A MAGNETOTELLURIC INVESTIGATION OF THE CASCADIA SUBDUCTION ZONE PLATE INTERFACE

by

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Zones of reduced ‘Episodic Tremor and Slip’ along the Cascadia Subduction Zone (CSZ) are known to correspond to fluids anomalies at the Juan de Fuca-North American plate interface. We process Magnetotelluric models of the conductivity of the CSZ to isolate conductivity values adjacent to plate interface, as well as to compute a vertical conductivity ‘gradient’ away from the interface. We compare the average conductivity and non-volcanic tremor density in windows of various sizes along the Mantle Wedge Corner (MWC) and compute their correlation. Tremor and conductivity correlate moderately along a window extending 100km up-dip from the MWC. The correlation is weaker for windows of different sizes or those centered down-dip, which suggests a coupling mechanism along the interface up-dip of the MWC, linking conductivity and tremor occurrence. The conductivity gradient is anomalously low surrounding regions where serpentinization reactions are known to take place. Finally, we investigate the regions near crustal faults, around which tremor occurrence is suppressed. We find that conductivity anomalies do not consistently occur around these faults, and thus that the effect of these faults on tremor is likely mechanical.

Acknowledgements

I would first and foremost like to thank Prof. Dean Livelybrooks, Blake Parris, and Prof. Casey Shoop for their patience, assistance, and mentorship throughout this process, and for helping me to gain a foothold in college, the field of Physics, and scientific research. This thesis rests on the work of the Livelybrooks research group, including undergraduate members Nicholas Wogan, Shura Zeryck, Alex Cook, and Max Kant, among others. I would finally like to thank Prof. Ray Weldon, Prof. Alan Rempel, and Quentin Bletery for answering questions about Cascadian geology near the end of the writing process, as dense and deep a subject as the Earth itself.

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Introduction

Earthquakes are abrupt reminders of the Earth's constant shape-shifting, when *terra firma* is anything but, and when the same processes that over eons sculpt and mold the landforms around us bring human-made structures tumbling down. Many countries, such as Japan, have taken steps to contend with the threat of large earthquakes. Geologically, the threat is just as real for the Pacific Northwest -- a large earthquake is imminent; however, the region has come of age not yet having witnessed such an event. The Pacific Northwest (PNW) lies along the Cascadia Subduction Zone (CSZ), which is the region where the Juan de Fuca and North American plates meet. Along the CSZ, the Juan de Fuca plate subducts under the North American plate, in the process building up stress and releasing it periodically in "megathrust" earthquakes. The next large earthquake in the Northwest, the "Big One," is likely to be such an event.

The Earth's crust is not one piece; rather, it is made up of semi-rigid continent-sized plates floating on a relatively gooey liquid mantle. Although these tectonic plates move at a snail's pace, the lines along which they meet bear witness to some of the Earth's more active geological features and processes: mountain ranges, volcanoes and earthquakes, to name a few examples. Off the Pacific Northwest coast, the Juan de Fuca plate meets the less dense North American plate and is pushed under through a process called subduction, a process that involves the plates sticking and slipping. Along the Cascadia Subduction Zone, stress gradually builds and releases suddenly *on average* every 434 years**.**[1] The last big quake occurred in 1700, and so in that sense, we are "overdue" for another in the coming century, an eventuality recently

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[1] Goldfinger et al. 2016

brought back to public awareness in 2015 by articles in *The New Yorker* and *The Atlantic.*[2] The general public has more difficulty understanding that megathrust occurrence is *quasi-periodic,* meaning that the intervals between events vary widely.

Although the "Big One" looms large in the public's awareness, the reality is that small Episodic Tremor and Slip (ETS) events (i.e. non-volcanic tremor) occur regularly along the fault. Far from cataclysmic, they merely transfer the stress from the interface between the subducting slab and overriding continental crust up-dip and westward to the "locked" or "pinned" zone, which holds the majority of the stress. ETS events are marked by minuscule yet GPS-measurable displacements (a few tens of mm horizontally) at the surface. Their occurrence and periodicity should depend on the properties of the plate interface, namely the stresses involved, the rock types in contact, and the presence or absence of fluids — a factor important as ETS events are rarer along the Oregon section of the fault than in Washington or northern California. ETS events are worth studying because they are believed to transfer stress along the plate interface, stress buildup having the potential to lead to more sudden and catastrophic earthquakes. The more is known about how stress distributes itself in the CSZ, the better officials can help people living in high-risk areas to prepare.

This thesis will investigate the plate interface through a sensing method known as Magnetotellurics (MT), which uses measurements of long-period electromagnetic radiation to discern changes in conductivity in the Earth's crust. The conductivity of the crust depends notably on the conductivity of the rock as well as the saturation of fluids there. The steady-state presence of fluids plays a crucial role in the subduction process.

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[2] Schultz, Kathryn. "The Really Big One." *The New Yorker*. 7/20/2017. Accessed 5/5/2017. http://www.newyorker.com/magazine/2015/07/20/the-really-big-one.

I have analyzed conductivity models derived from an array of sensors, placed over the Pacific Northwest, known collectively as “Magnetotelluric Observations of Cascadia using a Huge Array” (MOCHA). I seek to answer the broad question: How do heterogeneities or discontinuities in bulk conductivity near the interface of the two plates affect ETS occurrence along the Cascadia Subduction Zone? This thesis will analyze specifically conductivity variations just above the interface between the Juan de Fuca plate and the North American plate. Conductivity, or its inverse resistivity, in the Earth’s crust is a proxy for fluid accumulation, as water is orders of magnitude more conductive than rock — yet minerals such as magnetite can be highly conductive, too. This thesis will take four main routes of analysis. The first is to map variations of resistivity immediately above the interface. The second is to map the vertical resistivity gradient, a quantity that refers to how quickly the resistivity of the crust changes as one moves up from the plate interface, moving from an interface where fluids can travel relatively freely to more impermeable rock. The third and fourth are to compare the average tremor occurrence and average conductivity across lines of latitude along the subduction zone, and finally to compute the correlation between those two datasets in order to quantify any correlation between fluid concentration and tremor density, loosely suggested by papers such as one by Phil Wannamaker in 2014[3] This thesis brings a novel approach in using 3D conductivity models and in quantifying the datasets.

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[3] Wannamaker 2014

Geology

Background

The Cascadia Subduction Zone lies along the meeting point of the young Juan de Fuca plate and the older North American plate (and the Gorda and Explorer plates at the southern and northern extremes, respectively). The relative motion of the two plates varies from 30-45mm per year.[4] The fault is a thrust fault, meaning part of the movement is a buckling perpendicular to the interface. Between megathrust events, this motion manifests in two forms, as uplift (as the North American plate buckles and creates an observable bulge) and as ETS.

The tops of the plates meet offshore. Sediments are scraped off the Juan de Fuca plate as it moves downward. Then it encounters a locked zone at about 15km depth, which lies onshore.[5] Eastward and down-dip of the locked zone is a transition zone, where temperatures and pressures increase, the slab softens and the process of fluid dehydration begins. Many minerals on Earth have water in their chemical make-up left over from their formation, which high temperatures and pressures bring back out. This process forces fluids into the subduction channel and up into the overlying plate. These conditions are thought to prevent the plates from locking as they do at shallower depths.[6]

The weakened interface, however, can store small amounts of strain for short periods of time in the ETS zone, which is responsible for the sticking, slipping and seismicity of ETS, movement measurable with seismometers, GPS and water-level

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[4] Schmalzle et al. 2014
[5] Krogstad et al. 2016
[6] Audel et al. 2010

measurements. These events happen roughly every 10 months in northern California, 14 months in Washington, and in Oregon roughly every two years.[7] The ETS zone is about 70km east of the edge of locking.[8] Adjacent to this is the Mantle Wedge Corner (MWC), where the subducting oceanic plate (the ‘slab’) meets mantle material underlying the North American plate, forming an eastward-thickening wedge shape of more viscous mantle rock. Here the exsolved fluids mix with mantle rock and are forced back up-dip and into the overlying plate. The pressure from these fluids, known as *pore pressure*, plays a role in precipitating ETS.[9]

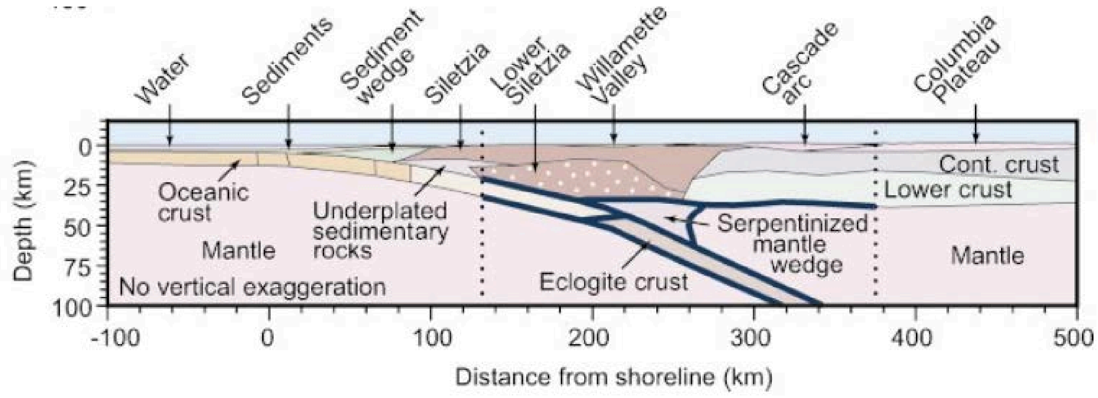

Plate interface across the Willamette Valley

Credit to Blakely et al.

While the Juan de Fuca plate bends downward into the mantle, a largely offshore (as modeled) inter-plate locked zone serves to compress the North American plate approximately eastward, effecting elastic plate deformation responsible for the ‘historic uplift’ at the coast and nearby, evident in tide measurements and highway-

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[7] Schmalzle et al. 2014
[8] Hyndman et al. 2015
[9] Audet et al. 2010

leveling records**.**[10] The Oregon portion of the CSZ shows reduced uplift compared to the rest of the margin. Among several hypotheses, Schmalzle et al. attributes this to weak offshore locking in the Oregon segment, while Krogstad et al. theorizes a secondary locked zone farther onshore (essentially right beneath the city of Eugene!). [11][12] Alternately Tréhu et al. attribute this to a series of subducted seamounts that have locally stalled subduction, disrupting the uplift process as well as ETS. [13]

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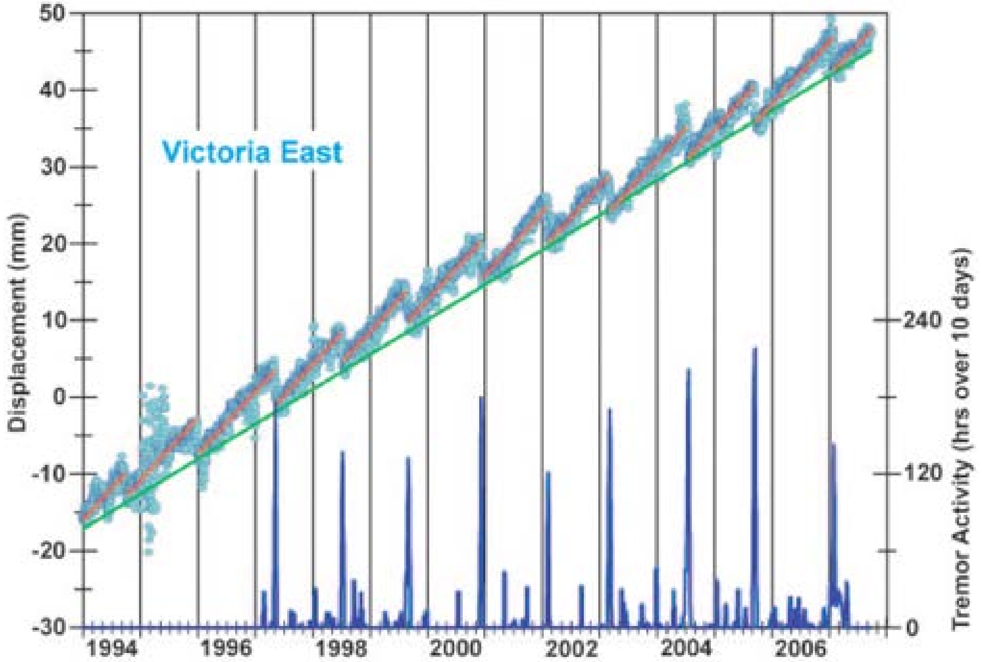
[10] Burgette et al. 2009
[11] Krogstad et al. 2016
[12] Schmalzle et al. 2014
[13] Tréhu et al. 2012



ETS generally eastward (up) plate movement and seismicity

Episodic tremor and slip refers to both the saw-toothed movement of the crust (downward segments as blue dots and red lines) and the associated non-volcanic tremor (dark blue lines at bottom), here recorded on Vancouver Island. Credit to Rogers & Dravet 2003.

Additionally, along the line of contract, the North American plate exhibits several different generalized rock types, or terranes, which have been accreted under the overlying plate and which have more influence over seismicity and uplift than do variations of the composition of the Juan de Fuca plate. The Klamath terrane extends from northern California into southern Oregon and is continental and relatively weak and less dense.**[14]** Siletzia terrane has more oceanic properties and is thick, rigid and buoyant southward toward Oregon, while becoming thinner, more deformable and

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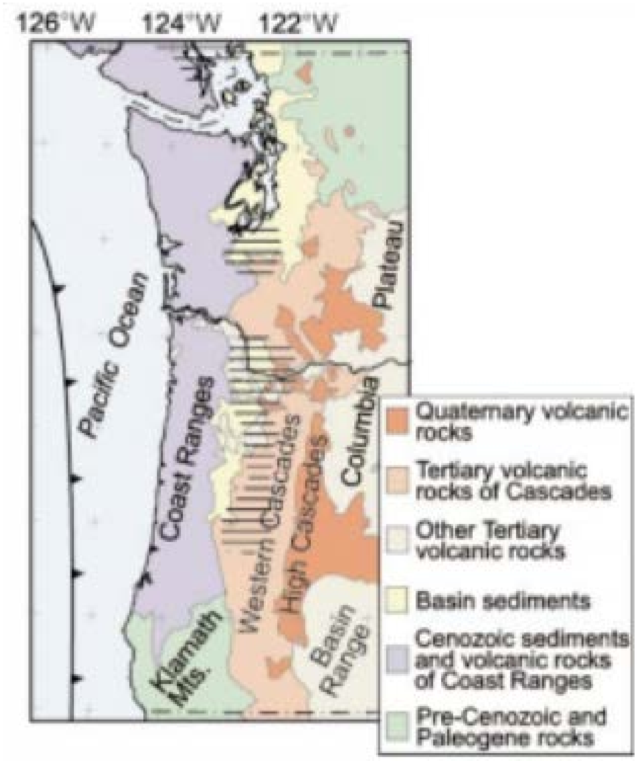
[14] Brudzinsky & Allen 2007

permeable approaching the Olympic range and Vancouver Island.[15] Terrane is important not only because of its susceptibility to bulge and buckle as uplift, but also because of its permeability, its ability to transport fluids and withstand their pressures.



Crustal types along Cascadia

This thesis references the Siletz and Klamath terranes, left in purple and green, respectively. Credit to Blakely et al.

Literature Review

I will approach the literature review by explaining the findings of several recent papers on the different ways Cascadia is known to, and might, change along *strike* (i.e. along the axis of least variability, in this case North-South), in addition to the possible underlying mechanisms**.** To summarize, variations in tremor/slip occurrence along the CSZ can be explained by differences in the fluid environment along the slab interface,

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[15] Tréhu et al. 1994

crustal terrane differences and differences in local/global plate geometry, strength and locking.

Segmentation

ETS periodicity, as mentioned above, varies between three main segmentation zones. For one, Bruzinski and Allen speculate that variation in the overlying plate, namely in its terrane, control differences between these zones.[16] Alternately, Audet et al. discuss the role of a terrane's ability to contain high pore pressures as a control of ETS.[17] A further factor is the geometry and mechanical strength of the plates, that is to say the relative rates and direction of subduction along strike, as well as how different crustal faults dissipate stress.[18]

We will first address changes in the overlying plate. Terrane distinctions and variations in uplift are but two examples of how the overlying plate changes along strike. Brudzinski and Allen analyze zones of ETS recurrence along the length of Cascadia, which they ultimately attribute to variations in the overlying plate rather than the subducting slab, although the latter is segmented by the Blanco Fracture Zone and the Nootka Fracture Zone.[19]

Zones with similar ETS periodicity do not match up to the rates of subduction along the margin. Neither does the pattern of ETS correspond with the age of the subducting Juan de Fuca plate or fracture zones. Furthermore, ETS occurs at depths above the slab interface, not below it. The article concludes that divisions in ETS

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[16] Brudzinski & Allen 2007

[17] Audet et al. 2010

[18] Schmalzle et al. 2014

[19] Yeats, Robert S., "Living with Earthquakes in the Pacific Northwest." Accessed 5/5/2017. http://oregonstate.edu/instruct/oer/earthquake/06%20chapter%205_color.html

periodicity zones correspond roughly to the boundaries of the Cascadian terranes of the North American plate, such as between the Siletz and Crescent Formations. [20]

The locking patterns up-dip of the ETS zone are not well understood, but they are considered to different substantially along strike, such as by changes in plate geometry. The Olympic portion of the margin is characterized by a strong locked zone and a narrow transition zone, while the Oregon portion of the margin is characterized by reduced but broadened uplift between megathrust events, a weak locked zone and a wide free-sliding transition zone. In northern California, the plate interface has a relatively shallow slope and is characterized by a strong locked zone and a broad transition zone.[21]

As mentioned previously, there is some evidence for a secondary locked zone down-dip from the primary (offshore) one in Oregon, inferred from how uplift distributes itself. Such a locked zone may be closely linked the conductivity and fluid anomalies in the region and would greatly change how stress builds up over the short term in the ETS zone.[22]

Fluid Processes

Now we turn to the effects of fluids in the interface. ETS is an approximately *lithostatic* process, meaning that the largest sources of pressure, namely the effective normal stress (i.e. weight of the overlying earth) and pore pressure, nearly balance each other out, and additionally that the factors that precipitate a slip event do not affect the pressure along the interface all that much. ETS correlates with the tides, for example.

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[20] Brudzinski & Allen 2007
[21] Schmalzle et al. 2014
[22] Krogstadt et al. 2016

That tidal variations, relatively small forces compared to the weight of the overlying crust, can precipitate slip events, implies that pore pressure nearly balances out effective normal stress along the interface.[23]

Before we delve into the methods that many of these papers use to discern where fluids lie, we must understand fluids' effects on seismic waves, which are resolved through a technique called tomography. Seismic tomography is a sensing method that can augment MT models. It analyzes the ways that sound waves travel through the crust. Just as for conductivity, we can take a quantity known as Poisson's ratio as a proxy for fluid composition and geochemical changes, which stands for the ratio between the velocities of shear waves (disturbances perpendicular to the direction of travel) and pressure waves (disturbances parallel to the direction of travel) through the crust. In general, lower values of Poisson's ratio imply elevated fluid content because shear waves cannot propagate as fast through fluids as through solids. Seismic methods can also resolve physical boundaries like faults and terrane changes.

Some commonalities across the whole margin are a seismic low-velocity zone at 20-45km pointing to relatively high fluid content pore pressure, with fluid from the formation of eclogite at around 35-40km as a proposed source.[24] In Oregon, seismic evidence supports the existence of the layer of subducted sediment about 1km thick, with a narrow region of locking offshore.[25] From these depths, fluids migrate upward along the slab interface and hydrate the MWC in serpentinization reactions, "producing a reduction in its velocity, and thus substantially obscuring the overlying seismic

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[23] Nakajima & Hasegawa 2016
[24] Hyndman et al. 2015
[25] Wannamaker et al. 2014

Moho," which is the seismically discernible boundary between the overlying plate and the mantle wedge corner.[26] The takeaway from this result is that chemical reactions blur the resolution of the slab interface as they allow fluids to bleed out into the crust. Along the Japanese Nankai Subduction Zone seismologists have found that metamorphic reactions, like serpentinization, anti-correlate with ETS[27].

Much of Magnetotellurics relies on an empirical relationship known as Archie's law. Archie's law is an empirical law generalizing the relationship between conductive fluid saturation in a rock and its electrical conductivity. Water containing electrolytes is highly electrically conductive, while rock is considerably more resistive. The more water is present in a given volume of rock, whether it be seeped through the pores or actually incorporated into the mineral's chemical structure, the more conductive it will be.

Yet, the link between fluids and conductivity may be more nuanced than as described in previous sections. Geochemical reactions in ETS zone, such as serpentinization reactions, have the potential to drastically change the conductivity of the surrounding crust, beyond simply indicating the presence of fluids. Mathilake et al. find from laboratory-based measurements that the expected concentration of fluids in the MWC environment yields conductivities lower than what are inferred from MT inversions (~1 S/m).

The authors speculate that, "the released aqueous fluid also rehydrates the mantle wedge and stabilizes a suite of hydrous phases, including serpentine and chlorite." The first component of this transition raises the conductivity of the mixture to

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[26] Hyndman et al. 2015

[27] Nakajima & Hasegawa 2016

the order of 10^{-3} S/m, and the second component raises the conductivity further to the order of 1 S/m, by “the growth of an interconnected network of highly conductive and chemically impure magnetite mineral phase.”[28] Since this mechanism reduces the amount of fluid required in the MWC, it would suggest lower pore pressure in this region, pore pressure that would otherwise promote ETS. [29] Thus, this hypothesis allows a weaker link between conductivity anomalies and tremor in the ETS zones of Cascadia than a mechanism involving merely the presence of fluids.

This hypothesis, positing magnetite in the MWC, has the secondary implication of magnetic and gravitational anomalies along the MWC as suggested by Blakely et al, who find further evidence of hydration reactions from the subducting to the overlying slab in magnetic and gravitational anomalies up-dip and above the Mantle Wedge Corner. Magnetite, a product of serpentinization reactions, has a high magnetic susceptibility but a low density, precisely what the magnetic and gravity anomalies indicate. In sum, chlorite-related serpentinization of the MWC enhances both the magnetizability and conductivity of the supra-slab interface (the former property manifest in magnetic anomalies, and the latter magnetotellurically). This correlation between ETS and the presence of magnetite holds in Washington but not in Oregon, a discrepancy the authors attribute to changes in plate geometry.[30] In sum, fluid processes along the plate interface exist in a state of quasi-equilibrium; this is where the greater part of the conceptual physics comes in, through high temperatures, pressures and stresses. We can resolve some of the geochemical and seismic processes that work to

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[28] Mathilake et al. 2016
[29] Audet et al. 2010
[30] Blakely et al. 2005

maintain this quasi-equilibrium, giving a window through which to infer the sub-surface conditions.

Faulting

The effects of crustal faults on ETS may demand a unique synthesis of the above mechanisms. We have seen theories of how tremor/slip frequency variation may depend on terrane differences, differences in fluid composition as well differences in local/global plate geometry and strength. Crustal faults theoretically provide, at once, lines of structural weakness and routes for fluids to migrate. Seismic data resolve faults down to 25-35km.

Wells et al. finds that tremor density originating in the region of depth between 30-40km statistically anti-correlates with “upper-plate faults that accommodate northward motion and rotation of forearc blocks.” They speculate whether this is because the faults provide pathways for fluid escape and release of pore pressure.[31]

Research Questions

Here we pose several research questions. The overarching question here is how variations in the fluid environment, detectable by MT methods, correlate to ETS. A central assumption between all of these is that the conductivity of the ETS zone relates to ETS. Several of the above hypotheses posit intra-terrane variations in tremor as well as in fluid saturation and pore pressure, but it is important to note that MOCHA coverage does not provide high resolution beyond Siletzia. Several of the authors above show how a high pore pressures and metamorphic reactions can obscure seismic

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[31] Wells et al. 2017

contrasts such as the low-velocity zone. We will explore whether MT inversions can detect these conditions. The main test case will be in the regions of magnetic anomalies.

As mentioned in Wells et al., local crustal faults have been shown to suppress tremor. This thesis will address whether they are resolvable in local variations of conductivity along the slab, which would indicate whether fluids are dissipating away from the fault. If so, then faults might suppress tremor nearby by reducing pore pressure at plate interface depths. The lack of fluid-anomalies at crustal fault lines would suggest that they suppress tremor by mechanical means. Finally, we will test in aggregate the correlation between tremor occurrence (namely tremor density) and average conductivity along a swath of the plate interface near the MWC. If the presence of fluids in the plate interface is in indeed a control of ETS, we will see a correlation. If not, then another factor must predominate.

Magnetotellurics

Background

The research method will involve analyzing the long-period electromagnetic fields at magnetotelluric measuring stations throughout the Pacific Northwest and offshore, in order to create reconstructions of what lies beneath the surface, which include the tectonic plate boundary and regions of fluid and molten rock. While the fields originating from outer space are relatively constant from point to point, those re-emitted by the Earth are not; they depend on the subsurface conductivity, which is how well materials beneath the surface can conduct electricity. From these variations among MT stations, one can “invert” the data using computers, to approximate where these conductive and resistive (non-conductive) regions might lie and thus determine where fluids lie along the subduction. Throughout the Northwest, gridded arrays of MT stations placed in the ground record the electromagnetic radiation coming from space and reflecting back from the Earth. The particular array used in this project is known as MOCHA. But before I describe the data acquisition, it will be helpful to better understand electromagnetic radiation: what MT actually measures and analyzes.

Electromagnetic Radiation

Electromagnetic radiation consists of fluctuating electric and magnetic fields, which propagate through space at the speed of light, as light is electromagnetic radiation. A changing magnetic field induces a changing electric field, which induces a changing electric field, and so on and so forth. This is true for the light we can see as well as for the fields measured by the MT stations. Just as light is altered traveling through water or a windowpane, low-frequency fields are changed by the Earth’s crust. Radiation entering the earth from space induces electric currents, which re-emit one part of their energy as new radiation and the other part as resistive heat. The waves attenuate with depth, losing energy through inducing currents. Additionally, a conductive medium changes the relative phase between the electric and magnetic fields, which is to say, how they synchronize. A single number, called the impedance, the complex ratio of electric to magnetic fields, encompasses these alterations.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Maxwell’s Equations of Electromagnetism

MT bases itself the theory of EM radiation through linear conductive media. From top to bottom: Gauss’s law, Gauss’s law for magnetism, Faraday’s law of EM induction, and Ampère’s law.

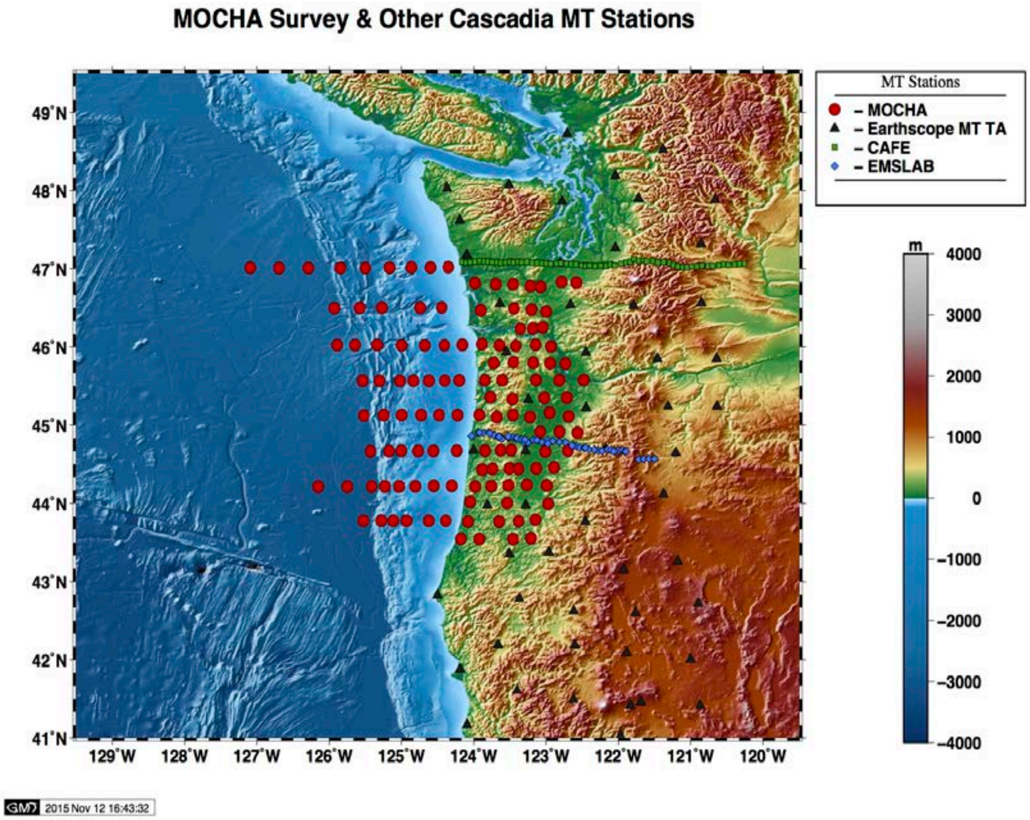
The properties of EM radiation can be summarized in Maxwell’s equations. **J**, **E** and **B** are vectors, which means they have magnitude and direction. **J** is current density, the rate at which charge flows through a surface. **E** and **B**, respectively, refer to electric and magnetic fields in a vacuum. The operator ‘∇x,’ the curl, refers loosely to the amount of rotation in the field. An electric field (a.k.a. ‘E-field’) ‘circulates’ about a region of changing magnetic field, and vice versa. On the other hand, the divergence,

‘$\nabla\cdot$,’ quantifies how much a field ‘radiates away’ from a point. Positive electric-charge densities are ‘sources’ for the E-field, whereas negative-charge densities are ‘sinks’. Magnetic charges have never been observed, so magnetic field lines have no beginnings or ends. MT uses a form of the equations shown that have been adjusted for the effects of linear conductive media, which means the charges in it flow and pool in a mathematically consistent way. In sum, disturbances in electric and magnetic fields perpetuate each other and radiate through space according to Maxwell’s equations and the conductivities of their encompassing media.

Methods

This thesis concerns magnetotelluric sensing methods which involve measuring both electric and magnetic fields over a period of days to months over a wide swath of area. MT land stations consist of a central data-logging computer, a three-axis magnetometer and two pairs of electrical ground probes perpendicularly spanning 100 meters. Sea stations are smaller. By this setup, the station can record three dimensions of magnetic field and the electric field induced in two dimensions parallel to the Earth’s surface.

As mentioned previously, the data used in this thesis come from the MOCHA array of stations, an amphibious array of MT stations spaced roughly 25km apart from the continental shelf to the Cascade range and from southern Washington to the southern Willamette Valley. The array was installed 2012-2014 with substantial assistance from undergraduates at UO and OSU. I helped install three sites in the Oregon Coast Range in the spring of 2014. Outside of this range, the data come from a more widely spaced array known as Earthscope, which span the entire margin onshore from the coast to east of the Cascades.[32]



Magnetotelluric Surveys over the Pacific Northwest

The Livelybrooks group primarily analyzes the MOCHA array and the lower-density Earthscope array. CAFE and EMSLAB are closely spaced 2-D lines. Credit to Max Kant, Livelybrooks Group.

Because MT stations collect several channels of data, there are several different modes that can be interpreted either together or separately. The combination of the north-south electric field and the east-west magnetic field is called the transverse-electric or TE mode. East-west magnetic fields and north-south magnetic fields comprise the TM mode. Vertical magnetic fields and east-west magnetic fields

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[32] Livelybrooks et al. 2016

comprise the ‘tipper’ mode. Under an assumption of prevailing two-dimensionality, where conductivity in this case is considered to be only slowly varying moving from north to south, the TE mode is more liable to introduce errors coming from 3D heterogeneities than is the TM mode.

These signals from MOCHA and Earthscope are processed through a Fast Fourier Transform (FFT), which picks out their periodicities. Just as the timbre of a musical instrument comes from its unique mix of overtones, each of the EM data streams can be seen as a superposition of difference frequencies. It is easier to analyze the data in so-called ‘frequency space,’ because any distortion is frequency dependent. As an example, lower frequencies (i.e. longer periods) can penetrate deeper into the crust than higher frequencies before they attenuate. This means that a deeper conductive anomaly will register more strongly in lower-frequency data than it will at higher frequencies; the opposite is for shallower anomalies. The FFT algorithm needs data spanning many full periods for each frequency, a fact that means that the longer the period we wish to detect, the longer the duration of data collection. It is worth noting that although stations collect data for the greater part of a month, their results give only a still portrait beneath the surface. This is because geological processes happen over a much longer timescale.

To predict the sub-surface structure through inverse modeling is a finicky process in practice. It is difficult to identify any feature with certainty using a single MT inversion. A certain pattern of conductors and resistors yields only one electromagnetic profile, one spectrum of overtones, but the inverse is not always true — such a profile could theoretically have come from one of many different conductivity structures.

Furthermore, MT stations collect a limited number of data points, giving the process a two-fold ambiguity. For these reasons, it is necessary to ‘prime’ the modeling software with known features and to force smoothness constraints, which is to assume that conductivity will vary smoothly rather than abruptly. Occam’s razor is a useful analogy to this approach. We aim to limit extraneous artifacts. These constraints help to whittle down the number of possible models to those that are both *most right* and *least wrong*. Specific to each inversion is a root-mean-squared misfit, a generalized error measure between the predicted results and the actual data, normalized by the inherent errors in the actual data. As a rule of thumb, the lower the misfit, the better. The conductivity model used in this thesis has been produced by a finite-difference inversion algorithm, called MOD-EM, developed by Anna Kelbert and Gary Egbert of Oregon State University.[33]

Procedure

The goal behind this thesis is to investigate the magnetotelluric properties of the Cascadia Subduction Zone slab interface. The main procedure for this attempt is to take ‘slices’ or ‘projections’ of 3-D magnetotelluric inversions that lie immediately above the interface. While the inversion returns a three-dimensional array, the slab projection is two-dimensional yet varying by depth just as the slab does. The depth of the interface from each point on the Earth’s surface is a known quantity; seismic methods resolve the contours of the boundary between the Juan de Fuca and North American plates.[34]

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[33] Kelbert & Egbert 2014

[34] McCrory et al. 2014

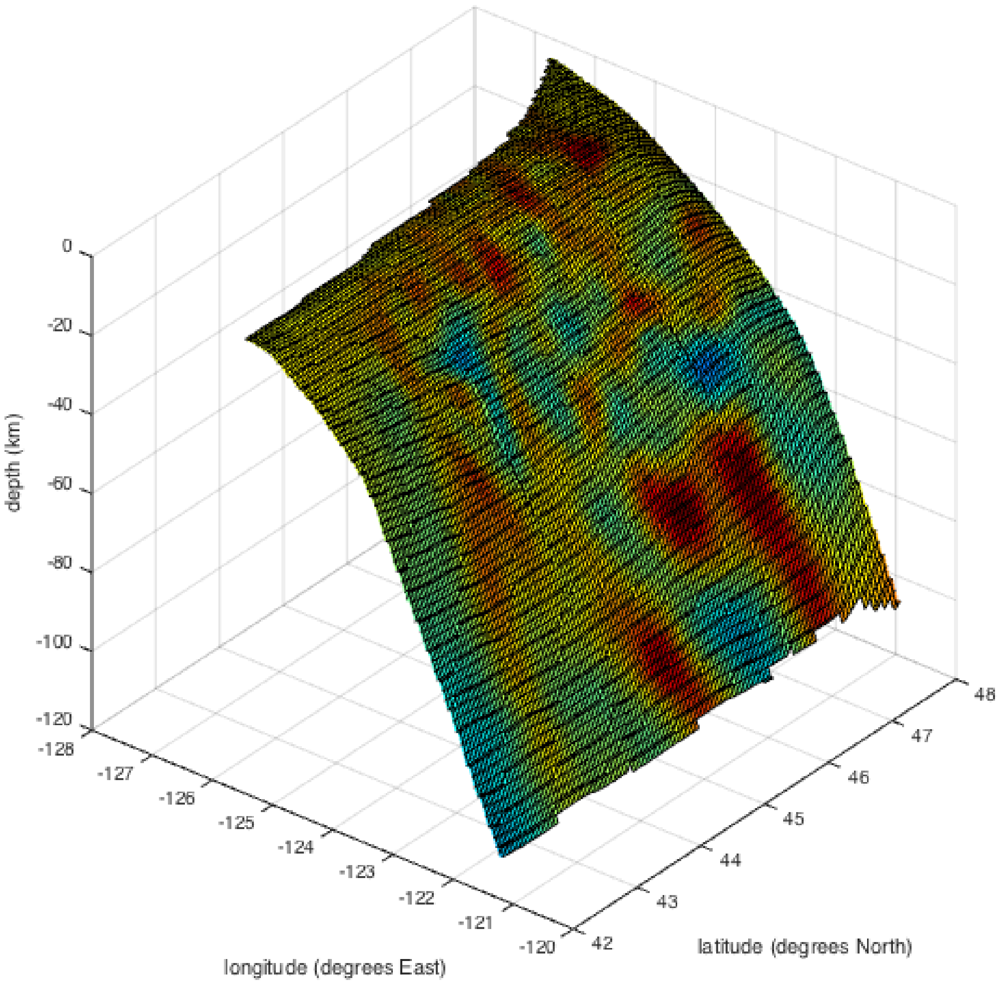
The values given in the inverse model and all subsequent calculations are *logarithmic*. The conductivities (and inversely, resistivities) of Earth's crust span many orders of magnitude. Seawater for example has a conductivity on the order of 10 S/m (10^{-1}ohms*m), while the more resistive regions along the slab have conductivities on the order of 10^{-4}S/m (10^{4}ohms*m). For this great range, it is more useful to compare the logarithms of conductivity. As an example, seawater has a logarithmic conductivity of 1 log(S/m) (a resistivity of -1 log(ohm*m)). Multiplicative inverses of each other, logarithmic conductivity and resistivity differ from each other only in a ± sign.

Conductivity Projection

Three routes of interpretation follow from this projection. The first route is to analyze the conductivity map in 'plan-view,' looking straight down from above. Each voxel, or 3D-grid element, of the three-dimensional conductivity model has a specific geographic extent, expressed in *x*- and *y*-indices, and depth range, expressed in *z*-indices. For each 'column' of voxels identified by the same (*x*,*y*)-coordinates, we select the voxel with the *greatest z*-index (and therefore greatest depth) that still lies *above the slab interface,* which we then project onto a map of the PNW.

Conductivity Gradient

The second route is to calculate the vertical conductivity gradient from these points, which is to say how quickly the conductivity changes as one moves up and away from the interface and toward Earth's surface. (From this we can infer the ways in which fluids diffuse into the overlying plate. The conductivity gradient at each (*x*,*y*)-index is calculated by taking the difference between the voxel above the slab interface and the voxel lying immediately above that, and dividing this quantity by the distance between the two. The quickness with which interface-specific conductivity anomalies fall off, or increase, as one moves away from the interface should be a function of the pressure in the region (pushing fluids out) and the composition/permeability of the overlying plate.



3D Projection of conductivity unto the plate interface

The 'plan-view' map of conductivity along the interface actually extends over a wide range of depths. Credit to Prof. Dean Livelybrooks.

Correlation with Tremor

The final route of interpretation is to compare average conductivity and ETS tremor density over lines of latitude within a given distance to the Mantle Wedge Corner. We use two windows, one spanning 50 km and the other spanning 200km on either side. Grouping these variables by latitude is legitimate because the subduction zone, with the partial exception of its northern extreme, is oriented north-south.

We take the geographic coordinates of the mantle wedge corner (MWC) from Schmalzle et al., data spanning a range from 48N to 44N.[35] Then we extend the range south to 42N by following the eastern edge of MWC tremor occurrence. Such an extension is justified because subduction-zone tremor follows the MWC up until that point. The possibility of deviations from the true MWC toward the south mean that the window may deviate slightly into zones with different mechanics, but this error will be much smaller in proportion from the 200km window than for the 50km one.

After this, we compute an average of each voxel of the MT inverse model, weighted by volume, along the slab projection within this window. A similar procedure follows for tremor occurrence. We use an automated Cascadia tremor-occurrence database tabulated by the Pacific Northwest Seismic Network (PNSN) from 2009-2017.[36] Then we construct an array of area cells on the surface of the Earth lying immediately above each voxel of the slab-conductivity projection. We count the occurrence of tremor within each cell. Then we add up all tremor events over the same latitudinal MWC windows as for the conductivity average, dividing this sum by the total area of each swath. Points around 43.5N have been culled because of an artifact of interface depth data, which caused the average resistivity to fall to unrealistic levels; this is evident in the gap in the plots below.

The above procedure gives two datasets, one of average conductivity and the other tremor density, along latitudinal transects of widths 200 km and 25 km.

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[35] Schmalzle et al. 2014

[36] https://pnsn.org/pnsn-data-products/earthquake-catalogs

Additionally, we take asymmetrical swaths to 100km on either side of the MWC. Then we compute the correlation coefficient between these datasets, a number that describes how closely variations in one variable, say tremor density, correspond to variations in the other, average conductivity. Correlation does not imply causation, but if there is no correlation between two phenomena, it does not make sense to say that one causes the other. As for the differing sizes and places of the swaths, we are interested in the ranges over which conductivity and tremor correlate more closely.

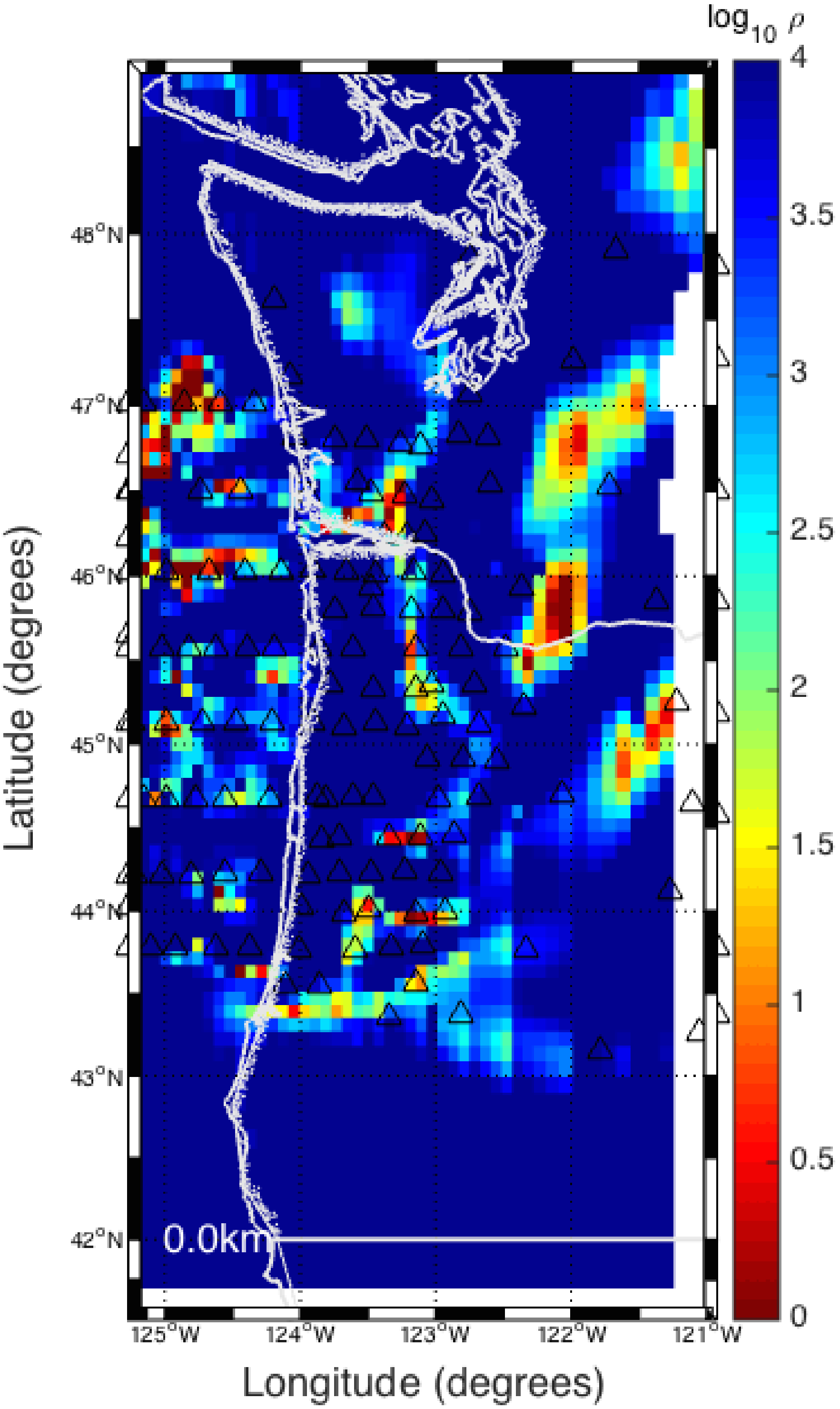
Results

Conductivity Projection

The plan-view projection of resistivity along the slab displays many features expected from prior knowledge. Details are finest in the region of the dense station coverage, extending from about 43N to 47N and 122.5W and 125.5W. Elsewhere they become more diffuse.

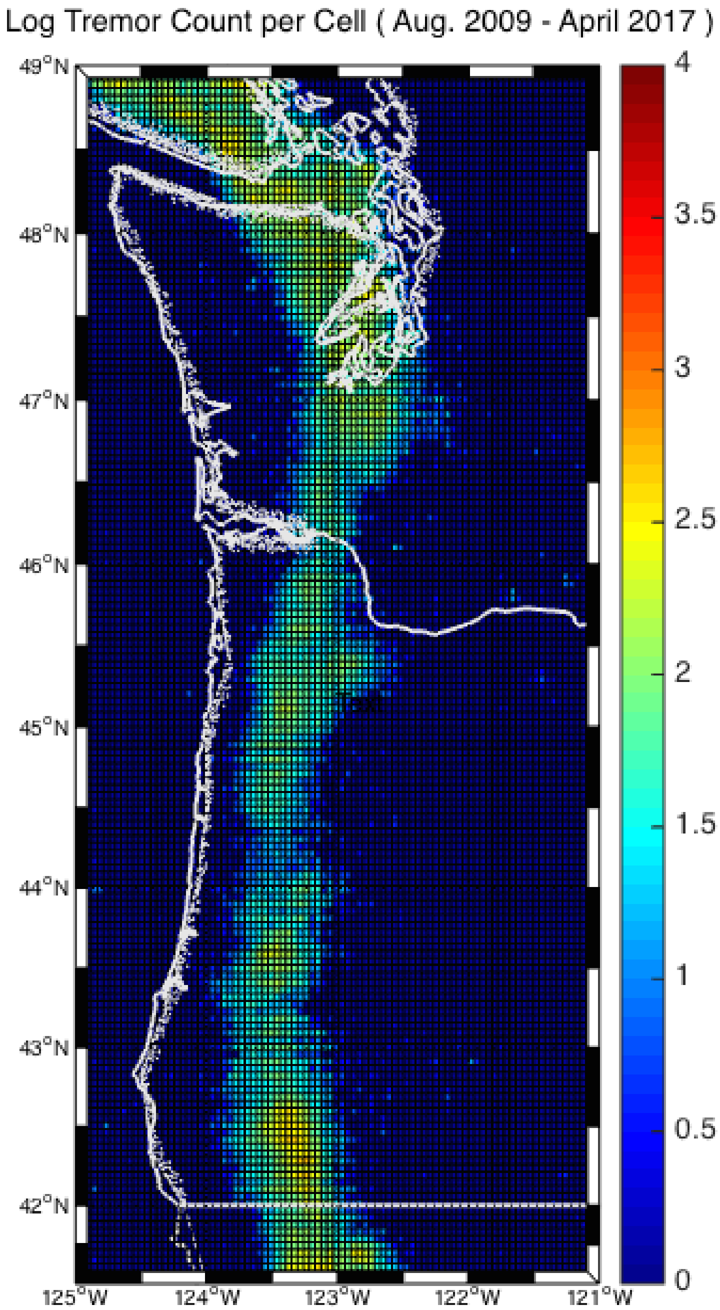
From the coastline to the westward extreme of station coverage we see a spattering of conductive regions. This portion of the slab is shallow, less than 5 km in depth**,** and so allows high resolution, but this section of the data set also comes from marine stations, which have a higher error and a limited period range. Thus, small-scale structures offshore do not hold much geophysical import**.** There is a notably large conductive patch about 0.5deg offshore of Aberdeen, WA.

Heading south, the projection resolves the Mantle Wedge Corner approximately tracing the eastern edge of the Oregon Coast range and heading diagonally from the Oregon border to southern Puget Sound. It branches just north of the Columbia River and leads to the coastline. At about 45.5N the filament becomes less conductive and appears to turn eastward before heading back west to end at a highly conductive longitudinally elongated patch beneath Corvallis. There is a clear gap in this filament between 44.5N and 44N, after which a brightly conductive region protrudes to the east. The gap between 45N and 44N corresponds to a zone of reduced tremor occurrence at the same latitude.



Resistivity plotted along the plate interface

Colors toward red denote regions of greater conductivity, toward blue greater resistivity. Black triangles denote MT station sites.



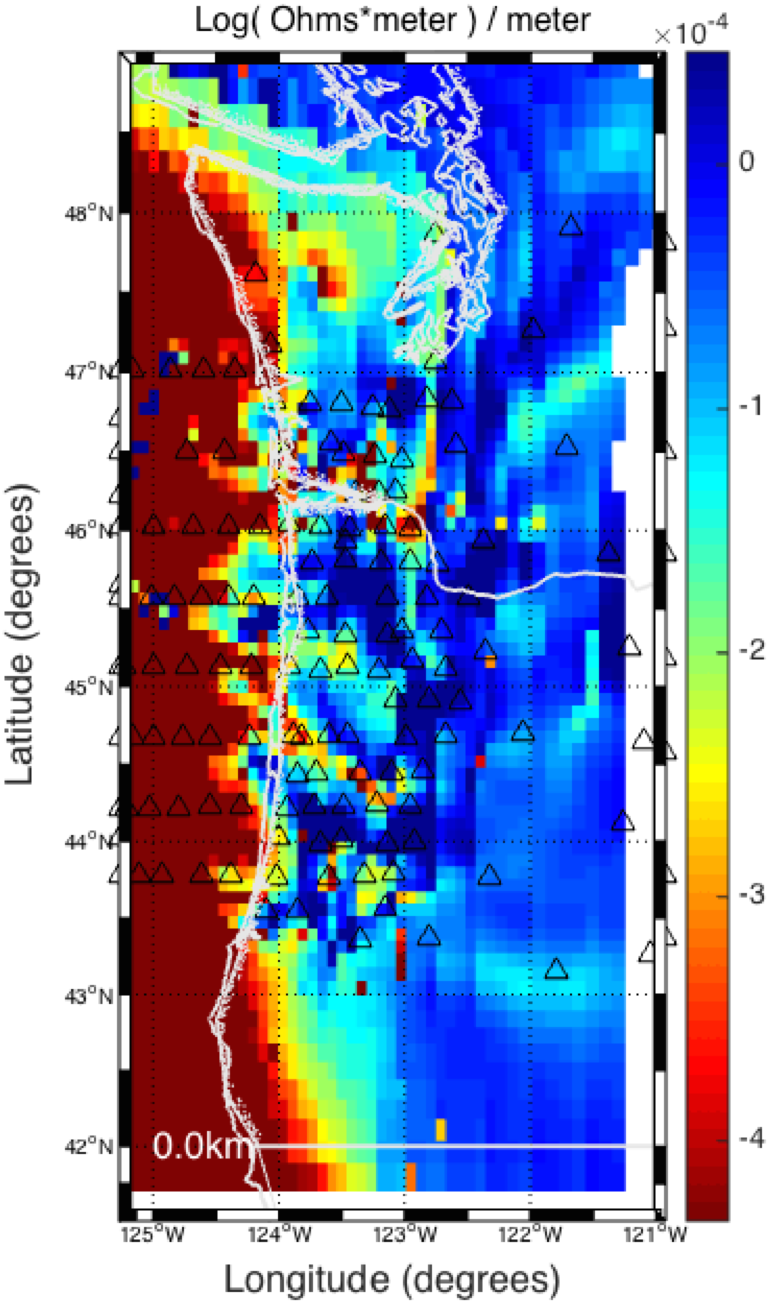
Log-tremor counts per array cell of model

Note zone of low tremor from 44-45N. Data from PNSN database.

In southern Washington around 122E we can see the possible signature of arc volcanism. A brightly conductive line marks the southern extent of land-station coverage and splits in two at roughly (43.5N, -123W) This feature is suspect because the inversion algorithm is known to place unrealistic features where there is little-to-no station coverage.

Conductivity Gradient

The map of the conductivity gradient vertical from the slab interface shows features that correspond to known geological structures, such as the Mantle Wedge Corner and volcanic arcs. Yet these features are offset from where the structures actually lie. The color scale has been normalized to bring into contrast features onshore in the vicinity of the MWC. This was done by taking the mean of gradient points on the western sides of Oregon and southern Washington as the center of the color map, and the range to be two standard deviations above and below. Colors toward the far blue end of the scale denote the crust becoming more resistive rising away from the interface. Thus we will refer to regions denoted by dark blue as *low-gradient* zones. Colors for negative values of the gradient (below the zero mark), denote the model becoming more conductive relatively slowly moving up from the plate interface; while on the other hand colors toward red denote the crust becoming more conductive relatively quickly. We will call these regions *high-gradient* zones.

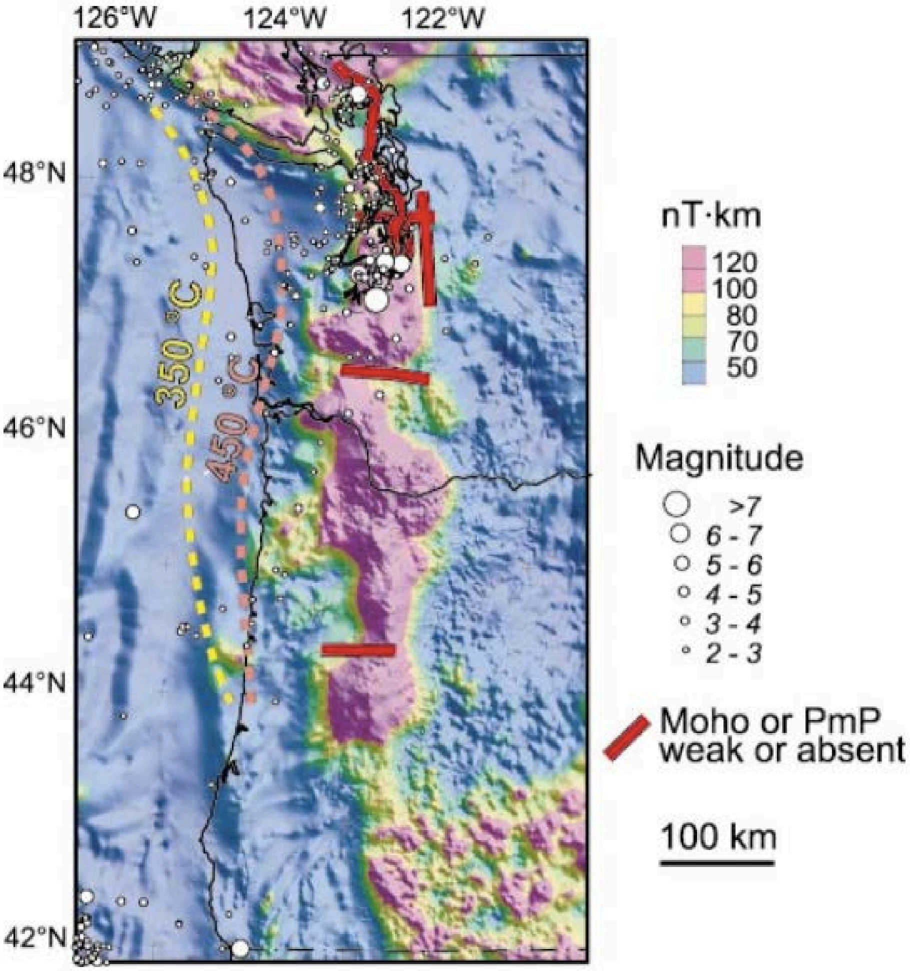


Map of conductivity gradient

Dark blue denotes crust becoming more resistive as one moves up from the slab interface; red denotes more conductive.

We see a conductive high-gradient feature we recognize as the Mantle Wedge Corner extending from southern Puget Sound to the central Willamette Valley. We see an arc of low gradient extending between ~44N and ~45.8N from the Oregon coast range to the Willamette valley. The southern extreme is more strongly defined. The arc is continuous but interspersed by filaments of high gradient, notably around 44.5N and 45.5N, as well as along the Columbia-River channel (as seen in the conductivity map). In Washington, the inversion resolves a low-gradient zone immediately south of Puget Sound, lying there next to a gap in the Mantle Wedge Corner.

We can compare this map to the map of magnetic anomalies given in Blakely et al. (See figure) The area of low gradient appears to hem the region of maximum magnetic anomaly, especially around the southern and central Willamette Valley. The correspondence is less pronounced at the OR-WA border, while the southern extremes of the low-gradient zone and the magnetic anomaly zones follow each other more closely.

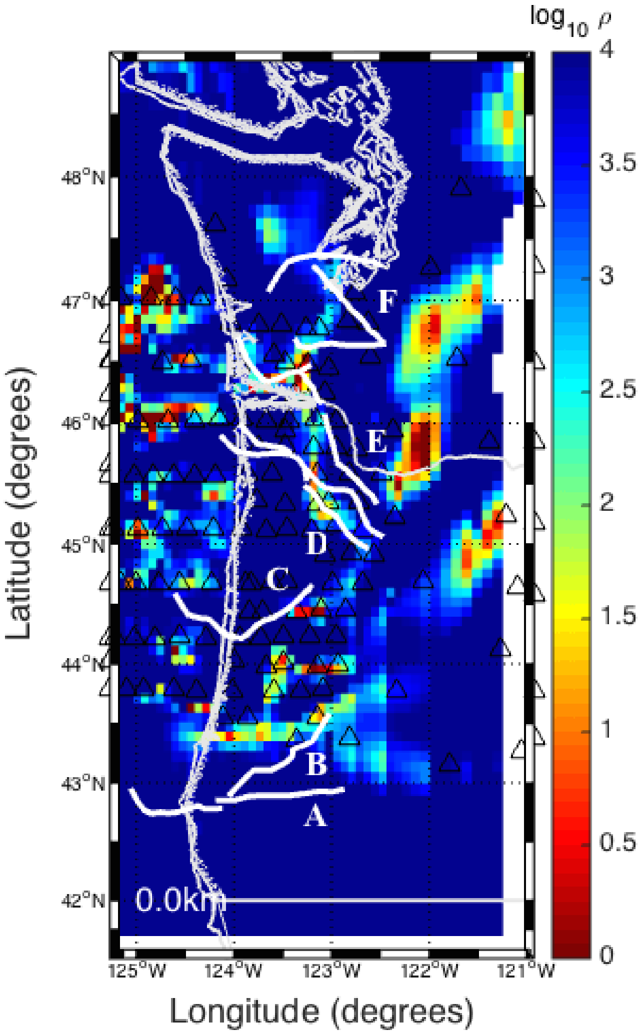


Geomagnetic anomalies over Cascadia

Magnetic anomalies indicate the presence of magnetite in the plate interface. Note how low-gradient zone seems to arc around the zone of greatest magnetic anomaly. Credit to Blakely et al.

Faulting

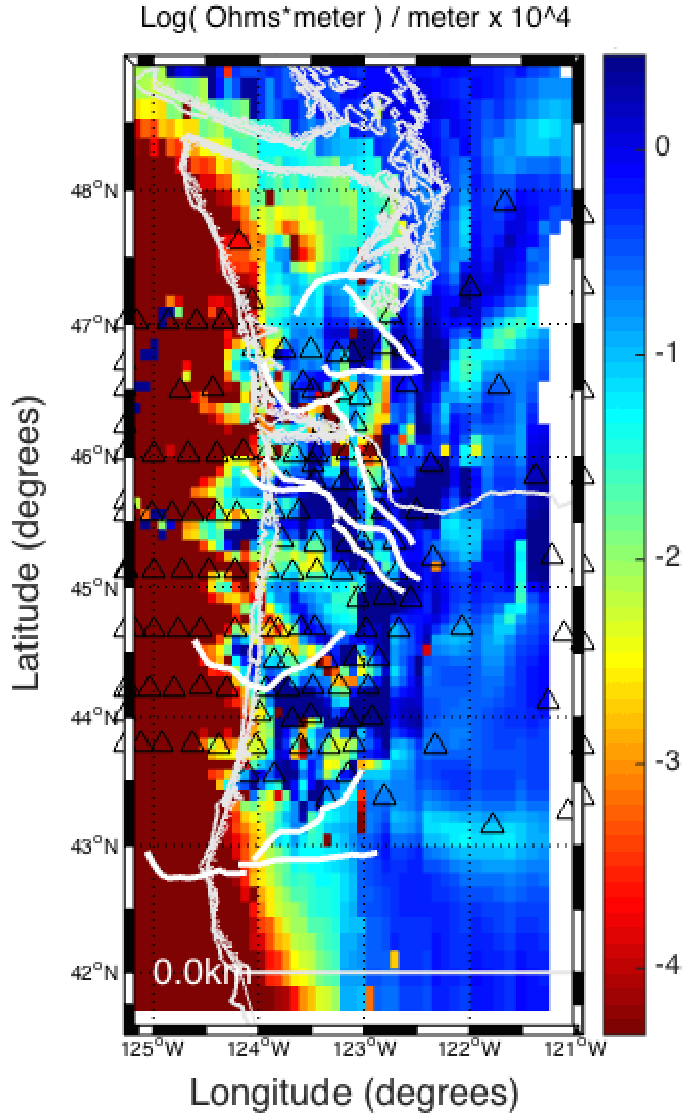
Only a fraction of the marked crustal faults shown by Wells et al. to correlate with reduced tremor frequency also appear to correlate with conductivity or gradient anomalies. The Gales Creek fault complex south of Portland and the Columbia-River Channel are the two, which are well resolved in the map of conductivity. Of honorable mention are the Doty fault and the Corvallis fault, both of which appear to cut across conductive filaments.



Map of slab-interface conductivity with crustal faults superimposed.

Faults lettered as follows: A: Canyonville; B: Wildlife Safari; C: Corvallis; D: Gales Creek; E: Portland Hills; F: Doty

As for the map of gradient, the Wildlife Safari fault appears to follow the southwestern extreme of the low-gradient zone, although this is arguably an arbitrary distinction since the color scale itself is somewhat arbitrary. Nonetheless, the relief there is sharper than along other stretches of the boundary.

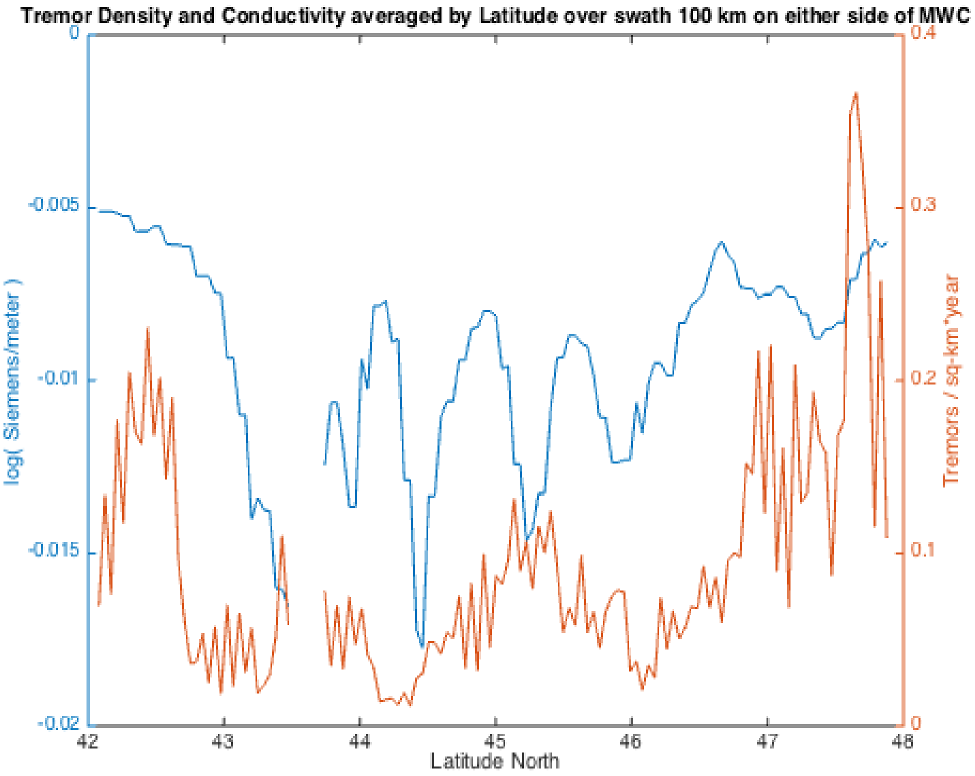


Map of conductivity gradient with faults superimposed

Note Wildlife Safari fault (second from bottom) lies on edge of low-gradient zone.

Correlation with Tremor

The plots of tremor density and conductivity averaged over a window 100km on either side of the MWC show many broad-scale features that have already been explained, among them suppressed tremor and lower average conductivity in the central-Oregon segment of Cascadia. However, we see that transects of average conductive vary widely in Oregon. They show fluctuations of a much smaller ‘spatial wavelength’ than the fluctuations in tremor occurrence. Despite registering less conductive *on average* than the rest of the margin, conductivity is not universally suppressed in Oregon. Instead, there are regions of low conductivity interrupted by regions of high conductivity. Outside of Oregon the variations dampen somewhat.

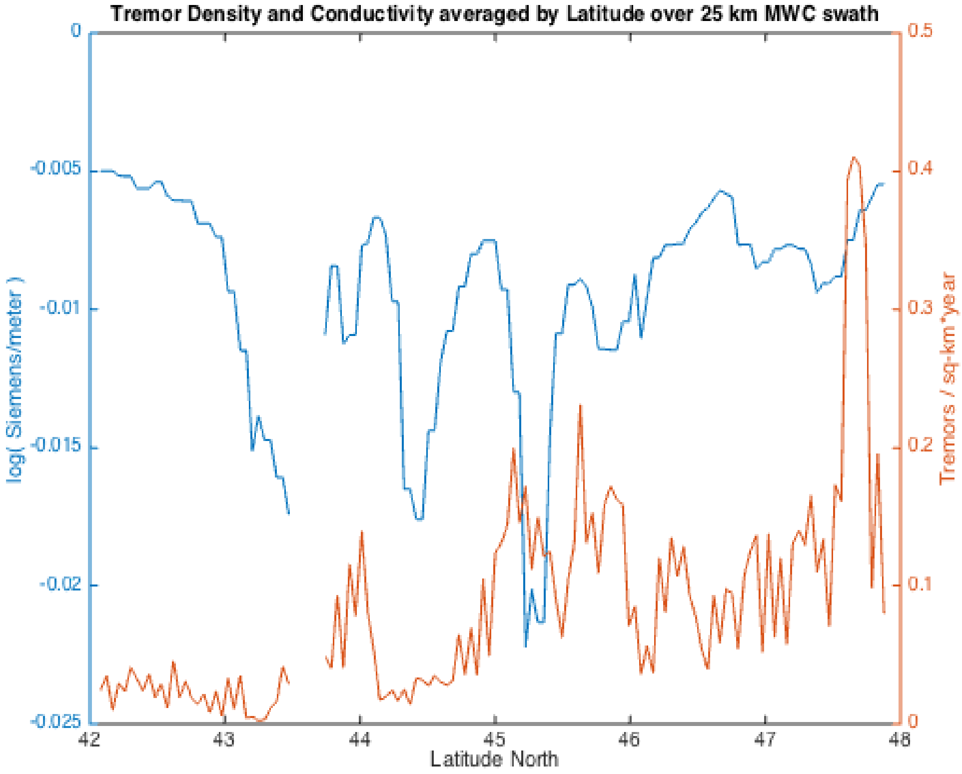


200km Tremor-conductivity plot by latitude

Tremor is suppressed in Oregon portion of the margin, yet not with the same short-range fluctuations as conductivity is decreased.

Beyond small-scale fluctuations in tremor, we see that tremor occurrence varies more slowly than conductivity. Furthermore, its fluctuations are not as strong as for conductivity. As expected we see more tremor in Washington and southern Oregon. The correlation between tremor density and conductivity along the 200km-across swath is 0.43 — a weak correlation, but a correlation nonetheless.

When we look at 25km swath along the MWC (50km across), we see stronger fluctuations in conductivity but weaker fluctuations in tremor. The attenuation of tremor toward the south may come from the error in extending the MWC line. However their respective minima and maxima occur at roughly the same latitudes to the 100km swath. The correlation coefficient is lower for this window: 0.03.

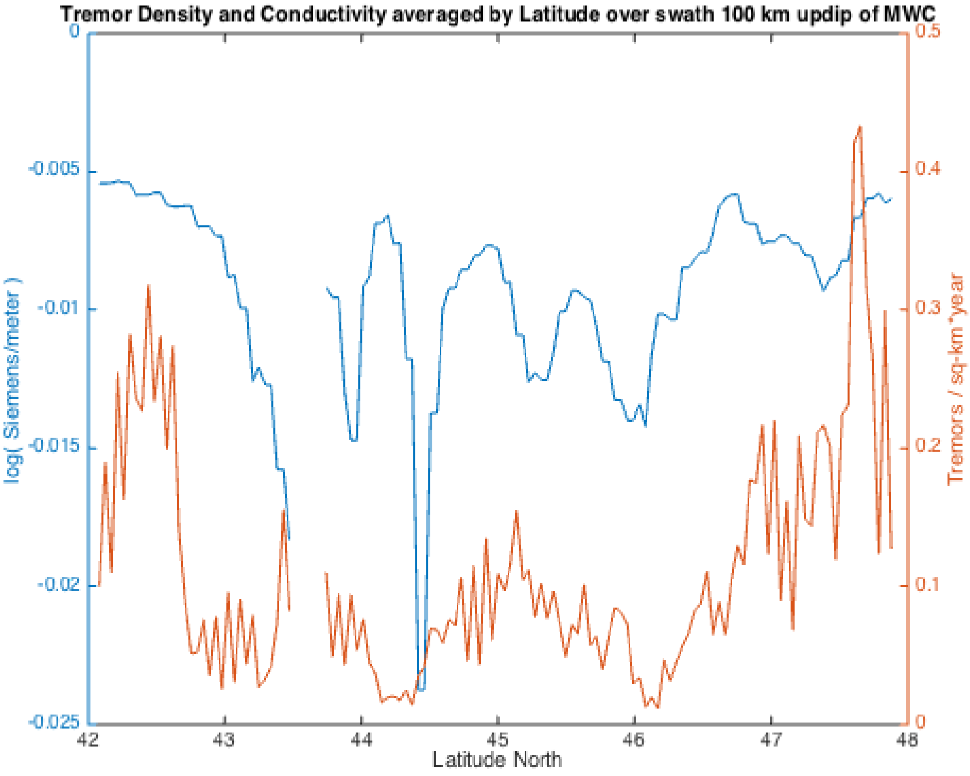


50km Tremor-conductivity plot by latitude

The long-range correlation seen in the 200km swath does not seem to exist here.

The asymmetric windows give asymmetric results. A window extending 100km up-dip of the MWC finds a higher correlation coefficient than the aforementioned

200km-across window: 0.43. In the window extending 100km down-dip of the MWC gives a very low correlation: 0.08. This hints at 'side-band' coupling between the two quantities up-dip from the MWC.



100km up-dip Tremor-conductivity plot by latitude

Up-dip of the MWC the correlation is even greater, and mid-period (~1/4deg) fluctuations in tremor appear weaker.

Discussion

Interpretation

Correlation

As mentioned already in the *Results* section, the average conductivity along the central-Oregon segment of Cascadia is not broadly suppressed, as is tremor. In fact there are places there along the MWC where conductivity nearly matches non-Oregon averages of the margin. Furthermore, variations between the two on smaller length scales do not appear to correlate. The weak correlation found between tremor and conductivity, by process of elimination, comes from long-wavelength fluctuations on the order of 1deg latitude. The two long-range heterogeneities we reference are those in plate geometry/stress and the terrane of the overlying crust.

Even from the four limited snapshots of tremor and conductivity we can draw several conclusions. First, an overall correlation along the MWC of the Cascadia margin exists, but likely the presence of fluids is not by itself a primary control over tremor occurrence. Second, variations in conductivity are more relevant up-dip than down-dip for tremor occurrence of the MWC, whichever way the arrow of causation may point. And indeed, the ETS zone is known to be slightly up-dip of the MWC[37]. Third, given that the correlation along the 25km window was much lower than for the 200km window, we infer that majority of a link between tremor and conductivity within that narrow range, insofar as such a generalized link exists, comes from coupling up- and

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[37] Wannamaker 2014

down-dip. The bias toward correlation up-dip suggests that the coupling would be up-dip, too.

Fluid Mechanisms

The mechanisms in Manthilake et al. and Blakely et al. may offer a partial explanation for why conductivity does not consistently follow tremor over small scales. Serpentization reactions occurring in the dehydration of chlorite-bearing rock may increase conductivity while sequestering fluids in conductive matrices.[38] Additionally, Nakajima and Hasegawa find that metamorphic reactions play a part in attenuating ETS by serving as fluid sinks and reducing pore pressure.[39] This process may be indicated in the apparent low-gradient ‘arc’ around the magnetic anomaly, down-dip of the region where fluids might soak up into the overlying slab. As for the up-dip correlation bias, maybe fluids, and by extension their control of pore pressure, exert more influence over tremor up-dip, while those down-dip serpentinize the MWC and decrease the pore pressure.

Faults

Tremor-altering crustal faults do not appear to consistently register as alterations in either the conductivity or gradient maps. Some do (e.g. Canyonville, Gales Creek, the Columbia River channel), but most do not. This suggests that their suppression of tremor is by mechanical but not fluid means. Perhaps those that appear conductive have formed as the result of processes that also drastically alter conductivity structures, such as the accretion of Siletz terrane. The high-gradient filamentary structures shown in the

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[38] Manthilake 2016

[39] Nakajima & Hasegawa 2016

gradient map are regions that become much more conductive rising from the slab interface. These seem too wide to be single fractures in Siletzia that have propagated upward. A less tenuous explanation is that they are irregularities in the accreted terrane, allowing fluids to migrate upward.

Limitations & Future Work

As for the idea of the conductivity gradient, fluid permeating through the overlying slab should for the most part be a function of permeability and pressure. Mathematically comparing the absolute conductivity and gradient along the interface might allow us to fish out those quantities. As of 2014, no study has directly measured the permeability of Siletzia in comparison to other terranes such as the Olympic Accretionary Complex or Klamath terrane.[40] The filaments of high gradient are worth studying further, as well, because of their potential to be routes of fluid migration down-dip.

As for the absolute conductivity along the slab, there is a lot to say about the ‘fluid budget’ of the subduction zone, especially as it pertains to serpentinization reactions and pore pressure controls of ETS. How much fluid from the surface reaches the MWC? Do fluids carried away from volcanic arcs affect tremor? Since serpentinite implies past alterations by fluid, it is worth exploring ‘fossilized’ conductivities, which may give clues to the plates’ movement over geological timescales.

As for the relationship between tremor and conductivity, we neglect to correlate along the northern Californian margin because, going by the data available at the time,

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[40] Schmalzle et al. 2014

extending the MWC swath past the bend of tremor occurrence at the Oregon border would have involved many assumptions about the plate geometry in regions where the subduction zone ‘jogs’. However, this would have extended the breadth of analysis substantially. For one, it would have included more of the Klamath accretionary complex (thinner than Siletz terrane), a wider range of plate geometries, and another region of frequent ETS. Even extending the MWC to 42N was a challenge, because a 50km window does not encompass the entire tremor zone.

There is much more investigation to do on which depth along the interface is the ‘zone of maximum correlation,’ and to be even more ambitious, the ‘pathway of maximum correlation,’ given the evidence for coupling up-dip of the MWC. Knowing this would help to understand the pathways of fluid migration and help to place constraints on a possible secondary locked zone.

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