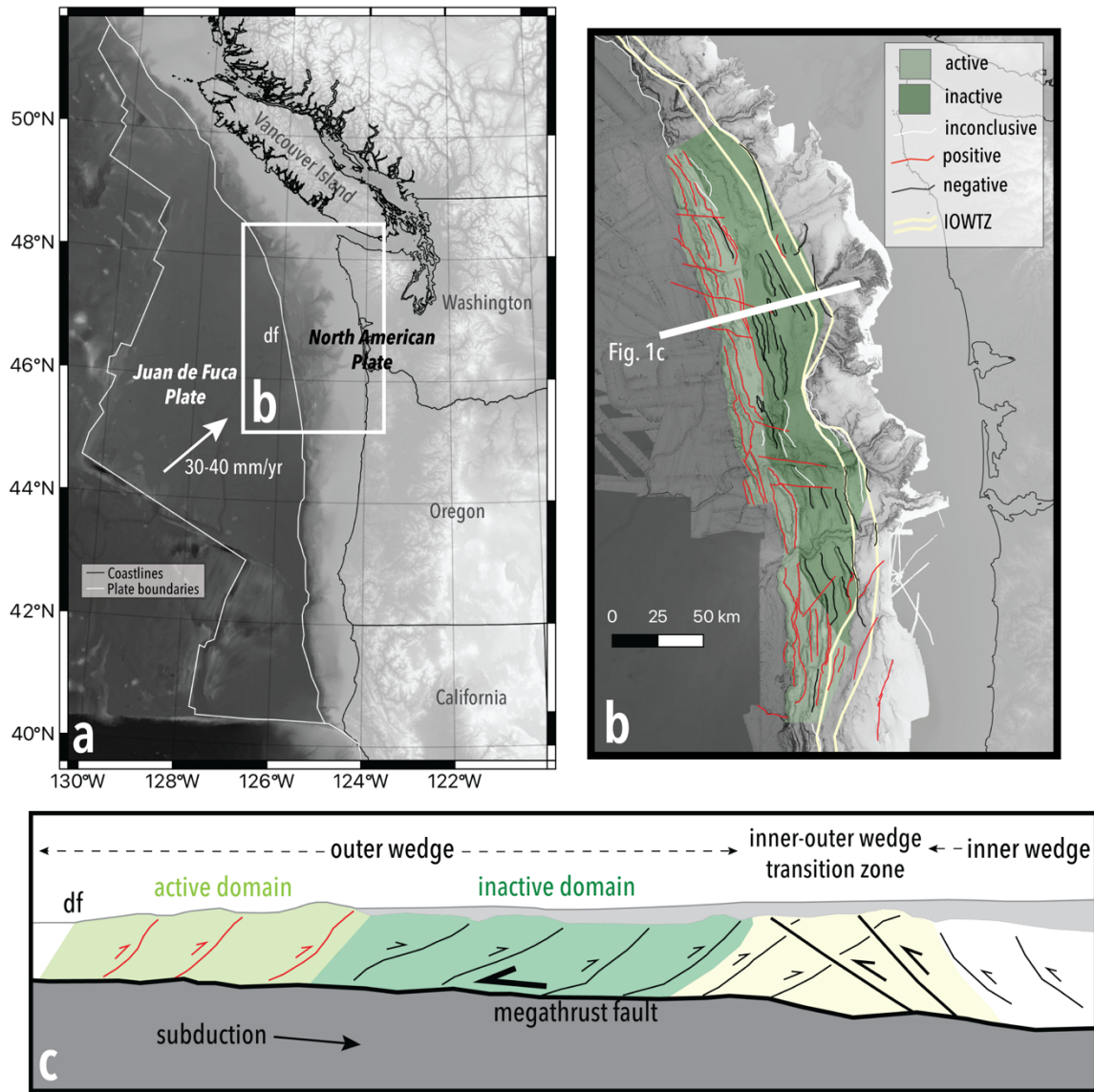


Figure 1. a. Map of GMRT 50-meter bathymetry showing Juan de Fuca Plate subduction beneath Northern American plate. White arrow shows plate convergence rate and vector (DeMets et al., 2010). b. Inset map in the region of the landward vergence zone. USGS 30-meter bathymetry overlaid with active (light green) and inactive (dark green) domains, fault locations and evidence for late Quaternary activity (inconclusive=white, positive=red, negative=black), and the inner-outer wedge transition zone (IOWTZ=yellow) (Ledeczi et al., 2024; Lucas et al., 2025). Thick white line shows extent of c. schematic cross-section of the accretionary wedge and the corresponding wedge domains (active, inactive, IOWTZ, outer wedge, inner wedge). df = deformation front.

3.2 Background

The processes that control the shape of submarine channel longitudinal profiles are not well-constrained (Jobe et al., 2016; Peakall et al., 2000). However, it has been established that tectonics exert a primary control on the concavity of submarine channel longitudinal profiles (Soutter et al., 2021). At active tectonic margins, high convexity of submarine channel longitudinal profiles has been linked to uplift on active faults and folds, which work to modulate the shape of the channel profile over time through seafloor deformation (Covault et al., 2011). The relative difference between uplift and erosion rates within submarine channels controls whether equilibrium longitudinal channel profiles are disturbed (Pirmez et al., 2000). For example, if tectonic uplift rates exceed erosion rates, a disturbance or “knickpoint” will be created within the channel profile (Gardner, 1983). Knickpoints can be generated by seafloor steepening due to fault uplift, which then subsequently migrates upstream (N. C. Mitchell, 2006; W. H. Mitchell et al., 2021). Knickpoints can also be generated by lateral variations in erosional resistance (e.g., Toniolo & Cantelli, 2007), reflecting changes in the underlying accretionary wedge lithology. The formation and migration of knickpoints has been suggested as a mechanism for how channels cut through actively uplifting thrust ridges (Heiniö & Davies, 2007). Rapid knickpoint migration (100-450 m/yr) has been observed within submarine channels and suggested to exert a primary control submarine channel evolution (Heijnen et al., 2020). To disentangle the complex relationship between tectonic deformation and longitudinal channel profile morphology, it is important to rely on independent constraints for subsurface deformation and structure.

How deformation affects submarine channel morphology and behavior is a growing area of study on submarine channels across the world. At the Levant Basin deepwater fold and thrust

belt in the eastern Mediterranean Sea, submarine channels interact with underlying structure and deformation to produce distinctive morphologies and patterns of channel evolution (I. R. Clark & Cartwright, 2009). These patterns have been shown to provide insight into the timing of channel-structure interactions and long-term channel evolution. At the Niger Delta fold and thrust belt, it has been quantitatively shown that submarine channels adjust to active deformation through increased channel slope and incision depth at growing faults and folds (Jolly et al., 2017; W. H. Mitchell et al., 2021) and decreased channel sinuosity (Ferry et al., 2005). At this same margin, submarine channel distribution is shown to be sensitive to fault strain rates, where relatively higher strain rate faults have less channel-fault crossings than lower strain rate faults (Pizzi et al., 2021). At the Barbados accretionary prism, it was found that systematic variations in channel gradient are closely linked to the active and inactive fault domains within the wedge (Huyghe et al., 2004). Furthermore, steep channel gradient generated within the active domain of the Barbados prism results in accelerated sediment flow and channel incision. Although each submarine channel system is unique, these works provide a foundation for our analysis and interpretation of submarine channel morphology behavior at the Cascadia accretionary wedge.

Most studies on Cascadia's submarine channels focus on the link between subduction zone earthquakes and turbidites. Turbidites are distinctive sedimentary layers deposited by turbidity currents and are found throughout Cascadia's submarine channels. Turbidite deposits are characterized by a sharp basal contact and are composed of a coarser sandy-silt basal layer grading up to finer silts, muds, and clays (e.g., Walton et al., 2021). Turbidity currents can be triggered by both seismic (i.e., earthquakes) and non-seismic events (i.e., river floods, coastal storms, gravity-driven landslides, etc.) (J. W. Beeson et al., 2017; Gavey et al., 2017; Lahr et al., 2025). Laboratory experiments replicating submarine channel processes using a flume have

shown that bed-erosion due to turbidity currents results in the upstream migration of knickpoints and are consistent with field observations of turbidity-induced knickpoint migration (Toniolo & Cantelli, 2007). Many studies aim to link turbidite deposits within submarine channels to coseismic shaking during earthquake events in order to constrain the timing and recurrence intervals of megathrust earthquake events at the Cascadia subduction zone (Goldfinger et al., 2012, 2016; Hill et al., 2022, 2026), along with regional (Goldfinger et al., 2003, 2008) and distant seismic events (Johnson et al., 2017). This body of work provides evidence for active erosional and depositional processes within Cascadia’s submarine channels during the Holocene (e.g., Goldfinger et al., 2012), which enables us to place additional constraints on recency of fault activity where faults intersect active Holocene channels. Furthermore, the record of turbidity currents in Cascadia submarine channels may also help to explain knickpoint migration, and consequently, how channel evolution is inherently linked to the earthquake cycle.

3.3 Methods

Here, we apply topographic analysis functions in *MATLAB*-based software *TopoToolbox* (Schwanghart & Scherler, 2014) to submarine topography. In doing so, we test the applicability of these tools to submarine settings by ground-truthing our geomorphic analysis with recent subsurface geophysical observations of accretionary wedge structure and deformation (Ledeczi et al., 2024; Lucas et al., 2025). For our analysis, we use a 30-meter resolution digital elevation model (DEM) that was compiled by the U.S. Geological Survey (USGS) with multibeam data from multiple previous bathymetric surveys of the region (J. Beeson et al., 2025; Dartnell et al., 2021, 2023). The USGS 30-meter DEM captures the surface expression of seven major Cascadia submarine channels that cross the subduction margin, from channel head to the deformation front

(Fig. 1). This allows us to apply *TopoToolbox* functions to extract longitudinal profiles and knickpoints along seven major submarine channels.

To prepare data for import into *TopoToolbox*, we clip the USGS 30-meter DEM to the extent of each submarine channel. We then import the clipped DEMs into *MATLAB* and apply the *fillsinks* function. Next, we follow standard *TopoToolbox* procedures to create a flow object and calculate flow accumulation. We then create a stream object and extract only the submarine channel trunk using the *trunk* function. Channel trunk longitudinal profiles, hereafter referred to as “channel profiles”, are smoothed to remove noise using the *quantcarve* function with the *tau* parameter set at the default of 0.5. For all the extracted and smoothed channel trunks, we run the *knickpointfinder* function at a selected tolerance of 35 in an effort to extract only major knickpoints and ignore potential artifacts in the channel profile. Knickpoints at the sharp transition from continental shelf to channel head are deleted. Where there is a more gradual and broader disturbance of channel slope, but a knickpoint is not automatically identified by the *knickpointfinder* function, we manually identify knickzones in channel profiles. At locations where overall channel gradient changes abruptly, we identify inflection points in the channel longitudinal profile. We apply this methodology uniformly across all seven submarine channels (Fig. 2) to allow for direct comparison between channels and to minimize bias in our interpretation of the resulting channel profiles.

For each channel, we compare results from our *TopoToolbox* analysis to our recent work using modern, high-resolution seismic data to analyze splay fault structure and activity in this region (Ledeczi et al., 2024; Lucas et al., 2025). This approach allows us to ground-truth the utility of this method in characterizing the presence and activity of splay faults where seismic data is lacking. Our approach is complementary to existing methods that characterize

accretionary wedge structures by applying tectono-geomorphic analysis tools to high-resolution bathymetry (Schottenfels & Regalla, 2021). We classify recency of fault activity into categories: Holocene-active (~10,000 years BP), late Quaternary-active (~100,000 years BP), and inactive (older Quaternary). These fault activity categories are applied consistently using definitions for Holocene and late Quaternary as in Ledeczi et al. (2024) and Lucas et al. (2025). Using sediment cores, Goldfinger et al. (2016) mapped the activity of submarine channels at the Cascadia subduction zone. They classified channels as active, inactive, intermittent, and unknown based on the identification of Holocene sedimentary sequences and turbidites. For our analysis, if we observe both a discrete fault scarp across a Holocene-active channel bed and a knickpoint within the channel profile that is co-located with the scarp and a fault structure on either side of the channel, we classify that fault as Holocene-active (McCalpin & Nelson, 1996). If a Holocene-active channel appears to be perturbed, is located near a fault structure, or is close to a knickpoint or knickzone, we classify the fault as late Quaternary-active. If neither of these are true or evidence remains inconclusive, we classify the fault structure as inactive where it intersects the channel. This methodology allows us to determine where active faults cross channels and where faults might terminate at channel intersection, enabling us to improve the resolution of fault mapping and refine constraints on recency of fault activity with the Cascadia accretionary wedge. It is important to note that faults or other structures characterized solely using bathymetry data must be ground-truthed with geophysical observations of subsurface structure to verify the underlying fault structure and activity.

3.4 Results

We applied our methodology to seven major submarine channels at the Cascadia margin: Barkley, Nitinat, Juan de Fuca, Quillayute, Quinault, and Willapa (**Fig. 2**). We focus on the region of the landward vergence zone offshore Washington and northern Oregon because recency of splay fault activity is structurally constrained to the late Quaternary with modern seismic reflection imaging (Ledeczi et al., 2024; Lucas et al., 2025).

Morphology varies across the seven submarine channels (**Fig. 2**). Channel flow direction is roughly east to west for all channels moving seaward from the coastline. In planform, some channels take a relatively linear, short path across the accretionary wedge (e.g., Willapa, Astoria, Quillayute), while other channels take a more circuitous, longer route (e.g., Juan de Fuca, Quinault). The Nitinat and Quinault Channels merge downstream with the Juan de Fuca and Willapa Channels, respectively, shortening their apparent length (i.e., distance upstream) and the number of associated knickpoints compared to the other channels. The number of knickpoints identified in each channel varies from 2-8, with an average of ~4.4 knickpoints.

We present in-depth results for all seven submarine channels considered in this study, highlighting how each channel profile and its associated knickpoints are linked to subsurface fault structure, activity, and accretionary wedge lithology of the region (e.g., Ledeczi et al., 2024, Lucas et al., 2025). For consistency, we present longitudinal channel profile results from the channel head to where the channel crosses the deformation front of the Cascadia accretionary wedge, following the direction of channel flow downstream.

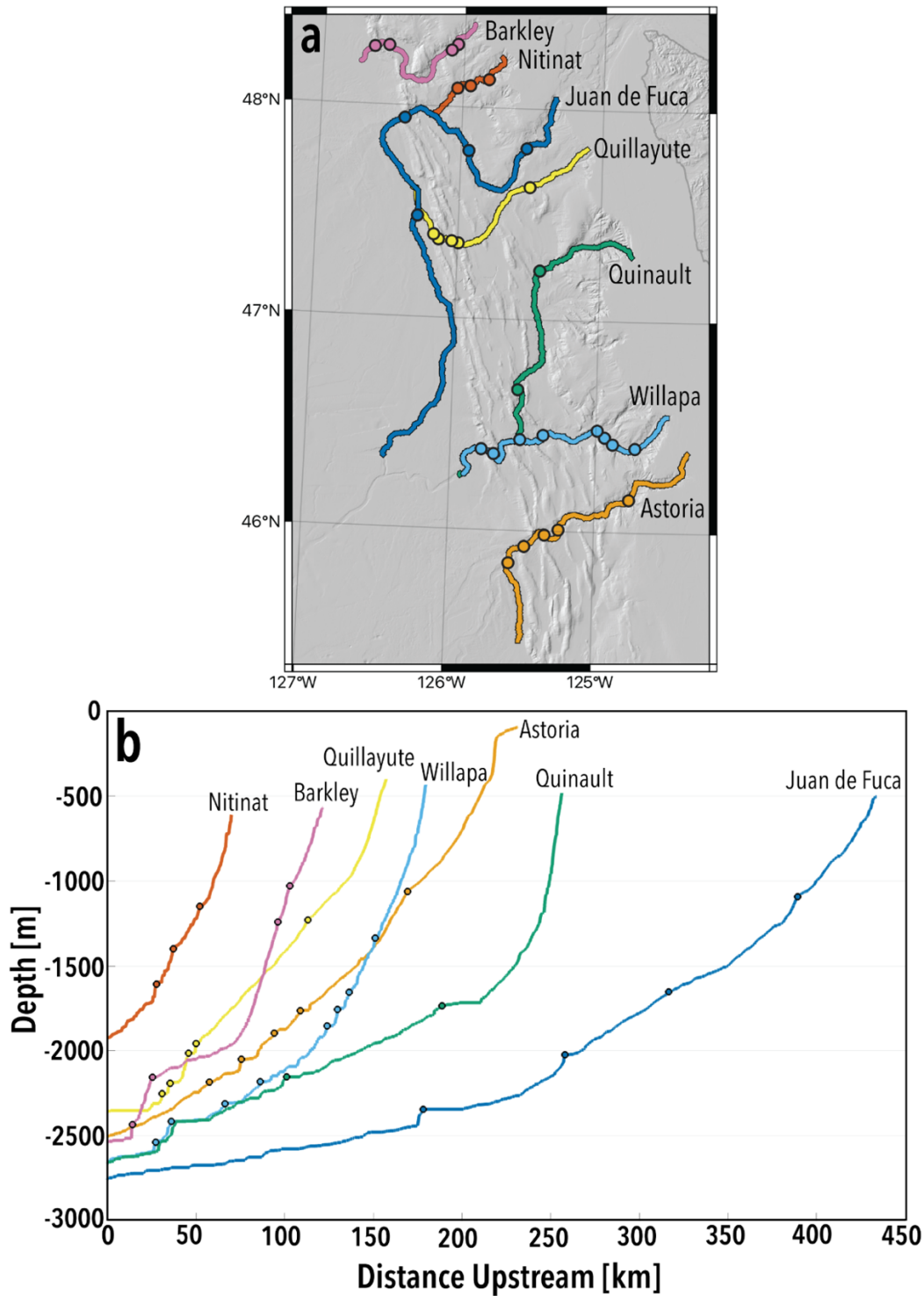


Figure 2. Cascadia submarine channel trunks. a. Planform view of the seven *TopoToolbox*-extracted submarine channel trunks overlaid on hillshaded 50-meter GMRT bathymetry (Ryan et al., 2009) and b. corresponding longitudinal channel profiles. Knickpoints are shown with circle icons.

3.4.1 Barkley Channel

Covering a distance of ~110 km from channel head to the deformation front, the Barkley Channel is relatively short in length compared to the other channels analyzed in this study. This is due to a narrower accretionary wedge where this channel is located. The Barkley Channel exhibits four knickpoints, two in the midslope region (Knickpoints 1 & 2) and two at the deformation front (Knickpoints 3 & 4) (**Fig. 3**). *Topotoolbox* results for the location of the channel trunk differ from channel mapping by Goldfinger et al. (2016). Goldfinger et al. map the Barkley Channel crossing the deformation at channel outlet “A” (**Fig. 3d**; “A”), whereas *Topotoolbox* calculates that the channel crosses the deformation front at channel outlet “B” based on the USGS 30-m DEM (**Fig. 3d**, “B”). Goldfinger et al. (2016) connect channel outlet B to submarine canyon systems further north. Channel outlet A is likely utilized by the Barkley Channel during periods of high-volume channel flow. For our analysis, we acknowledge this discrepancy but choose to rely on objective results from our *Topotoolbox* methodology because it is uniformly applied across all the submarine channels and constrained solely by seafloor topography.

Upon exiting Barkley Canyon, the Barkley Channel intersects two prominent NW-SE trending fault scarps at the seafloor that have not been previously mapped (**Fig. 3**). Each scarp exhibits further complexity at close range, including multiple fault strands (**Fig. 3a**) and channelization along the fault trace (**Fig. 3b**). This channel-fault intersection aligns with Knickpoints 1 and 2 and a major slope failure on the southern bank of the channel. At this location, we observe local topography within the channel bed (**Fig. 3c**) and the continuation of the fault scarps within the slope failure scarp (**Fig. 3c**). Although there is a lack of seismic data at this location, based on geomorphic evidence identified here, we can classify this fault system as

Holocene-active because the fault system is observed to deform Holocene channel features. This also indicates that the megasplay fault mapped with inconclusive evidence for fault activity by Lucas et al. (2025) is inactive (**Fig. 3d**, “megasplay trace”) based on geomorphic evidence.

At the seaward end of the inner-outer wedge transition zone (IOWTZ; Lucas et al., 2025) at ~72 km distance upstream, the channel gradient of the Barkley Channel decreases from 1.5° to 0.3°. This represents a 5x decrease in the channel gradient in the downstream direction. The inflection point where channel gradient changes abruptly is co-located with the beginning of the IOWTZ where there is a major lithologic boundary within the accretionary wedge between the younger, weaker Pleistocene-aged terranes of the outer wedge and older, stronger Miocene-aged terranes of the inner wedge. This finding suggests regional-scale longitudinal channel morphology is linked to the location of major terrane boundaries in the accretionary wedge.

Past the IOWTZ, the Barkley Channel approaches the deformation front (**Fig. 3d-e**, abbreviated “df”) after routing around a rounded, prominent topographic high (**Fig. 3d**, “high”). The channel turns north and traverses between the second (**Fig. 3d**, second ridge “r2”) and third (**Fig. 3d**, third ridge “r3”) splay fault thrust ridges from the deformation front until it reaches the base of the third thrust ridge. The second thrust ridge acts as a flow barrier that guides the channel north. The channel exhibits two knickpoints co-located with the seaward edge of each thrust ridge it crosses. At the deformation front, the first (**Fig. 3**, first ridge “r1”) and second thrust ridges intersect, and appear to be eroded by the channel.

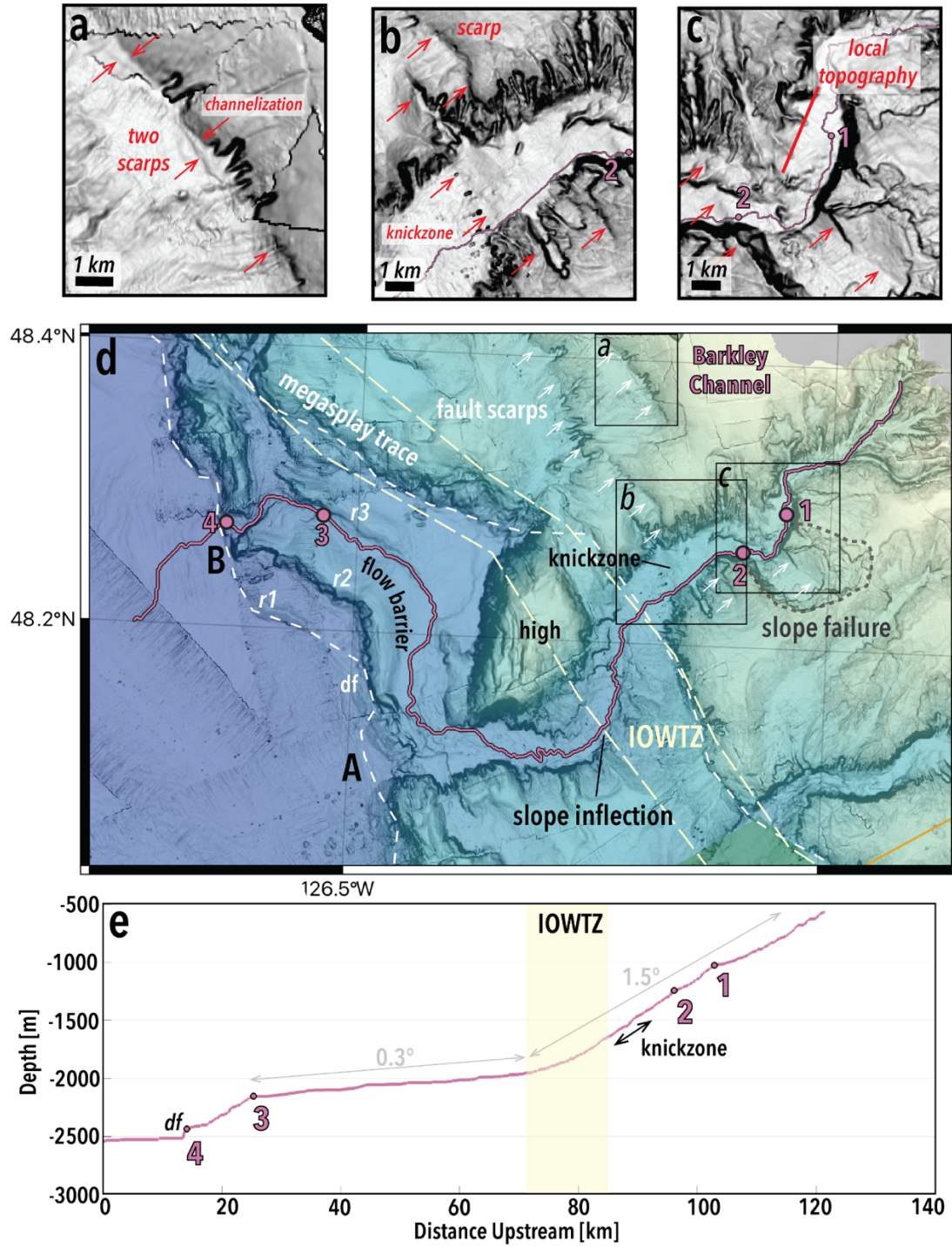


Figure 3. Barkley Channel. **a-c.** Slope map insets showing fault scarps and channel bed topography/knickzones. **d.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, and **e.** corresponding longitudinal profile.

3.4.2 Nitinat Channel

The Nitinat Channel (**Fig. 4**) runs a length of ~70 km from channel head to its connection point with the Juan de Fuca Channel downstream (see **Fig. 2a**). In total, the Nitinat Channel exhibits 3 knickpoints that occur prior to the IOWTZ and megasplay fault trace.

Knickpoints 1 and 2 are located near the apex of two southeastward bends in the channel planform (**Fig. 4a**). In the channel profile, these knickpoints are similar in that the channel profile shallows just before the knickpoint and then steepens after the knickpoint (**Fig. 4c**). This pattern in both channel planform and profile could indicate a similar mechanism in which these two knickpoints formed. We hypothesize that Knickpoints 1 and 2 were formed by older ruptures on this megasplay fault structure, and then these knickpoints migrated up the channel over time, explaining the similar morphologic character of these two knickpoints. However, Knickpoints 1 and 2 could also be related to uplift on unmapped faults, or other geomorphologic processes occurring within the channel unrelated to subsurface deformation.

Knickpoint 3 is co-located with a ~100-meter-high fault scarp that cuts across the channel bed (**Fig. 4b**). This scarp aligns with the trace of a megasplay fault mapped with inconclusive evidence for late Quaternary fault activity (Lucas et al., 2025). Because a discrete fault scarp deforms the seafloor across this Holocene-active channel, this provides strong evidence for Holocene activity of this megasplay fault (McCalpin & Nelson, 1996). This fault also aligns with the seaward edge of the IOWTZ, where there is a major lithologic boundary in the wedge that can work to focus fault deformation (e.g., Wendt et al., 2009). At the eastern edge of the IOWTZ there is a ~3.4x decrease in the overall channel gradient from 1.7° to 0.5° (**Fig. 4c**). Similar to our findings at the Barkley Channel, this indicates that regional-scale longitudinal channel morphology is linked to major transitions in accretionary wedge lithology.

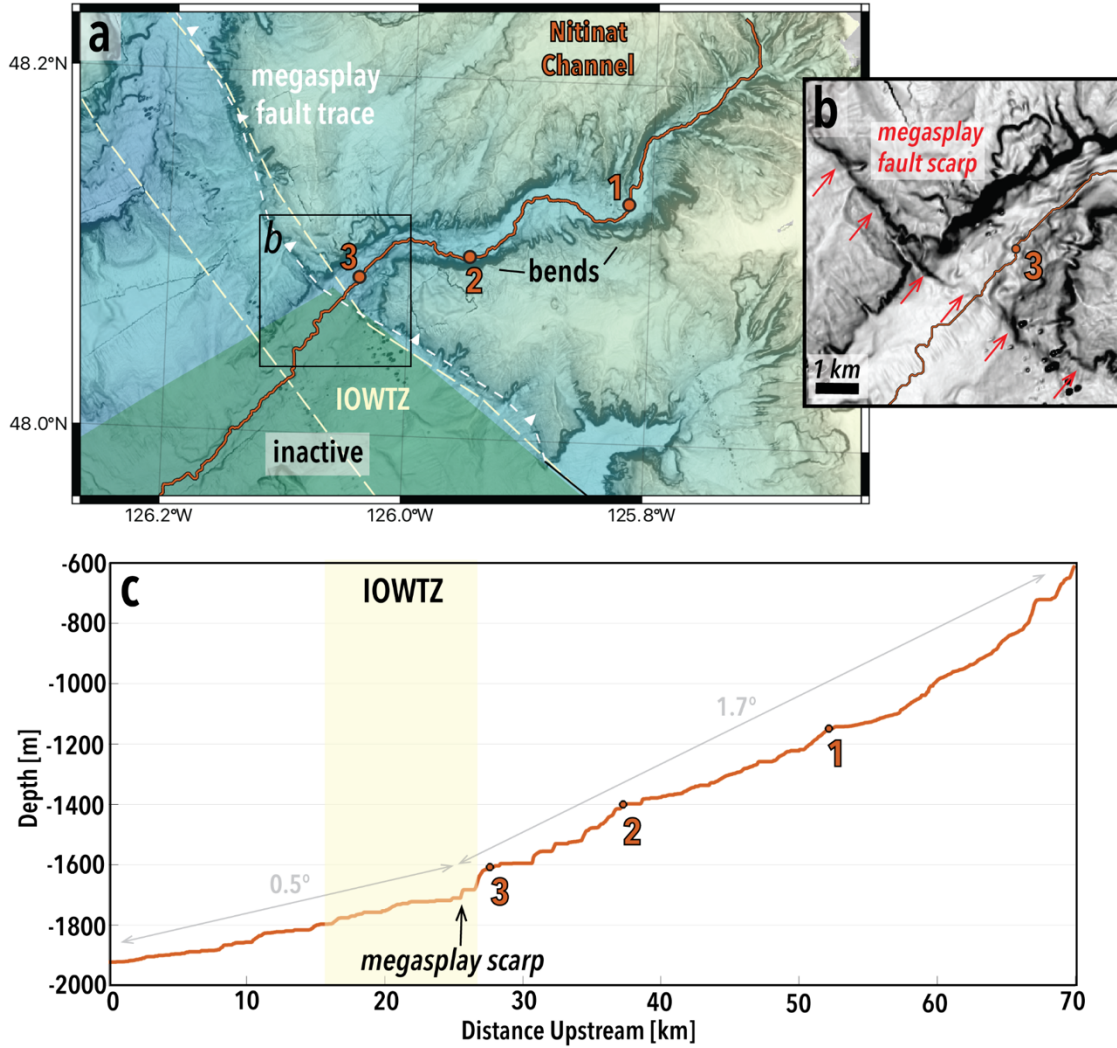


Figure 4. Nitinat Channel. a. Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, b. slope map inset of megasplay fault scarp, and c. corresponding longitudinal profile.

3.4.3 Juan de Fuca Channel

The Juan de Fuca Channel has 4 knickpoints along its profile. From channel head to where the channel first crosses the deformation front at Knickpoint 3, the Juan de Fuca Channel spans a length of ~180 km. The channel traverses across the landward vergence zone, including the active and inactive fault domains of the outer wedge (Ledeczi et al., 2024). The upper reaches

of the Juan de Fuca Channel east of $\sim 125.75^{\circ}\text{N}$ exhibit intermittent channel activity (Goldfinger et al., 2017). The Juan de Fuca Channel is unique in that it intersects the deformation front of the accretionary wedge twice (**Fig. 5**; df1 & df2).

Knickpoint 1 occurs just upstream of the IOWTZ within the region of intermittent channel activity. The overall gradient of the channel decreases at this knickpoint by 2.25x from 0.9° to 0.4° , and this inflection point in channel slope is co-located with the eastern edge of the IOWTZ (**Fig. 5c**). Since no previously mapped fault structures occur near this knickpoint, this indicates that this knickpoint may be generated solely by the lithologic transition between the outer and inner wedge domains. Due to a lack of channel activity within the Holocene, this knickpoint may be a relatively old feature compared to features identified in the Holocene-active regions of the channel.

Knickpoint 2 occurs within the inactive domain of the landward vergence zone and its shape is more diffuse compared to the other knickpoints in this channel, likening it to a knickzone rather than a knickpoint (**Fig. 5a,c**, “knickzone”). This knickzone is located at the confluence between the main Juan de Fuca Channel and an auxiliary channel (**Fig. 5a**). Both of these channels are mapped as Holocene-active by Goldfinger et al. (2016). The confluence of two channels at Knickpoint 2 likely contributes to its origin, as no faults or other seafloor features are mapped here. Sediment input and deposition from the auxiliary channel may contribute to the knickzone development upstream of the knickpoint.

The northern extent of the active domain as mapped by Ledeczi et al. (2024) ends where the Juan de Fuca Channel crosses the deformation front (**Fig. 5a**, “df”) at Knickpoint 3. Knickpoint 3 is much sharper compared to Knickpoints 1 and 2. Just to the south of Knickpoint 3, an active landward vergence thrust fault is mapped. This fault exhibits a discrete scarp at the

seafloor that can be traced across the channel bed (**Fig. 5b**). The presence of an active fault scarp within this Holocene-active channel provides evidence for Holocene activity of this fault.

After crossing the deformation front, the Juan de Fuca channel travels out onto the Nitinat Fan and then turns back towards the deformation front. The channel passes through an area of poor bathymetric data coverage and then crosses two active splay faults at the deformation front. The first of these active faults occurs in an area with poor bathymetric coverage and is not reflected in the channel profile. However, the second fault the channel crosses generates a sharp knickpoint within the channel profile, similar in shape to Knickpoint 3 (**Fig. 5c**). Again, this suggests Holocene activity of this frontal thrust fault strand.

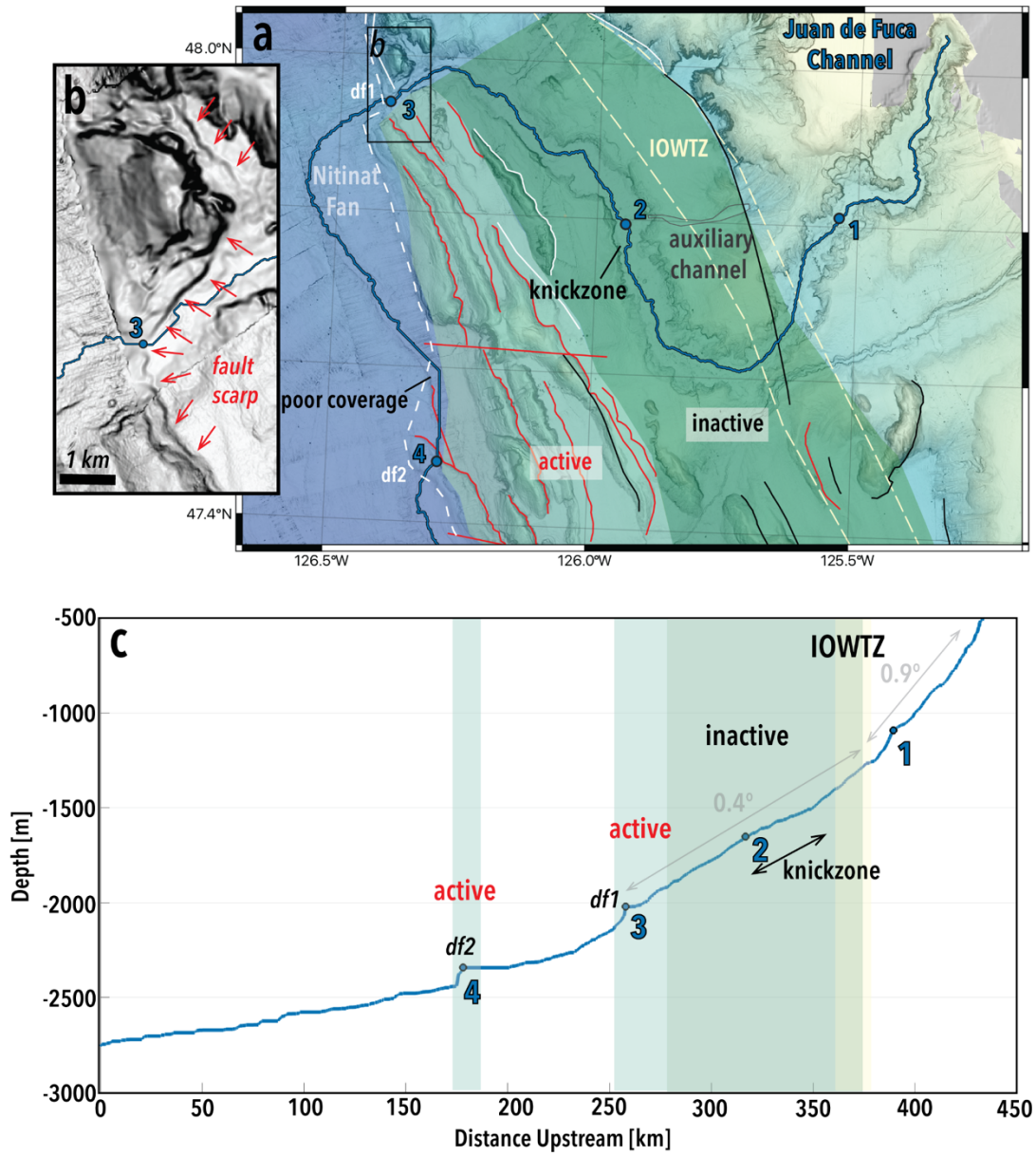


Figure 5. Juan de Fuca Channel. **a.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, **b.** slope map inset with fault scarp, and **c.** corresponding longitudinal profile with wedge domains from Ledeczi et al. (2024).

3.4.4 Quillayute Channel

The Quillayute Channel is ~140 km in length and exhibits 5 knickpoints along its channel profile (Fig. 6). The channel crosses the IOWTZ and both the active and inactive domains of the

accretionary wedge. The Quillayute Channel is narrower compared to the other submarine channels evaluated in this study (**Fig. 6a**).

Knickpoint 1 occurs within the midslope region of the accretionary wedge, just upstream of the IOWTZ (**Fig. 6b**). Prior to the knickpoint, the channel gradient decreases from 2.1° to 0.7° , a 3x decrease in slope (**Fig. 6d**). Downstream of the knickpoint, the channel gradient slightly increases from 0.7° to 0.6° . Knickpoint 1 is co-located with a north-south trending fault scarp at the seafloor (**Fig. 6b**). This scarp is not imaged by modern seismic surveys, so its subsurface structure is unknown. Because the scarp deforms the Holocene-active channel bed, we can assume Holocene activity of this structure. This particular area of the inactive domain is one of the only areas where active splay faults are mapped (Ledeczi et al., 2024). The presence of this structure in addition to the active fault to the southwest, suggests a localized zone of fault activity within the inactive domain. The occurrence of localized activity at the IOWTZ indicates that the wedge lithologic transition may play a role in the activation of these faults (**Fig. 6a**). Downstream of the area of localized fault activity, the channel profile of the Quillayute Channel is smooth and uniform throughout the rest of the inactive domain, despite the channel intersecting multiple prominent thrust fault ridges.

Knickpoints 2-5 all occur within the active domain and are co-located with active landward vergent splay faults near the deformation front. These thrust ridges are offset by an active left-lateral strike-slip fault which coincides with where the Quillayute Channel crosses the deformation front. The co-location of knickpoints with thrust ridges (**Fig. 6c**; r1-r4) indicates that uplift on active splay faults created these knickpoints, as they have not migrated up the channel and remain sharp. This also indicates Holocene activity on each of these splay faults, consistent

with independent structural mapping by Ledeczi et al. (2024) constrained by sparker seismic data.

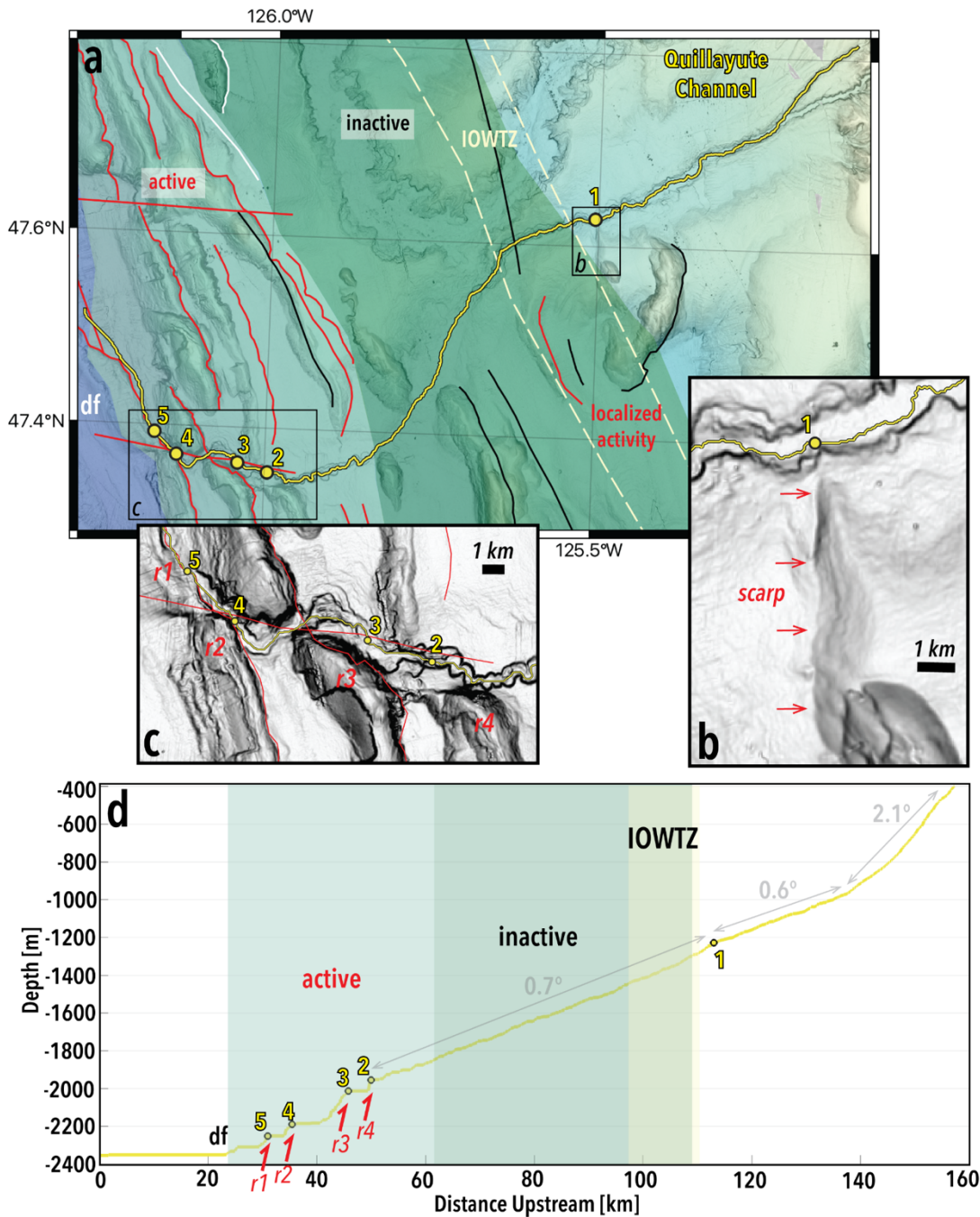


Figure 6. Quillayute Channel. **a.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, **b.** slope map insets with mapped splay faults, **c.** fault scarp, and **d.** corresponding longitudinal profile with wedge domains from Ledeczi et al. (2024).

3.4.5 Quinault Channel

The Quinault Channel spans ~200km from channel head to where it merges with the Willapa Channel (**Fig. 7**). The channel crosses the IOWTZ and the inactive domain, with two knickpoints identified along the channel profile (**Fig. 7c**). Unlike other channels analyzed, the Quinault Channel primarily traverses the accretionary wedge in the south-southwest direction. Upon exiting the very steep Quinault Canyon (**Fig. 7c**, “canyon”), the Quinault Channel crosses the IOWTZ. Within the IOWTZ, the channel longitudinal profile transitions from relatively steep (0.7°) to nearly flat (0.1°) (**Fig. 7c**). This represents a 7x decrease in channel gradient at the beginning of the IOWTZ. This abrupt change from steep to nearly flat at the IOWTZ is associated with Knickpoint 1 and may indicate a strong link between the channel profile and underlying wedge lithology, as observed for other channels so far.

Past the IOWTZ at Knickpoint 1, the channel turns south and steepens again to 0.3° , passing between splay fault thrust ridges of the outer wedge and midslope topography of the inner wedge. Between Knickpoints 1 and 2, the channel maintains a smooth, near constant gradient. At Knickpoint 2, there are not any observed faults, however at the channel bed we observe the seafloor expression of an adjacent inactive splay fault thrust ridge (**Fig. 7b**, “ridge”). Channel banks appear to have been cut into this ridge (**Fig. 7b**, “banks”), which provides evidence that the channel may be incising the ridge. This could be due to relative uplift along the active strike-slip fault mapped just to the south of this knickpoint, which would work to expose basement rocks of adjacent inactive thrust ridges and promote channel incision and passage. It may also be due to geomorphic processes unrelated to fault activity.

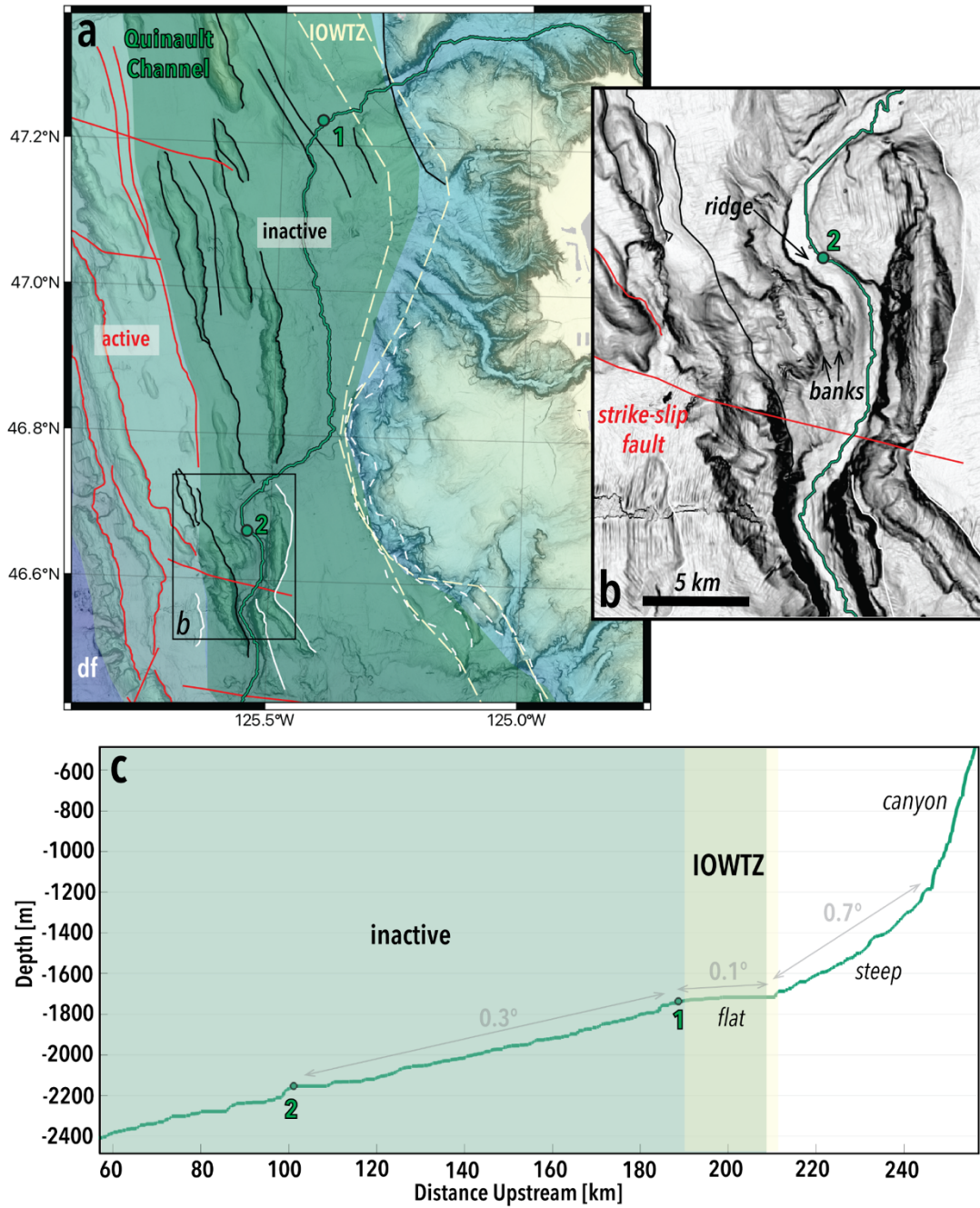


Figure 7. Quinault Channel. **a.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, **b.** slope map inset of Knickpoint 2, and **c.** corresponding longitudinal profile with wedge domains from Ledeczi et al. (2024).

3.4.6 Willapa Channel

Spanning a length of ~180 km, the Willapa Channel crosses one of the widest portions of the Cascadia accretionary wedge at an angle nearly perpendicular to the deformation front (**Fig. 8**). The channel exhibits 8 knickpoints and crosses the IOWTZ and both the active and inactive domains of the accretionary wedge until it exits at the deformation front onto the Astoria Fan (**Fig. 8a**).

Knickpoints 1-4 occur within the inner wedge and IOWTZ domains. These knickpoints occur near thrust faults mapped with both inconclusive and negative evidence for late Quaternary fault activity. Their formation may be linked to the presence of these faults, or potentially other channel bed processes unrelated to underlying wedge deformation. At the IOWTZ, overall channel gradient decreases by ~3.5x from 1.1° to 0.3° , reflecting the same transition from inner to outer wedge observed at other channels (**Fig. 8c**).

Knickpoints 5 and 6 occur within the inactive domain of the wedge. These knickpoints are not directly co-located with any mapped seafloor structures (**Fig. 8a**). However, at this location, a newly identified 42-km-long left-lateral strike-slip fault (Ledeczi et al., 2024) runs along the channel axis. This fault was mapped based on apparent offset of splay fault anticlines. The presence of two knickpoints in the vicinity of this structure provides additional evidence for late Quaternary activity on this structure. This structure may also work to route the Willapa Channel across prominent splay fault ridges at this location and out to the deformation front. Knickpoint 6 occurs just before the confluence of the Willapa and Quinault Channels, providing an alternate mechanism for its formation independent from fault activity.

Knickpoint 7 is located near the trace of an identified late Quaternary active splay fault within the active domain of the wedge (Ledeczi et al., 2024). However, this knickpoint appears

to more closely coincide with a potential right-lateral strike-slip fault that we observe to offset the splay fault ridge at the deformation front. We identify geomorphic evidence of this structure, including truncated thrust ridges on both sides of the channel and a likely scarp across the channel bed (**Fig. 8b**). Where active splay faults just upstream of Knickpoint 7 intersect the channel, the longitudinal profile is relatively unperturbed, suggesting that these faults do not extend as far south as currently mapped (**Fig. 8a**, “no fault signature”). Knickpoint 8 is located just outside of the active domain, seaward of the mapped deformation front. The presence of this knickpoint suggests that active splay faults at the deformation front extend further seaward than currently mapped (**Fig. 8a**, “extends further north?”). This would expand the extent of the active domain west at this location.

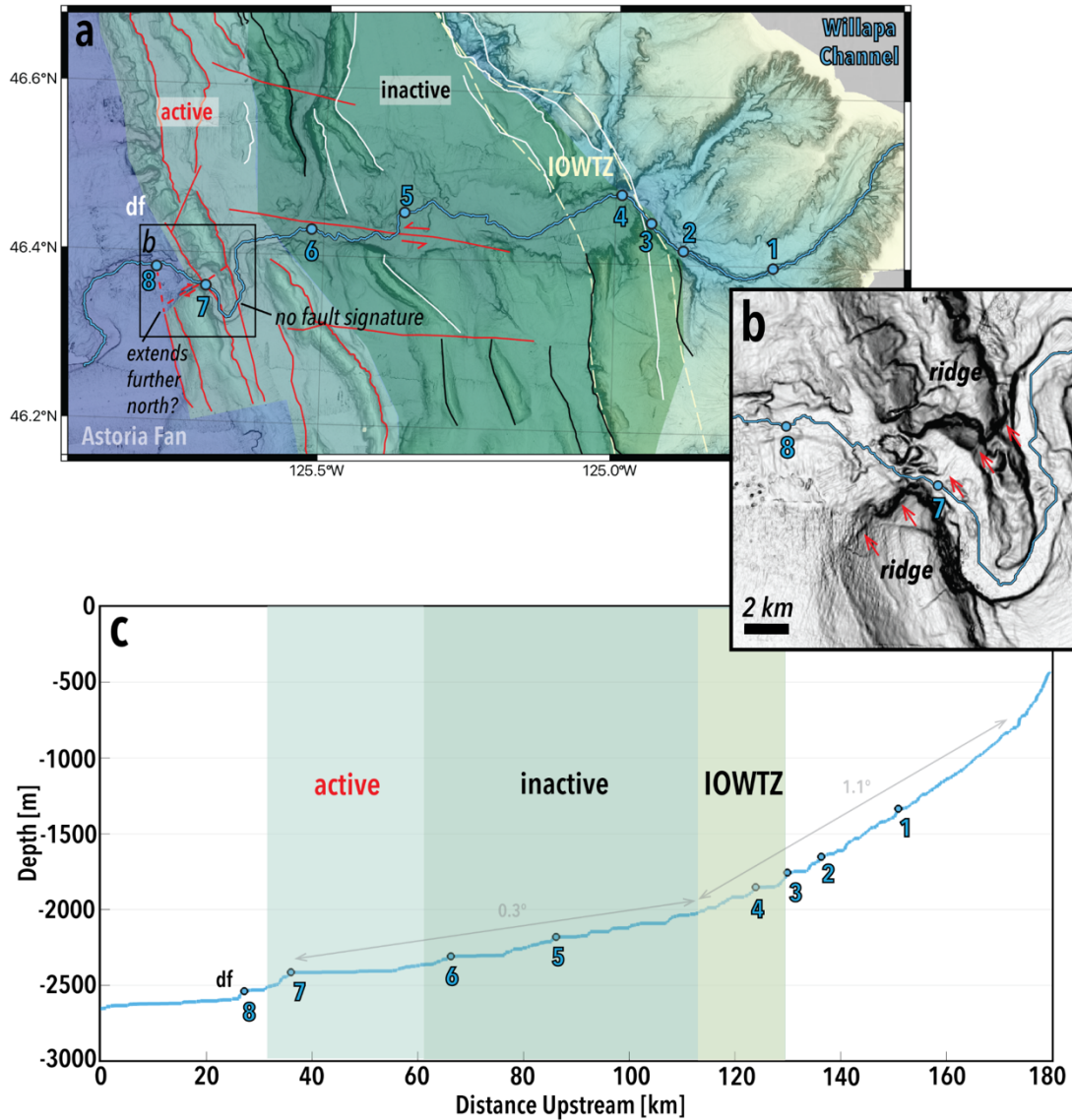


Figure 8. Willapa Channel. **a.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, **b.** slope map inset of channel-crossing strike-slip fault, and **c.** corresponding longitudinal profile with wedge domains from Ledeczi et al. (2024).

3.4.7 Astoria Channel

The Astoria Channel spans ~200 km from the shelf edge to the deformation front (**Fig. 9**). The channel exhibits 5 knickpoints, with most of these knickpoints located within the outer wedge domain. Intersecting numerous active and inactive splay fault thrust ridges at the seafloor,

the Astoria Channel incises deeply into the accretionary wedge and intersects the margin roughly perpendicular to the deformation front.

From the shelf edge, the Astoria Channel descends gradually down the midslope until Knickpoint 1. Knickpoint 1 is characterized by a broad knickzone between ~160 and 180 km distance upstream (**Fig. 9a,c**). The knickzone occurs just prior to the IOWTZ and is adjacent to a large slope failure on the southern bank of the channel (**Fig. 9a**). The IOWTZ begins at the base of the knickzone (Knickpoint 1) and is associated with a ~1.5x decrease in the channel gradient from 0.8° to 0.5°.

Knickpoints 2-5 occur within both the active and inactive domains of the wedge, but are focused near the active domain (**Fig. 9a,c**). The five knickpoints have a similar shape to each other, in contrast to the knickzone (Knickpoint 1). Knickpoints 2 and 3 are closely co-located with the trace of adjacent splay fault ridges. The presence of Knickpoint 2 allows us to map the trace of a new, active splay fault ridge north of the Astoria Channel. Knickpoint 3 allows us to identify more precisely where the active splay fault intersects the channel to the south. Both of these fault structures appear to truncate upon reaching the channel, as we cannot trace their expression across the channel. Knickpoint 4 is located near multiple active splay faults at the deformation front. However, upon close inspection, we identified a fault scarp that crosses the bed of the Holocene-active Astoria Channel that is more closely co-located with Knickpoint 4 than the other nearby splay faults (**Fig. 9a-b**). Knickpoint 5 also occurs along the trace of this fault scarp, where the fault appears to truncate a ridge seaward of the mapped deformation front (**Fig. 9a**, truncated ridge). This finding provides robust evidence for the presence of a Holocene-active fault intersecting the Astoria Channel. Based on the apparent offset of splay fault ridges by this structure, we interpret this fault as a right-lateral strike-slip fault. The sense of motion on this

structure is consistent with nearby strike-slip faults identified at the Willapa Channel (**Fig. 8**) and the Albatross Fault System mapped by Lucas et al. (in review). Similar to the Willapa Channel, offset created by this fault likely provides a conduit for the Astoria Channel to cross active splay fault ridges at the deformation front.

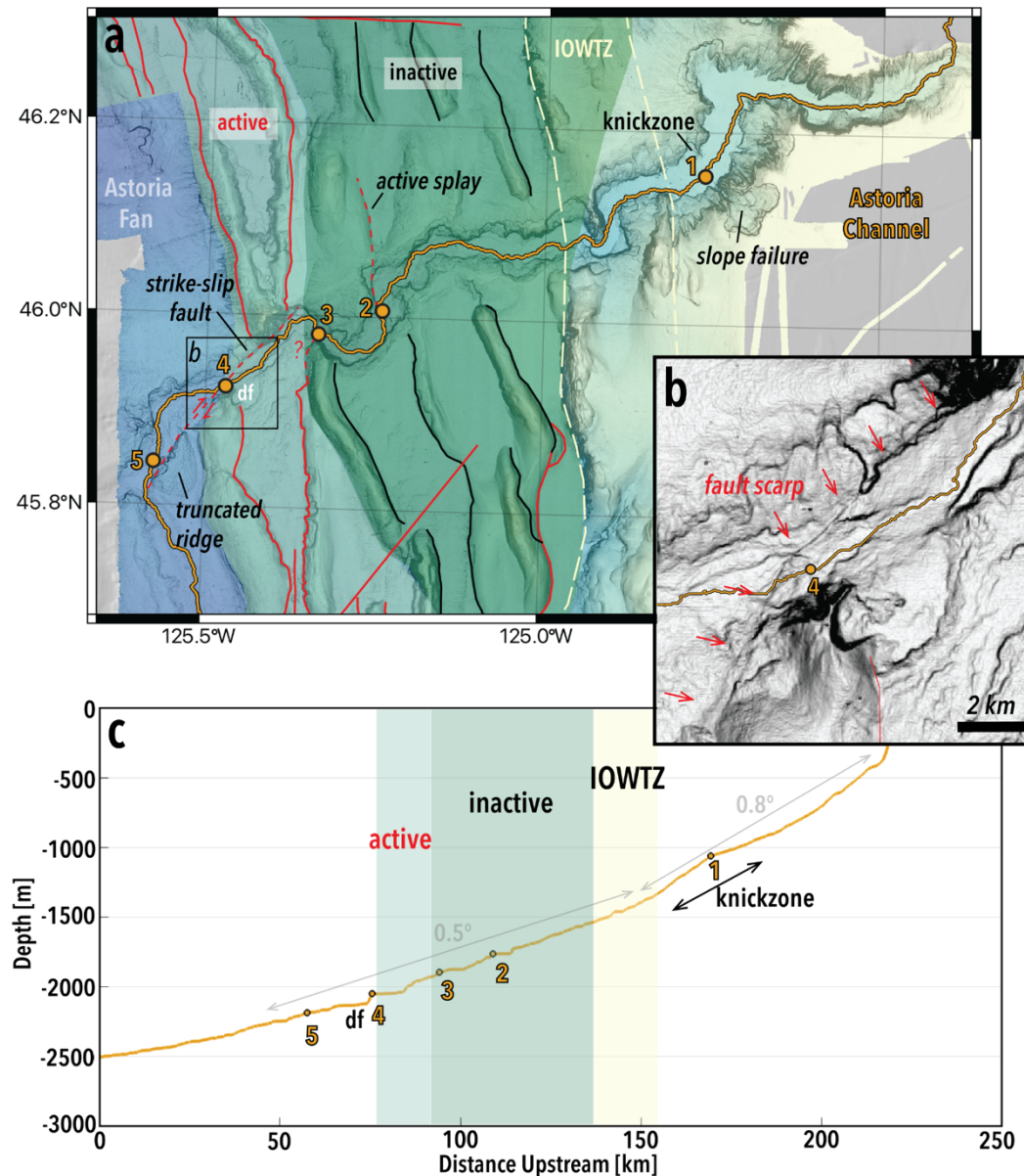


Figure 9. Astoria Channel. **a.** Partially transparent 30-meter USGS bathymetry overlaid onto slope map showing channel trunk, knickpoints, fault mapping, and IOWTZ, **b.** slope map inset of

channel-crossing strike-slip fault, and **c.** corresponding longitudinal profile with wedge domains from Ledeczi et al. (2024).

3.5 Discussion

Through systematic geomorphic analysis of seven major Cascadia submarine channels using *MATLAB*-based *Topotoolbox* and a 30-meter DEM, we demonstrate that channel morphology contains useful information about accretionary wedge deformation, faulting, and evolution. In ground-truthing our geomorphic observations with geophysical observations of subsurface structure, we have shown that geomorphic analysis tools in *TopoToolbox*, commonly used for subaerial topographic analysis, can also be applied to submarine topography to yield new insights into subsurface deformation. Our in-depth analysis of Cascadia submarine channels reveals the location of previous unmapped accretionary wedge faults, helps to further constrain fault locations and recency of fault activity, and provides insight into the processes that contribute to the co-evolution of submarine channels and the accretionary wedge through time.

3.5.1 Update of fault maps for the Cascadia accretionary wedge

We have identified and mapped new faults at each of the seven submarine channels analyzed in this study by combining evidence of channel longitudinal profile morphology with the observed bathymetric expression of faulting in 30-meter bathymetry (**Fig. 10a**). Based on our analysis, we present an updated fault map for the Cascadia accretionary wedge (**Fig. 10**) which supplements and improves upon previous fault maps for the region (Ledeczi et al., 2024; Lucas et al., 2025; Goldfinger et al., 2023).

Beyond mapping new faults, our methodology allows us to also improve the location of mapped faults, especially where faults intersect channels. Oftentimes, based on seafloor

expression alone, it is not clear how to map faults across submarine channels using only 2D seismic lines and bathymetry. In systematically analyzing the longitudinal channel profile morphology of seven Cascadia submarine channels, we have also improved fault mapping at each of the submarine channels. From our observations of deformation within Holocene-active submarine channels, we can further constrain fault activity at many locations beyond the late Quaternary and into the Holocene (**Fig. 10b-d**). This work represents a new methodology for mapping faults across submarine channels and determining their activity.

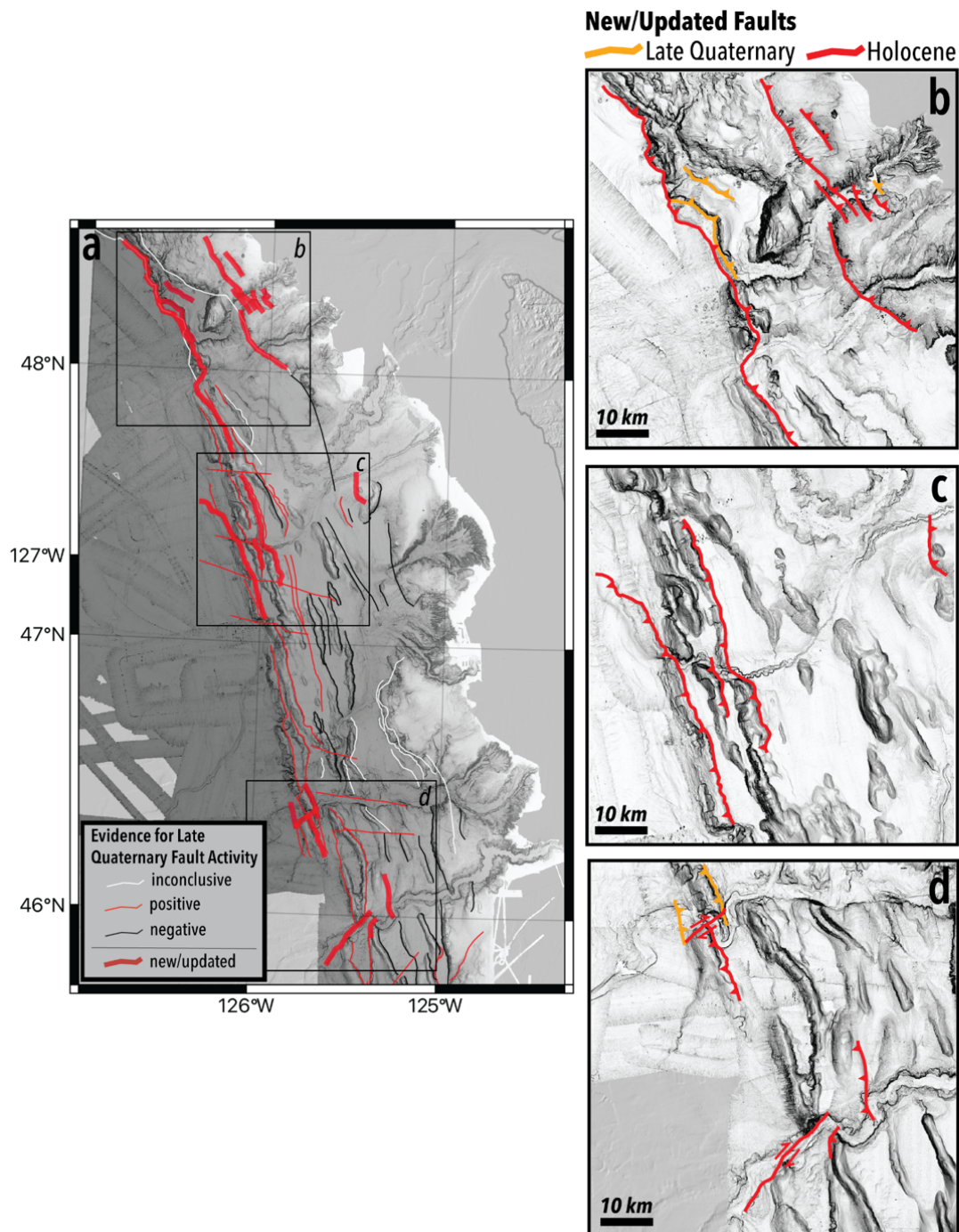


Figure 10. Updated fault map for the landward vergence zone of the Cascadia accretionary wedge based on morphologic analysis of submarine channels. a. Map highlighting new/updated late Quaternary faults mapped in this study with thick red lines. Mapping from previous studies shown in thin lines and color-coded based on evidence for late Quaternary fault activity. b-d. Insets showing late Quaternary and Holocene fault activity based on channel morphology. The type of faulting is indicated.

3.5.2 *Links between channel morphology and wedge structural mapping*

For all seven submarine channels analyzed, we found that systematic variations in longitudinal channel profile morphology (e.g., knickpoints, knickzones, channel gradient) correspond to mapped variations in accretionary wedge structure and recent fault activity (Ledeczi et al., 2024, Lucas et al., 2025). This suggests that the evolution of submarine channels at Cascadia is closely linked to accretionary wedge structure and behavior. Because of this linkage, submarine channel morphology can provide new insight into our overall understanding of subduction zone processes at the Cascadia margin.

We find that regional changes in channel gradient correspond well to the location of the IOWTZ where there is a major lithologic boundary between the younger, less-deformed outer domain and the older, more-deformed inner wedge domain (**Fig. 11a**). Channel gradients are generally observed to decrease seaward after crossing the IOWTZ. At the Quillayute, Quinault, and Astoria Channels (**Fig. 6, 7, 9**), we also observe low channel gradients within the IOWTZ. The mechanism for low channel gradients within the IOWTZ may be due to the transition from landward to seaward vergent thrust faulting, resulting in a net flattening of the channel profile in this zone due to fault uplift of opposing vergence. The lack of fault-related knickpoints within the region of the IOWTZ further supports the argument that there is no evidence of an active margin-spanning megasplay fault in this zone based on modern seismic and bathymetric datasets, but instead, that there are areas of localized out-of-sequence fault activity along the margin at the IOWTZ (Lucas et al., 2025). Overall, our results of longitudinal channel profile morphology reflect the major lithologic transition at the IOWTZ observed in CASIE21 seismic imaging.

The locations of fault-related knickpoints within channel profiles are highly consistent with the locations of splay faults mapped using CASIE21 seismic profiles and high-resolution

sparker seismic data (Ledeczi et al., 2024). Knickpoints concentrated within the active domain of the accretionary wedge are co-located with late Quaternary-active splay faults, whereas, within the inactive domain, there is a lack of splay fault-related knickpoints. This pattern in knickpoint distribution is especially apparent at Astoria, Quillayute, Barkley, and Nitinat Channels. Knickpoints occurring with the inactive domain are attributed to active strike-slip faults, variations in accretionary wedge structure (i.e., IOWTZ), and other surface processes (e.g., landslides, channel confluences). Excluding Astoria Channel, none of the knickpoints within the inactive domain are associated with splay fault thrust ridges, despite numerous channel intersections of these ridges. Astoria exhibits two knickpoints within the inactive domain, suggesting the active domain extends further eastward than currently mapped. At other channels, such as the Willapa Channel, knickpoints occur within the inactive domain, but are associated with an active left-lateral strike-slip fault.

Based on our analysis of channel-fault intersections, we can extend the mapping of the active and inactive domains further north of mapping completed by Ledeczi et al. (2024) north of 48°N (**Fig. 11b**). Because analysis methods used in this study are ground-truthed with high-resolution geophysical data, we are enabled to extend domain mapping of fault activity into this region where seismic data is lacking, but bathymetric coverage is excellent. The pattern of active faulting near the deformation front, an inactive domain further eastward, and then activity of faults past the IOWTZ is highly consistent with findings for the rest of the outer wedge domain by Ledeczi et al. (2024) and Lucas et al. (2025) (**Fig. 11c**). This high degree of consistency between submarine channel morphology and subsurface fault structure and activity strengthens arguments made previous works (Ledeczi et al., 2024; Lucas et al., 2025) describing modern accretionary wedge behavior and the likelihood of different splay fault rupture scenarios in the

next Cascadia megathrust earthquake. However, our results must be verified with subsurface geophysical imaging of this region.

North of this $\sim 48.5^\circ\text{N}$, publicly available bathymetric coverage offshore central and northern Vancouver Island is poor (greater than 50-meter grid resolution). Therefore, we cannot extend our analysis into this region until this data is made available. However, interpretation of CASIE21 seismic data and GMRT 50-meter bathymetry by Lucas et al. (2025) suggests that there is preliminary evidence of late Quaternary fault activity in this region as well, but this hypothesis has yet to be verified with high-resolution seismic and bathymetric datasets. Because channels cross the accretionary wedge offshore central and northern Vancouver Island, there is the potential to apply our methodology when adequate bathymetric datasets become available.

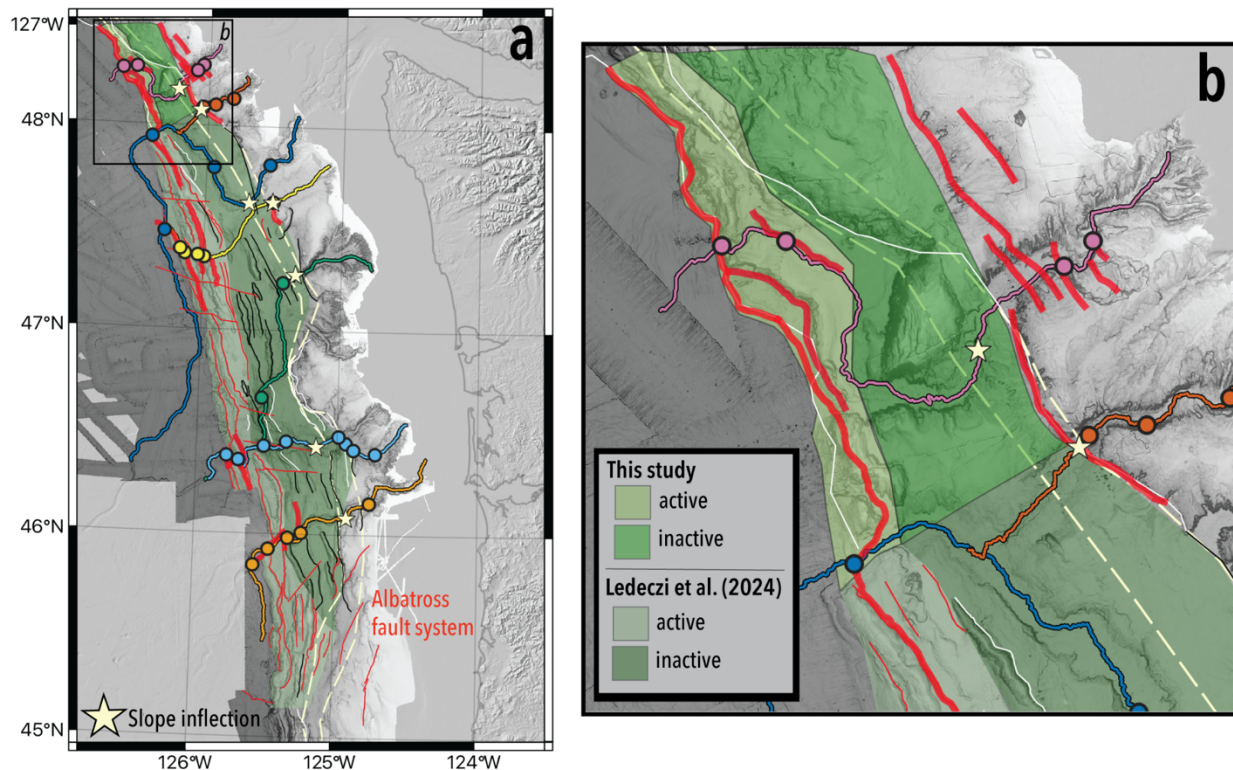


Figure 11. Accretionary Wedge Structural Domain Mapping. **a.** Summary map showing accretionary wedge domains, channel locations and knickpoints, channel gradient inflection

points, and fault mapping. **b.** Map showing extension of active and inactive domains enabled by this study. **c.** Schematic figure modified from Ledeczi et al. (2024) showing the inflection point relative to the inner-outer wedge transition zone (IOWTZ) and megasplay faulting.

3.5.3 *Relationship between megathrust coupling and accretionary wedge faulting*

Lucas et al. (in review) and Lucas et al. (2025) characterized the Albatross fault system, a series of en echelon right-lateral strike-slip faults near the IOWTZ between 45°N and 46°N (**Fig. 11**, “Albatross fault system”). In this study, we have identified a system of previously unmapped faults north of 48°N at the IOWTZ. From modern GPS and GNSS-Acoustic datasets, it has been determined that the shallow megathrust in central Cascadia is likely fully coupled at the deformation front (DeSanto et al., 2025; Lindsey et al., 2021) (**Fig. 12**). The fully coupled portion of the megathrust has also been shown to correspond with active faulting at the deformation front within the landward vergence zone (e.g., Ledeczi et al., 2024). Areas of active faulting within the IOWTZ (**Fig. 12**, “active faulting”) are observed to follow contours of the slip rate deficit (coupling) ratio from Lindsey et al. (2021) at the northern and southernmost ends of the most highly coupled region. A similar pattern between megathrust coupling and accretionary wedge faulting has been observed at the New Zealand subduction margin (Lamb et al., 2018). This observation suggests interseismic stress at the Cascadia subduction zone accumulates along megathrust coupling contours. This could help explain why active accretionary wedge faulting at Cascadia appears to coincide with coupling contours determined by Lindsey et al. (2021) as well as the lack of fault activity at the IOWTZ between 46°N and 48°N (Lucas et al., 2025) (**Fig. 12**, “IOWTZ”).

3.5.4 *Co-evolution of submarine channels with the accretionary wedge*

The Quinault and Juan de Fuca Channels appear to be routed to both the north and south of the highly coupled region of the deformation front in central Cascadia (**Fig. 12**). This planform pattern in channel routing suggests faults in this coupled region may have a relatively high strain rate compared to surrounding faults (**Fig. 12**, “high strain rate?”) (e.g., Pizzi et al., 2021). This would also imply that accretionary wedge fault activity is linked to the degree of megathrust coupling. If this is true, accretionary wedge fault behavior could be used to help constrain megathrust coupling and ground-truth geodetic coupling models for Cascadia. Overall, both structural and geomorphic observations of fault activity are highly consistent with geodetically constrained observations of plate coupling. Improved resolution of offshore coupling will help to further refine our understanding of the inter-dependence between megathrust coupling and accretionary wedge behavior.

The Quillayute Channel does cross the deformation front through the proposed high strain rate region. This is likely enabled by accommodation space created by offset of splay fault thrust ridges by a left-lateral strike-slip fault (**Fig. 6**). Similar processes have been observed at the Yinggehai Basin of the South China Sea, where strike-slip faults are observed to control the generation and evolution of submarine channels. Strike-slip fault activity can work to align channels within the tectonic architecture and cyclically modify accommodation space, dictating the location of sediment depocenters (Noda & Toshimitsu, 2009). In addition, the relatively straight path the Quillayute Channel takes across the wedge further suggests high fault uplift rates in this region because decreased submarine channel sinuosity is linked to active fault uplift (Ferry et al., 2005; Clark and Cartwright, 2011).

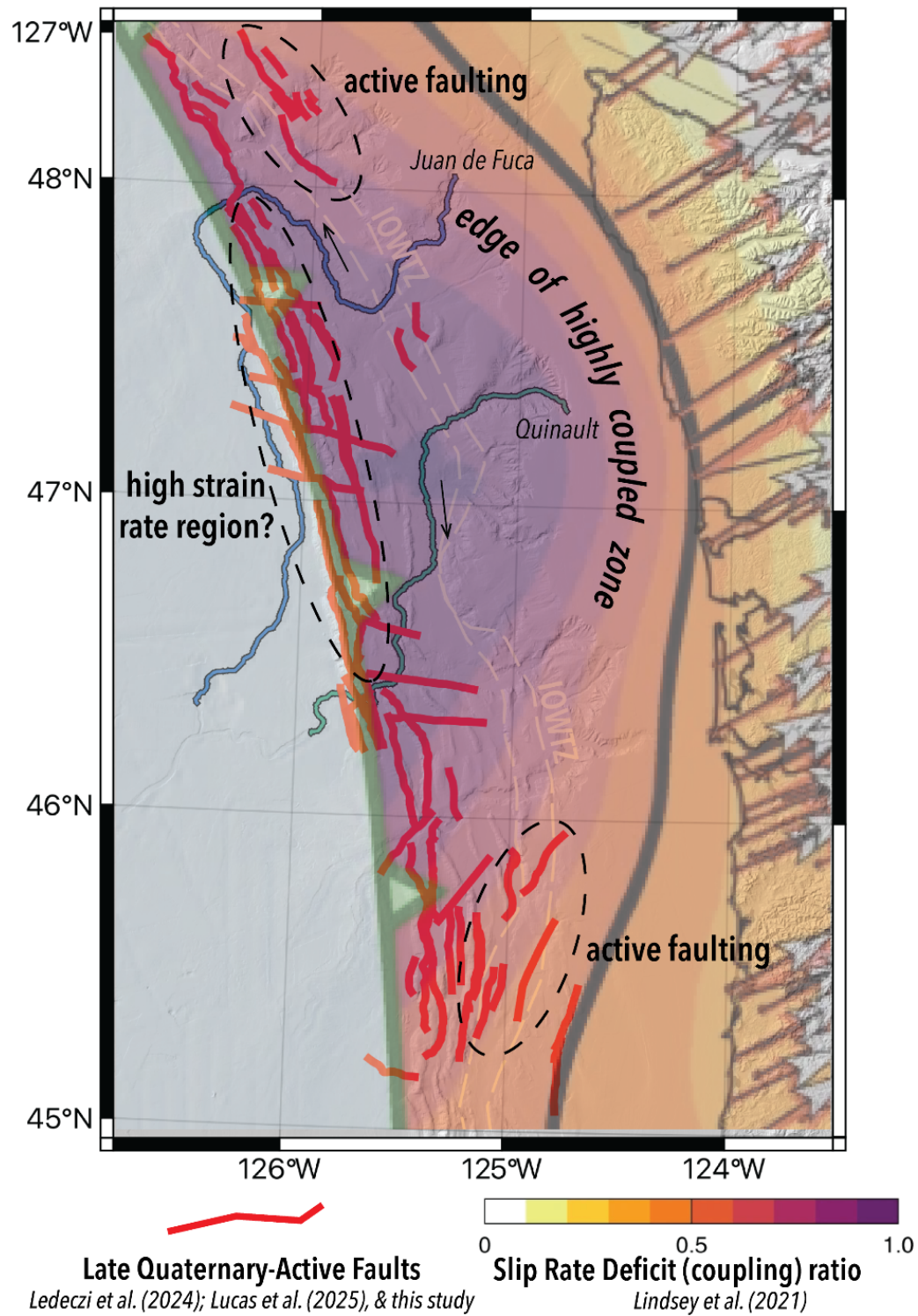


Figure 12. Cascadia best-fit slip deficit model from Lindsey et al. (2021) overlaid onto Late Quaternary-active faults as mapped by Ledeczi et al. (2024), Lucas et al. (2025), and this study.

3.6 Conclusion

In this study, we demonstrated the utility of applying traditionally subaerial topographic analysis tools in *MATLAB*-based *TopoToolbox* to quantify the longitudinal morphology of submarine channels. Overall, we found that late Quaternary active faults within the Cascadia accretionary wedge can be correlated with knickpoints in submarine channel longitudinal profiles, while inactive faults are generally not correlated with knickpoints. Using this methodology, we mapped new late Quaternary and Holocene active accretionary wedge faults across Cascadia submarine channels and improved the locations of previously mapped faults at channel-fault intersections. In addition, we found that the location of the inner-outer wedge transition zone is correlated with an inflection point in the slope of each longitudinal channel profile, indicating submarine channel morphology is linked to underlying variations in wedge structure and lithology. Our results provide new insights into the co-evolution of the Cascadia accretionary wedge and submarine channels. Our methodology is easily reproducible and widely applicable to other active plate margins with good bathymetric coverage. We find that it is important to ground-truth geomorphic observations with geophysical observations of subsurface deformation prior to applying this methodology to locations where geophysical data is lacking or non-existent. By examining our results within the broader tectonic context of the Cascadia subduction zone, we find that regional-scale patterns in channel planform and profile morphology appear to be linked to geodetically constrained megathrust coupling behavior.

4. Chapter 4: The Riverways Model: Culture and Science Exchange with the Quileute Tribal School

T'ísik^wls Madeleine Lucas. Híli hók^wat. Ótíx^wli Mishigamaw. Híli piłashìk^wáyo ó chí
Washitódlo k^wolhawísti. Paqítli x^w shi?íq^wal tsikáti híxat x^wpido?ásh.

*My name is Madeleine Lucas. I am of European descent (literal translation: person living in
drifting house). I am originally from Michigan. I am a student at the University of Washington. I
work on earthquakes and tsunamis.*

I respectfully recognize and honor the students, teachers, staff, and community members
of the Quileute Tribal School (QTS) and the Quileute Tribe, for the knowledge they have
generously shared with me over the past four years through participation in the Quileute Culture
and geoScience Exchange (Quileute CASE) program within the University of Washington's
Riverways Rural and Tribal Partnerships Programs (UW Riverways). This chapter is dedicated to
all individuals who have contributed to and supported Quileute CASE and STEM Alternative
Spring Break (STEM ASB) at QTS since the program's inception more than a decade ago.

The contents of this chapter reflect my personal experience serving as a Quileute CASE
Team Leader for three years (2022-2025) and lessons I have learned from engagement with the
Quileute community through the program from 2022-2026. This chapter is presented as an
autoethnography examining experiences in educational partnership with the Quileute community
to explore how these experiences may inform approaches to building relationships between

academic institutions and rural and tribal communities. This chapter does not represent the Quileute Tribe or QTS.

Sincere acknowledgement is extended to Alice Ryan, Miss Ann Penn-Charles, Scott Jackson, Dame Jones-Smith, Charlotte Penn, Cole Peregrine, Alexis Ward, Cody LeClair, Marie Riebe, Miss Ramona, Susan Meeds-Bashe, James Jaime, Jacob Anderson, Sierra Hemmig, Jill Silver, Shannon Fasola, Noelani Villa, Doug Gibbons, Marcus Conde, Harold Tobin, and the Quileute Drum and Healing Circle for their support of the Quileute CASE program over the years.

Recognition is also given to all past, present, and future members of the Quileute CASE team, particularly Mya Baker, Verónica Gaete-Elgueta, Julia Grossman, Abbey Moore, Alyssa Iverson, Paul Morgan, René Castillo, Bering Tse (2025-26 Quileute CASE Team Leader), Elizabeth Davis, and Abigail Natoli. Further thanks to UW Riverways staff Richard Parra and Alison Horn for their tireless efforts to make this program run year after year. Your dedication to the Riverways mission is immensely valued and appreciated.

Finally, support from the NASA Northwest Earth and Space Science Pathways (NESSP) Program, the Cascadia Coastlines and Peoples (CoPes) Hazards Research Hub Pilot Project Program, the Pacific Northwest Seismic Network (PNSN), and the Cascadia Region Earthquake Science Center (CRESCENT) Seed Grant Program is gratefully acknowledged.

Liʔatskál xabá!

Thank you, everybody!

4.1 Riverways pedagogy

The UW Riverways program mission is “connecting students, schools, and communities towards tribal sovereignty and racial justice”. The program intentionally practices *culturally sustaining* and *place-based pedagogy* in the development and teaching of K-12 curriculum. Culturally sustaining pedagogy supports the continuation of Indigenous language and cultural practices while enabling engagement with dominant societal systems (Paris, 2012). Placed-based pedagogy centers curriculum within the local environment and communities, emphasizing experimental and context driven education (Sobel, 2006). Together, these approaches align with the concept of *two-eyed seeing*, which integrates Indigenous and Western knowledge systems to support holistic understandings of the world (Bartlett et al., 2012; Cirkony et al., 2023; Hatcher et al., 2009; Smith et al., 2023).

4.2 Building educational partnerships *in a good way*: The Riverways Model

The UW Riverways program aims to build educational partnerships with rural and tribal communities across Washington state that are based in trust and reciprocity. Historical and ongoing impacts of settler colonialism have contributed to well-documented distrust of academic institutions among indigenous communities (Burnette et al., 2011; Burnette & Sanders, 2014; McKinley, 2022; Smith et al., 2023; Talaga, 2025; Wolfe, 2006). Building these relationships requires long-term commitment, humility, cultural competency, and collaboration with Indigenous community members and scholars (Matson et al., 2021; RedCorn, 2016; Riley & Kaneakua, 2024).

UW Riverways uses a staged approach to building educational partnerships with rural and tribal communities in Washington state. Sequentially, the stages include:

- 1) Day-long site visits and campus visits
- 2) Quarter-long STEM Alternative Spring Break
- 3) Year-long Culture and Science Exchange program

Through each stage, relationships are built between UW Riverways and the community that strengthen over time. Throughout this process, it is crucial to continuously seek permission and consent to engage with the rural or tribal community you are partnering with (Fitzpatrick et al., 2016).

4.2.1 Stage 1: Site and campus visits

One-day site visits are the first step in starting a new educational partnership with a rural or tribal school and their community. Site visits are an opportunity for Riverways students to build relationships with the school's students, teachers, and staff. More so than teaching, these visits are an opportunity for UW Riverways students to learn about the culture of the community and to experience *place* through the community's perspective. This step is crucial because it enables Riverways and the community to begin co-developing a K-12 curriculum that sustains the unique culture of the partnering community and ensures that the local environment is at the center of all educational programming. Multiple one-day site visits may be needed before taking

the next step to STEM Alternative Spring Break, as building relationships is a continual activity for this work.

4.2.2 *Stage 2: STEM Alternative Spring Break (STEM ASB)*

STEM Alternative Spring Break (STEM ASB) is a quarter-long Riverways program in which UW undergraduate and graduate students take an *Education* seminar course during Winter quarter led by UW Riverways staff. During this seminar, teams of 3-6 UW students learn how to create and teach a culturally sustaining and place-based K-12 STEM curriculum. Over UW spring break, the Riverways student teams travel to rural and tribal schools across Washington state to teach the curriculum they built over the quarter (**Fig. 1**). During STEM ASB, UW students are encouraged to attend community events, foster relationships with students, teachers, and community members, and experience the local environment. By spending time in community and in place, UW students are exposed to new cultures and customs, get an opportunity to practice their cultural competency skills (e.g., Santiago, 2017), and increase their overall awareness and understanding of rural and tribal issues in Washington state.

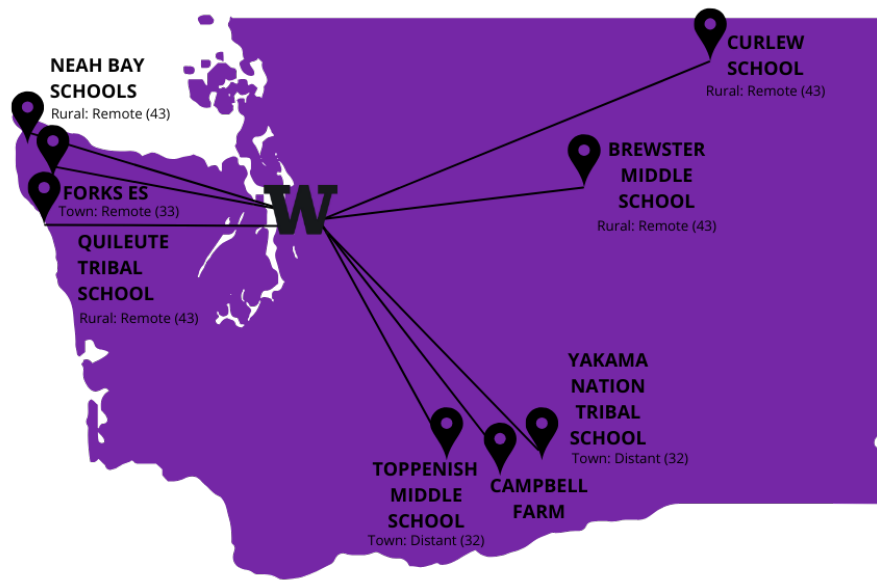


Figure 1. Map of UW Riverways educational partnerships with K-12 schools across Washington state. (Credit: Riverways)

4.2.3 Stage 3: Culture and Science Exchange (CASE)

The Culture and Science Exchange (CASE) program is a year-long Riverways program that prioritizes cultural exchange, K-12 student mentorship, indigenous STEM education, and career pathways after high school. During CASE, Riverways student mentors make multiple site visits to partnering tribal communities throughout the year in addition to STEM ASB. Site visits include, but are not limited to, attending cultural and community events, leading or participating in local field trips, and arranging mentorship meetings and workshops with QTS students participating in the CASE high school internship program. By tying culture and science together, the CASE program aims to sustain the culture of tribal K-12 students through place-based STEM education (Santos & Parra, 2021).

Inspired by the growing philosophy of braiding together Indigenous and Western knowledge systems *in a good way* (Bowles et al., 2026; Eisenberg et al., 2024; Kimmerer, 2013;

Mehrtretter et al., 2024), the growth of educational partnerships between UW Riverways and tribal communities can be visualized as a braided river. In this *Riverways Model*, the confluence of two rivers, one representing Indigenous Knowledge Systems and one representing Western Knowledge Systems, creates a new braided river system where aspects of both knowledge systems are woven together into K-12 education (**Fig. 2**).

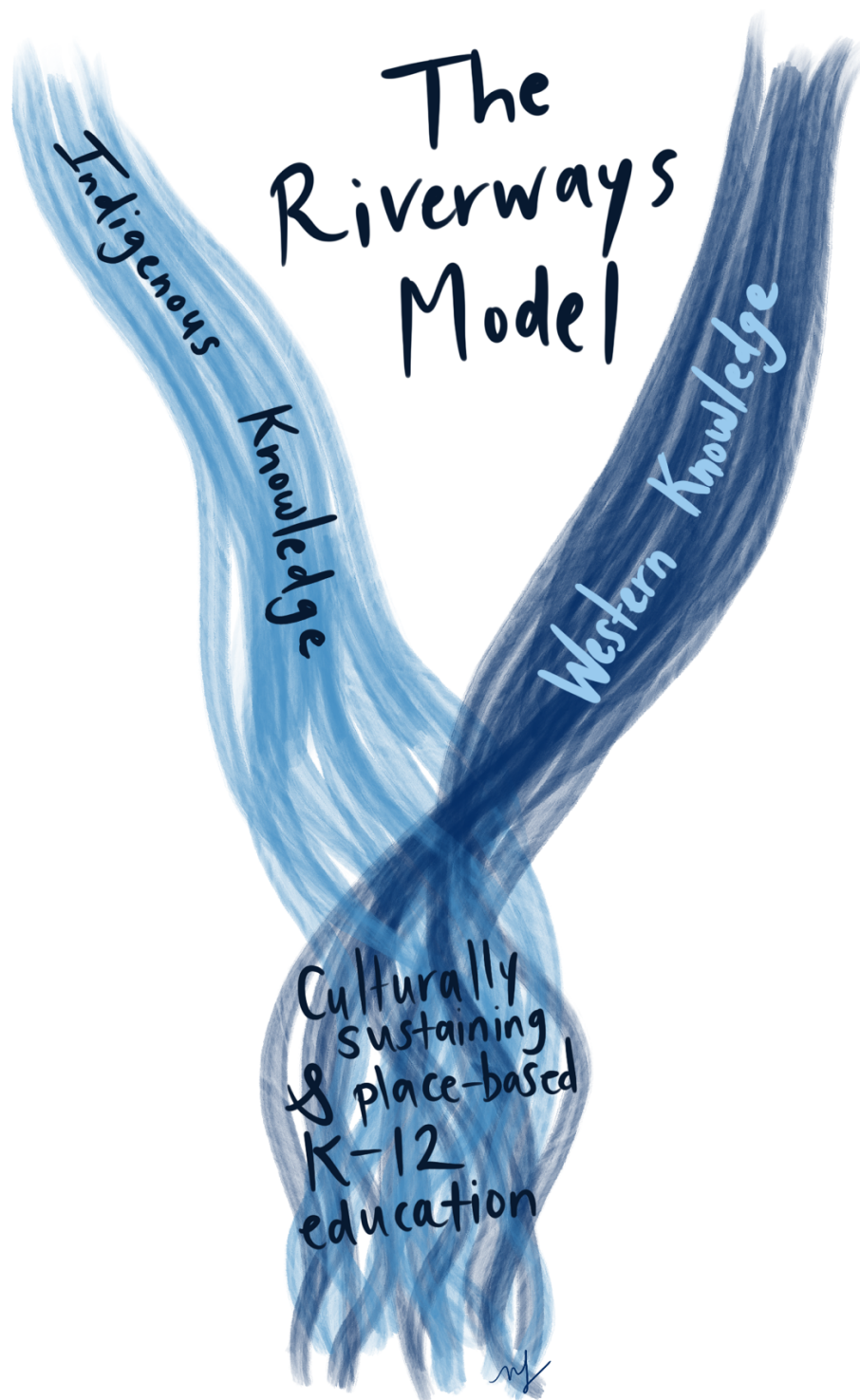


Figure 2. Drawing of the Riverways Model representing the braiding of Indigenous and Western knowledge into culturally sustaining and place-based K-12 education.

4.3 Quileute Culture and geoScience Exchange Program

4.3.1 *Overview*

Over the last four years (Winter 2022-Spring 2026), the Quileute High School STEM ASB program grew and transformed into the Quileute Culture and geoScience Exchange (Quileute CASE) program. The Quileute CASE program aims to respectfully and intentionally engage in reciprocity with the Quileute Tribe through culture and science exchange. With every passing year, educational partnerships between UW Riverways and QTS grow stronger alongside relationships between Quileute CASE team members, QTS students, teachers, and staff, and the Quileute Tribal community (**Fig. 3**). Each year of the Quileute CASE program features a new curriculum focusing on a different geoscience topic relevant to the Quileute Tribe: geology (2022-23), seismology (2023-24), geomorphology (2024-25), and sedimentology/tsunamis (2025-26). In curriculum development, we prioritize using culturally sustaining and place-based pedagogy by incorporating Quileute culture and language into our lessons and focusing on local geoscience questions and topics relevant to the Quileute Tribe. We also invite Quileute Elders, knowledge-holders, and Quileute Tribal employees to share their stories, wisdom, experiences, and career pathways with the QTS students where it relates to the year's topic. Every year STEM ASB includes a one-day field trip to a local site where students apply what they learn in the classroom to their real-world environment. In addition, the Quileute CASE team has mentored two cohorts of paid high school interns to complete geoscience projects relevant to their community and will be recruiting the next internship cohort in Summer 2026. In the following sections, I provide examples of how the Quileute CASE program applies culturally sustaining and place-based pedagogy to the development and teaching of high school geoscience

curriculum at QTS. I also expand upon how we engage in co-mentorship, cultural exchange, and knowledge-sharing with QTS and the Quileute Tribe.



Figure 3. QTS High School class, QTS Science Teacher Alice Ryan, 2022-23 Quileute STEM ASB Team holding up Quileute Tribe's flag during STEM ASB 2023.

4.3.2 Culturally sustaining and place-based pedagogy

K^woʔliyoʔiskʷa (Quileute language) is the defining element of Quileute culture (Quileute Tribe, accessed May 2026). Therefore, as teachers we must learn the Quileute language and incorporate it into our geoscience lessons to create a culturally sustaining curriculum. To this end, every year, the Quileute CASE team takes a class with Quileute language teacher Scott Jackson to learn how to pronounce Quileute and to develop our Quileute introductions (see beginning of this chapter for my Quileute introduction). Outside of language classes, the

Quileute CASE team studies books on Quileute language and culture (Powell, 2016; Powell et al., 2017; Woodruff & Powell, 2017). In addition, we use Quileute language resources available online, including the *Kʷoʹlíyoʹ* (Quileute) app and the *English to Quileute Online Dictionary* (Burtness et al., accessed May 2026) to learn Quileute vocabulary and practice our pronunciation. We apply what we learn by introducing ourselves in Quileute at the school and by using common Quileute phrases and greetings such as *Hačh čhiʹí* (Good morning) and *Liʹatskal* (Thank you). We also incorporate Quileute vocabulary into geoscience lessons, such as *kʹátla* (rock), *shiʹíkwál tsikáti* (earthquake), *pátlal* (flood/tsunami), *kʷáya* (river), and *laʹwáwat* (beach).

When René Castillo joined the Quileute CASE team as Culture Lead in 2024, she began leading the development of a “Science is Storytelling” curriculum based on Medicine Wheel pedagogy (Bell, 2014), two-eyed seeing, and the indigenous scientific method (Snively & Corsiglia, 2001). In this curriculum, students use the Medicine Wheel framework as a tool to help them make balanced scientific observations of the Earth based on the four directions (Credit: René Castillo). The students also explore how *science is storytelling*, in that indigenous oral histories are a way indigenous people synthesize their observations of the world and share this knowledge with others through storytelling (Datta, 2018; Iseke, 2013).

Híxas asaqlásalo kʷoʹlíyoʹ, yíx kʷoʹlíyoʹilo tsikáti (Quileute land is Quileute culture) (Credit: QTS/Quileute Tribe). Therefore, to create culturally sustaining geoscience curricula, the Quileute CASE team must respectfully learn about Quileute land from Quileute Elders and tribal members and, with permission, incorporate what we learn into the QTS High School curriculum. We also must fully recognize that the Quileute people know the most about their land and that they are the best teachers of its history, which is why we invite Quileute Elders into the

classroom during STEM ASB to share their knowledge of the land and its stories. For example, during STEM ASB 2024, we invited Quileute Elder Miss Ann to talk with the students about how the community is preparing for coastal storms, earthquakes, and tsunamis. Miss Ann connected community preparation work with stories passed down of a *Great Flood* that washed Quileute canoes and people far away (A. Penn-Charles, personal communication, March 18, 2024). We also invited Marie Riebe to share her mother Viola's stories of Thunderbird and Whale, her experience during the 1960 Chile tsunami at the mouth of the Hoh River, and about why we should go to high ground immediately when the ocean recedes (Riebe, 2015). She also shared Quileute stories of why we should *Run to High Ground* when the ground shakes through screening an animated short film made with Viola (*Run to High Ground*, 2018). Native American oral histories are a key reason why we know there have been earthquakes and tsunamis in the Pacific Northwest, and a crucial element of any culturally sustaining curriculum on this topic.

Towards place-based learning, each year during STEM ASB, the Quileute CASE team leads a day-long high school geoscience field trip to a local site relevant to the Quileute Tribe (**Fig. 4**). In STEM ASB 2023, we led a geoscience scavenger hunt at Second Beach – located just a short walk away from the school. During the field trip, students applied what they learned in class about how to make geologic observations to local geology, and importantly, the students had fun in the field doing geoscience (Bisson & Luckner, 1996). In 2024, we partnered with the Pacific Northwest Seismic Network (PNSN) and PNSN staff member Doug Gibbons to give the QTS high schoolers a hands-on and interactive tour of the *HOHM* strong motion seismic station just off Highway 101 along the Hoh River. This gave students an opportunity to learn about scientific monitoring of earthquakes going on where they live, ask questions to PNSN staff, and learn about how seismometers work. In 2025, we made multiple stops along the Quillayute

River, accompanied by the Quileute Tribe's Riparian Biologist Sierra Hemmig, the 10,000 Years Institute Executive Director and Ecologist Jill Silver, and UW Tribal Climate Adaptation Specialist Noelani Villa. We learned about how the Tribe is adapting to environmental change through the implementation of nature-based engineered logjams to reduce river erosion at the lower village of La Push. This year, in 2026, in cooperation with the Quileute Tribe's Cultural Resources Department and Director James Jaime, the high school students collected sediment cores along the banks of the Quillayute River at the lower village of La Push to observe sedimentary layers and learn about the stories these layers can tell us about the environment and the land's history. Through local field trips, we connect what the students learn in the classroom to their real-world environment and community.

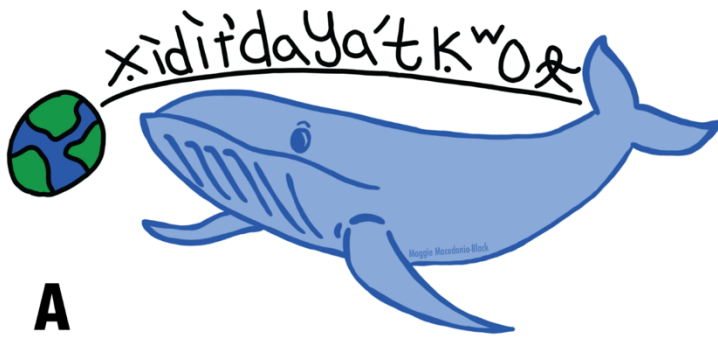


Figure 4. Class photos from each STEM ASB field trip with the Quileute Tribel School high school class over the last four years (2022-2026).

4.3.3 Co-Mentorship

Both QTS students and UW students are mentored throughout the Quileute CASE program. QTS students receive mentorship through their overall participation in Quileute CASE, STEM ASB, and the Quileute CASE High School Internship program. UW students receive mentorship from QTS teachers, staff, and Quileute community members through all aspects of the program, from in-class teaching to participating in community. Through co-mentorship, everybody involved in Quileute CASE is able to learn and grow as students, professionals, and people.

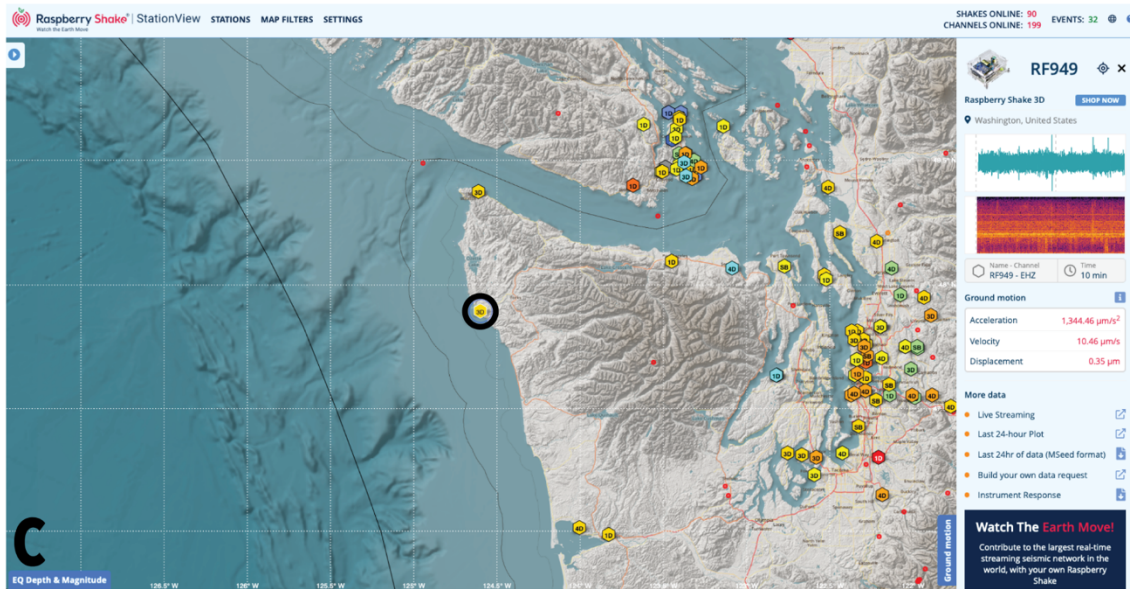
The QTS High School Internship programs gives QTS students an opportunity to engage in a place-based geoscience research project. In 2024, for their Seismology internship (**Fig. 5**), three QTS high school students worked with four UW student mentors as the “7 Shakers” team to install a *Raspberry Shake 3D* seismometer (RF949) in QTS (**Fig. 5B**), design and build a community seismic display in the QTS student lounge (**Fig. 5C**), monitor local and global earthquakes, and develop a new Quileute word for seismometer: *x̣idit̚daya’tk̚w̚ol* (**Fig. 5A**). In 2025, for their Geomorphology internship, four QTS high school students worked with UW students to monitor coastal erosion at Rialto Beach. To do this, each student identified and described a coastal tree and then measured its distance to the active erosion front along the beach. With time, students will return to the trees and measure the distance to the active erosion front again, thereby tracking the rate of coastal erosion using the trees’ location. As internship mentors, UW students get the opportunity to practice their K-12 mentorship skills. As internship students, QTS students explore a new topic that is relevant to their community and culture and discover potential STEM career pathways after high school.



A



B



C

Figure 5. Quileute CASE High School Seismology Internship (A) Artwork by 2024 QTS student and CASE intern Maggie Macedonio-Black with the Quileute word for seismometer: $\text{x̣iḍiṭdaya'ṭḳʷoʃ}$. Artwork digitized by Madeleine Lucas. (B) *7 Shakers* seismic display in QTS student lounge with student mentor Mya Baker showing a QTS student the display. (C) *Raspberry Shake* web interface showing location (black circle) of *Raspberry Shake* 3D seismic station RF949 (accessed April 27, 2026).

Through in-class teaching at QTS, UW students get the opportunity to teach at the K-12 level and receive feedback on their teaching performance from teachers and staff. Feedback

allows for the improvement of teaching skills and curriculum. Through community participation, participants receive guidance and instruction from Quileute community members on cultural customs and protocols. This engagement strengthens cultural competency and supports the development of a culturally sustaining curriculum.

An important aspect of Quileute CASE is providing resources to the high schoolers interested in college. The Quileute CASE team does this by participating in QTS Career and College Fairs and tabling during lunch every day of STEM ASB week. We also recently hosted the entire QTS high school class on UW Campus from February 21-22, 2025 (**Fig. 6**). During their visit, we toured UW campus, visiting the PNSN Seismolab, the Burke Museum, the UW Planetarium, and the Oceanography Puget Sound Table (**Fig. 6B**). In addition, nine Native and rural UW student mentors of the Riverways Guides program gave the QTS students a presentation about college access for indigenous students and provided mentorship on applying to UW.



Figure 6. QTS High School class visit to UW hosted by UW Riverways and Quileute CASE program in February 2025. (A) Group photo at Red Square in front of Suzzallo Library with Riverways welcome banner. (B) Lesson at UW Oceanography Puget Sound Table led by Abbey Moore.

4.3.4 Cultural exchange and knowledge-sharing

During our visits to QTS, we engage in cultural exchange with the Quileute Tribe. In school, we attend QTS Culture class to learn Quileute language and traditional crafting such as cedar weaving, drum making, beading, and formline design and drawing. Outside of school, we attend the Quileute Drum and Healing Circle and Culture Camp at the Akalat Center during STEM ASB, Welcoming the Whales in the Spring, and Canoe Journeys and Quileute Days in the Summer. Cultural exchange between UW Riverways, QTS, and the Quileute Tribe is represented by the Quileute CASE program logo (**Fig. 7**).



Figure 7. Quileute CASE program logo designed by a QTS middle school student Ellissyn Sedgwick and digitized by Richard Parra.

In addition to engaging with Quileute culture through community events, UW students share their own culture and life experiences with QTS students and the Quileute community. During STEM ASB, we give a presentation to the school where each member of the Quileute CASE team shares about their individual journey to college. Through sharing our own personal stories, we encourage the students in their own journey and provide them with examples of different possible career pathways after high school. As UW students, we also share our knowledge of undergraduate and graduate school, STEM degrees, scholarship opportunities, and more generally about college life and the transition from high school to college.

4.4 Lessons learned: A non-indigenous perspective

4.4.1 Lesson #1: We are all equal in the Circle.

As a non-indigenous person working in partnership with indigenous communities, this is the most important lesson I have learned. The nature of the Circle is that it can get bigger to include more people and that everyone is equal in the Circle (Absolon, 2010; Brandt & Kosko, 2009; Bukola, 2018; Lavery, 2016; Pranis, 2015). In Western society, we are often taught a *scarcity mentality* (Xenos, 2017), in that we must compete for limited resources and move up within a social or power hierarchy. By resisting this mentality, which is prevalent across modern-day academia, we instead work together as equals for the good of the whole Circle, instead of the individual. Working with QTS, the Quileute Tribe, and in collaboration with indigenous scientists has taught me that we are stronger when we all paddle together in our one big metaphorical (and sometimes literal) canoe. The Quileute CASE program belongs to everyone equally; and from this, notions of hierarchy or assertions that this program can be “owned” by someone or some-entity are strongly rejected and do not align with our program values.

4.4.2 Lesson #2: *Relationships in community are a life-long responsibility and commitment.*

As humans, when we build relationships and become a part of a community, this comes with responsibility. This responsibility to community does not simply end when you graduate, when your funding runs out, when you move away, when you get a new job, etc. In making a commitment to be part of a community, this commitment becomes a life-long responsibility. This should be considered prior to engaging with any community – asking yourself if you are ready for and committed to this responsibility. It is important to establish your “why” prior to engaging.

4.4.3 Lesson #3: *We learn more from our students than we teach them.*

When coming into a new classroom and community, it is important to have the mindset that you are there to learn from the students and the community. By exercising humility and having an open mind, over time you will discover where your personal knowledge and experience fit into the community and what is actually needed by the community.

4.4.4 Lesson #4: *Lead by example and be a role model.*

Many QTS students consider UW students on the Quileute CASE team as role models. Through learning and incorporating Quileute culture into the Quileute CASE curriculum, we aim to convey to our students the immense value that Indigenous knowledge brings to science. By sharing about our own individual cultures, stories, and how this influenced our pathways into

science, we model how the students can bring their individual culture and story to their education and future careers. When we are humble, honest, and candid with our students about our own pathways to science, we hope that they can also start to see themselves as scientists too.

4.4.5 Lesson #5: Consistently show up, be reliable, and embody a Riverway.

The school expects us to show up every year during UW's spring break for STEM ASB, and through CASE, we are also expected to visit multiple times a year for various community and cultural events. The importance of not breaking this trust and being reliable year after year is paramount to this program's success over the last decade. In alignment with the name of the program, *we are Riverways*. We are a river of people who care deeply about equity in K-12 education. When we show up, we demonstrate accountability and dedication to the community. This action builds trust over the years.

4.4.6 Lesson #6: Be a good guest.

In partnering with tribal communities, it is important to learn and adhere to local customs and cultural protocols, continually ask for permission, respect the privacy and sovereignty of the Tribe, engage in reciprocity with the land and its people, and always give thanks. Along the way, we must be mindful of how we carry ourselves as representatives of Quileute CASE: past, present, and future!

4.4.7 **Lesson #7:** *Ally with indigenous scientists and learn indigenous science.*

Growing up, I learned about science primarily from a Western perspective, and, therefore, Indigenous science is a relatively new topic for me. I think that non-indigenous scientists can be better allies to indigenous scientists and communities by becoming students of Indigenous science. By learning from indigenous scientists, knowledge-keepers, and Elders, we engage in reciprocity in science and STEM education, since indigenous students in the U.S. are typically expected to learn Western knowledge systems in order to advance in academia. Learning Indigenous science makes us better scientists because it expands the ways in which we can understand and think about the world. This is particularly relevant for the Earth and environmental sciences, fields of study closely connected to the land, its inhabitants, and its history.

4.5 Final reflection

The day I saw the Riverways sandwich board outside of Mary Gates Hall advertising the STEM ASB program opportunity changed my life. At the time of my interview with Riverways staff Richard Parra and Alison Horn, the QTS High School STEM ASB team was the last Riverways team that needed a Team Leader. So, by way of chance and a love for teaching K-12 geoscience, I found myself leading the QTS High School STEM ASB team in the Winter of 2022. I was excited to lead the team because my PhD research on earthquakes and tsunamis directly affects coastal communities in Washington. Also, my two-year term as Rockin' Out coordinator had recently come to an end and I was searching for a way to build a more long-

lasting and impactful relationship with a K-12 school beyond one-time site visits. It was the perfect fit for me in many ways.

I found myself well outside of my comfort zone during my first trip to teach at QTS. It was the first time that I had visited a Tribal community and experienced Native American culture firsthand. After our first day of teaching during STEM ASB, we realized that our curriculum did not meet the needs of our students in the way we had planned during the Riverways Winter quarter seminar. We had attempted to apply culturally sustaining and place-based pedagogy to Rockin' Out's geology curriculum, but we had never actually visited the Quileute Tribe at La Push or experienced Quileute culture beyond one Zoom call with Quileute Elder Miss Ann and QTS High School teacher Alice Ryan. Because of this, our curriculum did not respond to each individual students' experiences, interests, cultures, or learning styles. This knowledge can only be learned by going to a place, meeting the people, and experiencing the culture. Every evening after school for that first STEM ASB, we completely redid our curriculum to tailor it to the ways in which our students that year learned best. That week I learned that being humble and adaptable is key to building educational partnerships with tribal communities, or any community for that matter. Every single time we visit QTS and the Quileute Tribe, we learn something new that our team works to incorporate into our curriculum to ultimately better serve our students' educational goals. Exercising humility by recognizing that there is always something new for us to learn is crucial to the process of creating the best possible curriculum for our students and building a strong education partnership with the school.

It is important to recognize that CASE will look different for each individual educational partnership with a community. The Quileute CASE curriculum is designed with and for QTS and therefore cannot be taught at other schools. However, the *process* in which we create the

curriculum in partnership with the community and the lessons we learned through this process can be applied to partnerships with other schools. This is why it is important to learn from Quileute CASE but not attempt to replicate it with another community. The core principles and methodology of CASE are broadly applicable, not only in partnership with tribal communities, but with any community. By following the Riverways Model, we can start the process of building educational partnerships with tribal communities that are based in trust, relationship, care, and reciprocity. In sharing my personal experiences and lessons-learned from Quileute CASE in this chapter, I hope that others are inspired and empowered to start building educational partnerships with communities using the Riverways Model.

Dissertation Conclusions

In this dissertation, I use modern high-resolution seismic and bathymetric datasets to investigate accretionary wedge structure, deformation, and evolution at the Cascadia subduction zone. I address outstanding questions in our understanding of the Cascadia accretionary wedge by mapping wedge terranes and faulting, and by characterizing both surface and subsurface processes and evolution. The multi-disciplinary approach used in my dissertation research, spanning from structural geology to geophysical imaging to tectonic geomorphology, is applicable to other accretionary wedges around the world. Furthermore, my experience applying the Riverways Model to building an educational partnership with the Quileute Tribal School through Quileute CASE provides a model for how to create culturally sustaining and place-based K-12 geoscience curricula with communities that are directly affected by emerging research outcomes. Overall, in this dissertation, I demonstrate how geoscience research and community engagement go hand-in-hand towards understanding and preparing for earthquakes and tsunamis at the Cascadia subduction zone.

In Chapter 1, I analyze CASIE21 ultra-long-offset multi-channel seismic reflection and bathymetric data to test the pre-existing hypothesis for an active margin-spanning megasplay fault at the Cascadia subduction zone (i.e., L1 scenario, Witter et al., 2013). Upon mapping the inner-outer wedge transition zone using observations of structural style and seismic character, I find that there is no evidence for late Quaternary activity of this proposed margin-spanning megasplay fault structure. Instead, I find evidence for out-of-sequence megasplay-style fault activity at the inner-outer wedge transition zone at localized places along the Cascadia margin. In doing so, I improve our overall understanding of accretionary wedge structure, evolution, and

out-of-sequence fault behavior. My results provide crucial constraints for future modeling of Cascadia subduction zone earthquakes and tsunamis, which will inform the next generation of hazard mapping for the region.

In Chapter 2, using recently acquired ultra-high-resolution seismic reflection and bathymetric datasets, I discover and characterize the Albatross fault system, a system of en echelon Holocene-active right-lateral strike-slip faults within the Cascadia accretionary wedge. I find that the Albatross fault system works together with other accretionary wedge faults offshore Oregon to accommodate shear strain due to oblique subduction at the Cascadia subduction zone through distributed Riedel shearing. My work improves and builds upon prior theoretical models of accretionary wedge shearing and stress in this region and, for the first time, provides evidence for a Holocene-active margin-parallel strike-slip fault in the central Cascadia region. My findings advance our overall understanding of how accretionary deformation can work to accommodate plate convergence and are broadly applicable to understanding similar shearing processes at other plate margins around the world.

In Chapter 3, I test the applicability of subaerial topographic analysis tools to submarine topography, focusing on seven submarine channels intersecting the Cascadia accretionary wedge. Through systematic comparison with independent subsurface geophysical constraints of faulting within the Cascadia accretionary wedge, I find that knickpoints within longitudinal channel profiles are directly associated with the location of active faulting. By applying this methodology to regions with limited subsurface seismic constraints, I improve upon previous fault mapping and identify new geomorphic evidence for accretionary wedge splay faulting north of 48°N. In synthesizing my results, I find that patterns in accretionary wedge faulting are linked to patterns in megathrust fault coupling. The methodology developed in this chapter can be applied to plate

margins that are intersected by submarine channels in order to better understand and constrain subsurface deformation and faulting.

In Chapter 4, I present the Riverways Model for building educational partnerships with rural and tribal communities. I detail my experience creating culturally sustaining and place-based K-12 geoscience curricula in close partnership with the Quileute Tribal School and the Quileute Tribe of La Push, Washington. I conclude by sharing seven lessons I learned from my experience applying the Riverways Model through the Quileute Culture and geoScience Exchange program with the Quileute Tribal School. Overall, this chapter provides a framework and process that anyone can apply to building educational partnerships with rural or tribal communities.

In summary, my dissertation work advances our understanding of accretionary wedge structure and faulting at the Cascadia subduction zone through the multi-disciplinary analysis of modern high-resolution geophysical datasets. It also models how geoscientists can transform their research into educational partnerships with communities directly impacted by their scientific outcomes. This work provides a basis from which future research questions regarding the Cascadia accretionary wedge can be developed, and how this research can then better serve the broader community through educational partnerships.

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