Detecting Cascadia's changing shape with GPS

Nancy West and Shelley Olds

"If California slides into the ocean, like the mystics and statistics say it will, I predict this motel will be standing until I pay my bill…." Desperados under the Eaves," Warren Zevon

Plate tectonics is in the fabric of the western United States, whether people know it—or not. They become keenly aware of plate tectonics when an earthquake strikes. However, even in the absence of dramatic events, we know that plates are shifting, shortening, and shimmying continental crust in the Pacific Northwest because of research done with precise instruments. These include Global Positioning Systems (GPS), Light Detection and Ranging (LiDAR), and strainmeters. These new technologies provide a new approach to teaching plate tectonics and the kindred topics of earthquakes and tsunamis.

Figure 1. GPS station near Kneeland, CA.

With this module, you can teach plate tectonics using GPS data that shows the crust crumpling. We have known for 50 years that tectonic plates interact and cause earthquakes. We have known that ocean floor forms at mid-ocean ridges. We have used the stripes of reversed magnetic polarity to determine rates of this seafloor spreading and thus the rate of digestion of seafloor at trenches. That data was crucial to developing the theory of plate motion, and now we can measure it directly. This module is about using this up-to-date data as part of teaching plate tectonics.

You will find resources to help you teach plate tectonics, earthquakes, tsunamis, faulting, and folding to middle and high school students. This module offers suggestions for online resources that emphasize data, simulations, and models. It also presents new instructional materials on changes in continental crust wrought by plate tectonics—evidence from today, this day, that tectonic plates shift and buckle. They deform, and we measure it.

Students typically learn about crustal deformation by studying faults, earthquakes, and folds—the aftermath of tectonics acting over time. Now, we can see deformation as it happens and before faults slip in earthquakes. Nor do we need to wait tens of millions of years for rocks to fold and be exhumed by uplift and erosion. Instead, we can see where a GPS station has moved a few millimeters in a year. The instruments are that good.

Examples in this module are drawn from Cascadia—the region being compressed by the Juan de Fuca tectonic plate as it subducts under the North American plate in a convergent plate boundary. The region includes western portions of British Columbia, Washington, Oregon, and northern California. The subduction zone offshore generated a magnitude 9 or greater earthquake, and that triggered a tsunami that reached Japan's shores January 27, 1700. The story of how we know the time and magnitude folds together geology, tree rings, sunken forests, and Japanese historical documents. Further digging, literally, indicates that this earthquake was not unique. Studies of coastal strata and offshore cores tell of 41 such megathrust earthquakes in the last 10,000 years. When will the next event happen, and how will it shake society? Don't count on mystics, but do believe statistics.

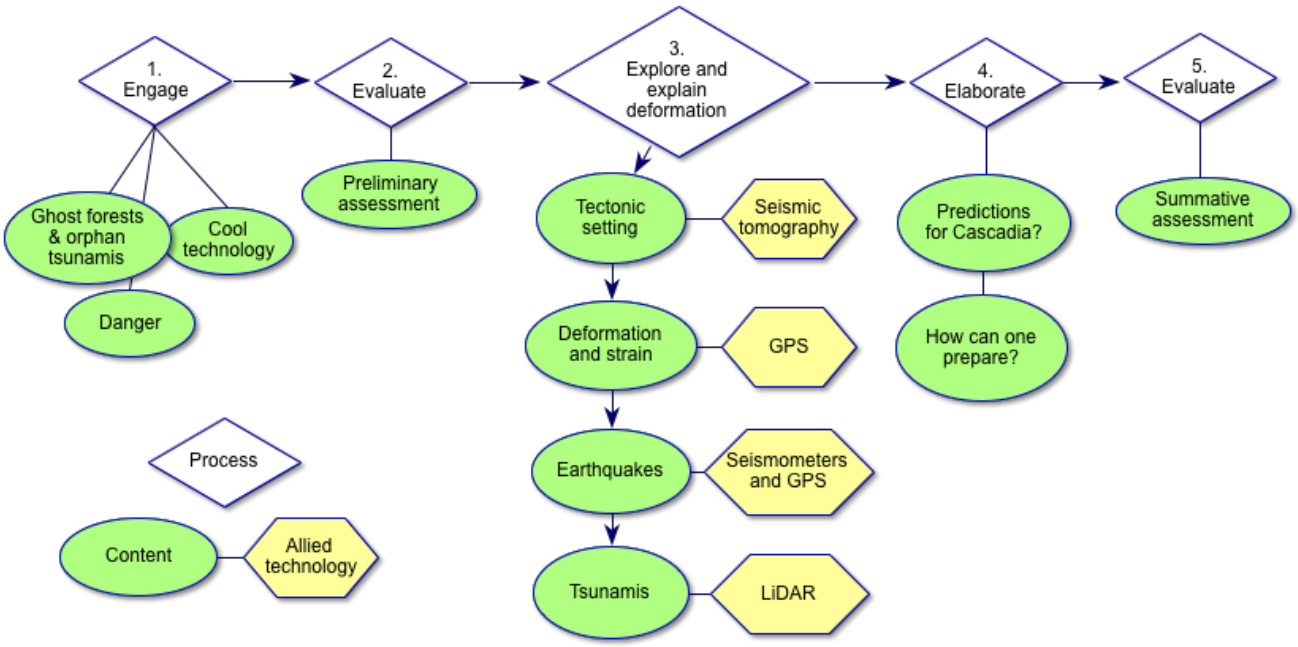
Module overview

Topics: Plate tectonics, earthquakes, subduction, megathrust quakes, crustal deformation, GPS, faulting, folding, and strain

Objectives: If students do the activities in this module, they will be able to:

- Describe the configuration of tectonic plates in Cascadia;
- Describe effects of great earthquakes arising from subduction;
- Define or describe deformation and strain;
- Explain how subduction causes crustal deformation;
- Explain how a GPS works and measures deformation;
- Graph GPS data by hand and interpret graphs of GPS data;
- Determine strain graphically, qualitatively, and even perhaps quantitatively in a triangle of crust defined by three GPS stations;
- Describe instruments used to measure or monitor Cascadia; and
- Use data to inform decisions.

Module overview: Click on a bubble to skip to that section (if reading this in Microsoft Word).'



Organization: The general sequence is laid out in the figure above. This module consists of five phases:

1 and 2. Introductory pieces to engage your students and evaluate what they already know;

3. Exploration and explanation of Cascadian plate tectonics— the tectonic regime, the resulting crustal deformation, earthquakes, and tsunamis; and

4 and 5. Concluding pieces in which students put their knowledge into action and you and they assess what they have learned.

Summary:

Students use data, models, and simulations to understand subduction zone tectonics in Cascadia. The module teaches about great earthquakes and resulting tsunamis. It has a special focus, though, on GPS data that shows Cascadia slowly deforming—building up to the next great quake. Deformation includes movement of blocks of crust, their rotation, and their distortion ("strain"). Students gain intuition with physical models before analyzing data graphically, qualitatively, and perhaps quantitatively. They can *see* how a triangle of land bounded by GPS stations changes position, orientation, and shape.

Next Generation Science Standards:

Performance Expectations:

MS-ESS2-2: Construct an explanation based on evidence for how geoscience processes have changed Earth's surface at varying time and spatial scales.

MS-ESS3-2: Analyze and interpret data on natural hazards to forecast future catastrophic events and inform the development of technologies to mitigate their effects.

HS-ESS1-5: Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks.

HS-ESS2-1: Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.

HS-ESS2-3: Develop a model based on evidence of Earth's interior to describe the cycling of matter by thermal convection.

HS-ESS3-1: Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity.

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics, as well as possible social, cultural, and environmental impacts.

See Appendix A for related Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas from *A Framework for K-12 Science Education*. Also, Appendix A includes connections to *Earth Science Literacy Principles*.

Grade Levels: 6 – 12

Teaching Time: This module will take a minimum of a week (55 minute classes) and as many as two to three weeks, depending upon which activities you choose and your use of homework.

General Procedure: The figure on page one lays out the general sequence. Numbers correspond to the following steps. Clicking on the following steps takes you to expanded sections with options and details.

Part 1. Engage your students—Use suggested resources and activities to draw your students into these lessons with videos, images, or an activity with a smartphone or an iPad operating as a seismometer. Three topics might do the trick: the story of how the January 26, 1700 earthquake was decoded; the danger of megathrust quakes and giant tsunamis; and *au courant* technology.

Part 2. Find out what they already know [Evaluate] about subduction zones or convergent tectonics, earthquakes and tsunamis, GPS, and deformation.

Part 3. Promote exploration and explanation—[Explore and Explain] Provide resources and guide students to explore Cascadian plate tectonics, deformation measured as it transpires, earthquakes and tsunamis.

A. Cascadia tectonic setting—Have students learn the tectonic playing field of Cascadia. Students can explore, or you can show them, a number of online sites that outline tectonic plates via earthquake epicenters, volcanoes, bathymetry, and continental physiography. If you "flip" your instruction, this could be a homework assignment.

B. Deformation, including strain—Have students explore deformation and strain (distortion) with physical models and GPS data. Students can analyze GPS data simply by plotting points on a graph (a separate activity supports students who struggle with that) and comparing graphs qualitatively. They can analyze data visually by drawing arrows showing the direction GPS stations move and how far they move. They can use the Pythagorean theorem, sines and cosines, and/or a spreadsheet-based calculator. Which method(s) your students use is your call. The module includes materials that explicitly connect science and mathematics.

C. Earthquakes—Teach about earthquakes as resulting from too much strain for brittle Earth materials to withstand. (Where a plate is deep and warm enough, crustal shortening from subduction can cause folding instead of faulting. Simulations demonstrate where this can occur in a subduction zone like Cascadia.)

D. Tsunamis— Follow up earthquakes with the tsunamis that sometimes ensue.

Part 4. [Elaborate] upon new knowledge and extend to action—ask your students to think about the future. From what they have learned about tectonics, geological history, deformation, and strain, what do they see in the tea leaves for the future of Cascadia? If they live there, what actions will they take? And if they do not live there, what actions will they take?

Part 5. Assess what students have learned— [Evaluate] what your students have learned from this module.

Materials:

- Materials depend upon which activities you choose for your students. They could include:
- Student lab sheets;
- Computers or a computer and projector;
- Graph paper, pencils, red and blue pens, and erasers;
- Protractors (circular preferred) or directional compass or compass app for smartphones or tablets;
- High-tech tee-shirt fabric, Silly Putty®, markers, rulers, bungee cords or sewing elastic, boards, and cards;
- Gumdrops, toothpicks, string, ring stands, modeling clay, transparencies, and bubble gum;
- Lasagna noodles, beakers, warm water.

Module Details

Introduction

Plate tectonics shapes and reshapes the western fringe of the Pacific Northwest, or "Cascadia." A spreading center to the west of the small Juan de Fuca plate[1] and a subduction zone to its east feed the plate northeastward under the North American continent (Fig.2). We watch and measure this process deforming crust from British Columbia to northern California. In the past, tectonic forces have pushed the leading edge of North America to the limits of its elasticity and the edge has suddenly sprung westward. The megathrust earthquakes produced have caused tsunamis that displaced coastal tribes in Cascadia and swamped villages in Japan. We can piece the most recent event together from upright dead cedar trees, marsh and sand deposits, offshore layered sediments called "turbidites," Native American oral history, and Japanese records of rice distribution to coastal villages. Furthermore, we have witnessed, measured, chronicled, and analyzed similar scenarios in Chile in 1960, Alaska in 1964, Sumatra in 2004, and Japan in 2011.

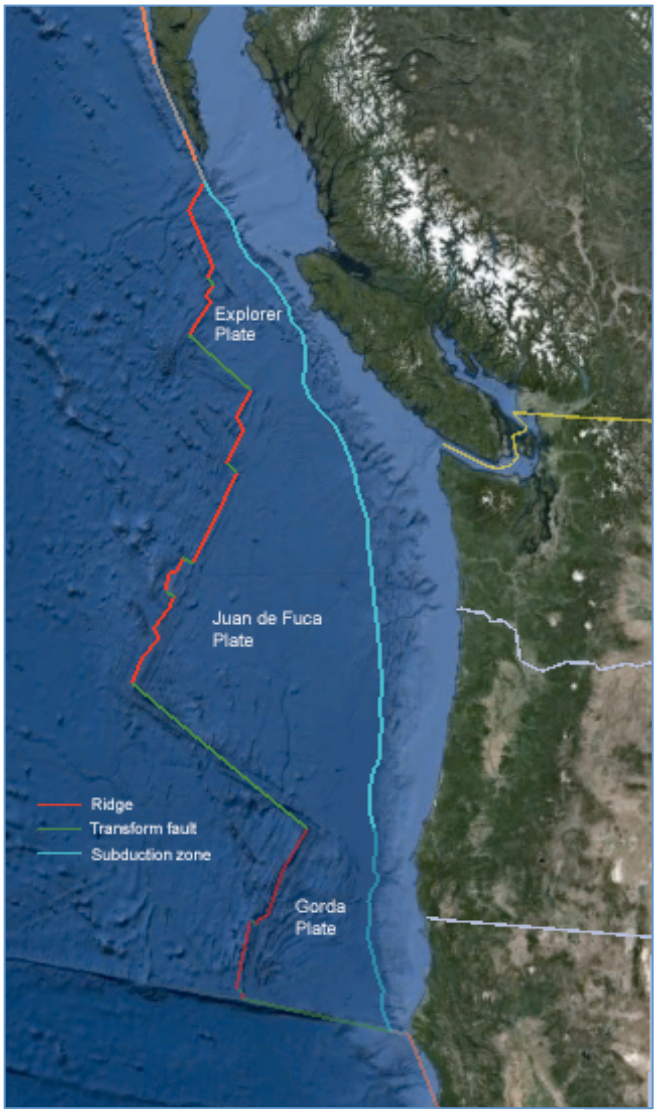


Figure 2. Plate boundaries in Cascadia. Adapted from Google Earth.

This module uses deformation data from GPS and the drama of earthquakes and tsunamis to help students learn about subduction zone plate tectonics. They will be studying grand concepts:

- How plate tectonics shapes Earth's surface;
- How the surface changes slowly and measurably--that is until it changes rapidly and devastatingly;
- How subduction zone events affect humanity; and
- How scientists improve their understanding of Earth processes.

Part 1. Engaging your students

Capture your students' interest in Cascadian tectonics, and you're on the way to a lively—in a good way—classroom. You only need to find the right bait. We offer several possibilities: a story of discovery from vastly different clues, the allure of danger through historical natural

[1] These materials refer to the three small plates in Figure 2 collectively as the Juan de Fuca Plate.

disasters, and intriguing applications of technology. Pick and choose among the activities and resources. Suggestions for quickly engaging students close this section.

Engage Option 1: A detective story—as a quick jigsaw activity or via media:

1. Sherlock Holmes could have led the team that pegged the last great earthquake in Cascadia to 9 p.m., Tuesday, January 26, 1700. Your students can have the experience of fitting four clues into a convincing story—of solving a mystery. As a jigsaw activity in which they form teams with "experts" about the clues, you can engage them in the history and future of Cascadia.

Appendix B provides the clues for the students. Summaries of the clues for you, the instructor, follow.

Jigsaw A. The corpses. Dead red cedar forests stand in water along Washington and Oregon's coast—they are "ghost forests." When and why did they die?

Figure 3. Ghost forest in the Copalis River, WA. Atwater, 2005.

The trees' deaths were dated two ways. Initially carbon-14 dating of the cellulose yielded death dates between 1695 and 1720. In the 1980s, scientists matched tree ring data from the dead trees against still living brethren ("witnesses"). But, death dates were too old because the tree ring samples came from battered trunks with missing bark. Finally, in 1996, when intriguing stories from Japan about a tsunami in 1700 emerged, scientists sought tree roots with the bark still attached. On eight samples of roots, seven trees died after the 1699 growing season, while one lingered into the next growing season.

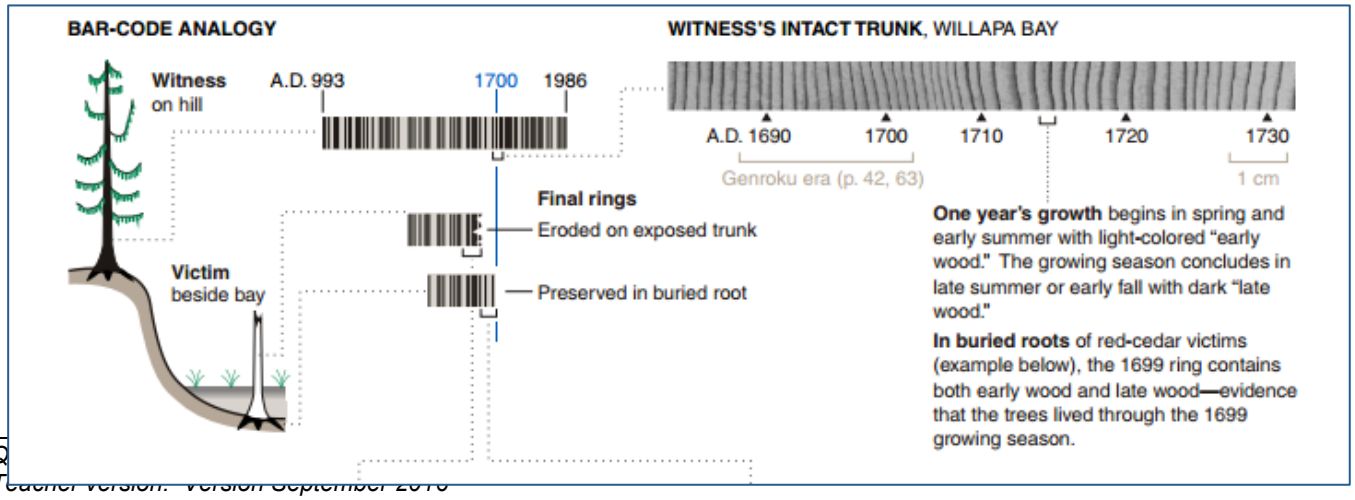


Figure 4. Dating trees from their rings. Atwater, 2005.

For a virtual field trip to a ghost forest, visit the Teachers on the Leading Edge site and select the Southwest Washington Coast trip to Copalis Beach. Viewpoint 3 and 4 show ghost forests. You can spin 360 degrees and zoom in on examples of ghost trees. (Search for "TOLE virtual field.")

Jigsaw B. Eye-witness accounts. Native people's tales speak of earth shaking and flooding. Some can be loosely dated. For example, Chief Louis Nookmis, was interviewed in 1964, at age 84. "These are stories from my grandfather's father about events that took place four generations before his time…over 200 years ago…the land shook…a big wave smashed into the beach." Estimates for the time of the quake and tsunami are between 1640 and 1740.[2] Beyond oral history tied to specific events, the cultural tradition of the Whale and Thunderbird battling tells metaphorically of catastrophic geological events. The tradition appears in stories, artifacts, and paintings on buildings.

Figure 5. Swai'xwe mask from British Columbia representing the shaking from an earthquake and the whirling of wind. Ludwin, *et al*., 2005.

Jigsaw C. Physical evidence. Coastal sediments have layers of sand and tidal muds lying over soil and vegetation. Some sites have charcoal, hearths, and woven fishing weirs at the soil horizon. Marshy soils and grasses usually lie above the tide or at the upper reaches of a tidal zone. Figure 6, though, shows them below sea level with beach sand covering them. (Marine microscopic organisms in the layer and its pattern of thinning inland indicate it is beach sand.) Muddy bay sediments lie above the sand. Examples of the sand deposits are found from northern Vancouver Island to northern California. In all cases, land must have dropped and been washed over by waves in order for the sand to be deposited. Similar sequences of sand sheets over soils were created by tsunamis after the 1960 Chilean and the 1964 Alaskan earthquakes.

[2] Ludwin, *et al*.,2005. p 142.

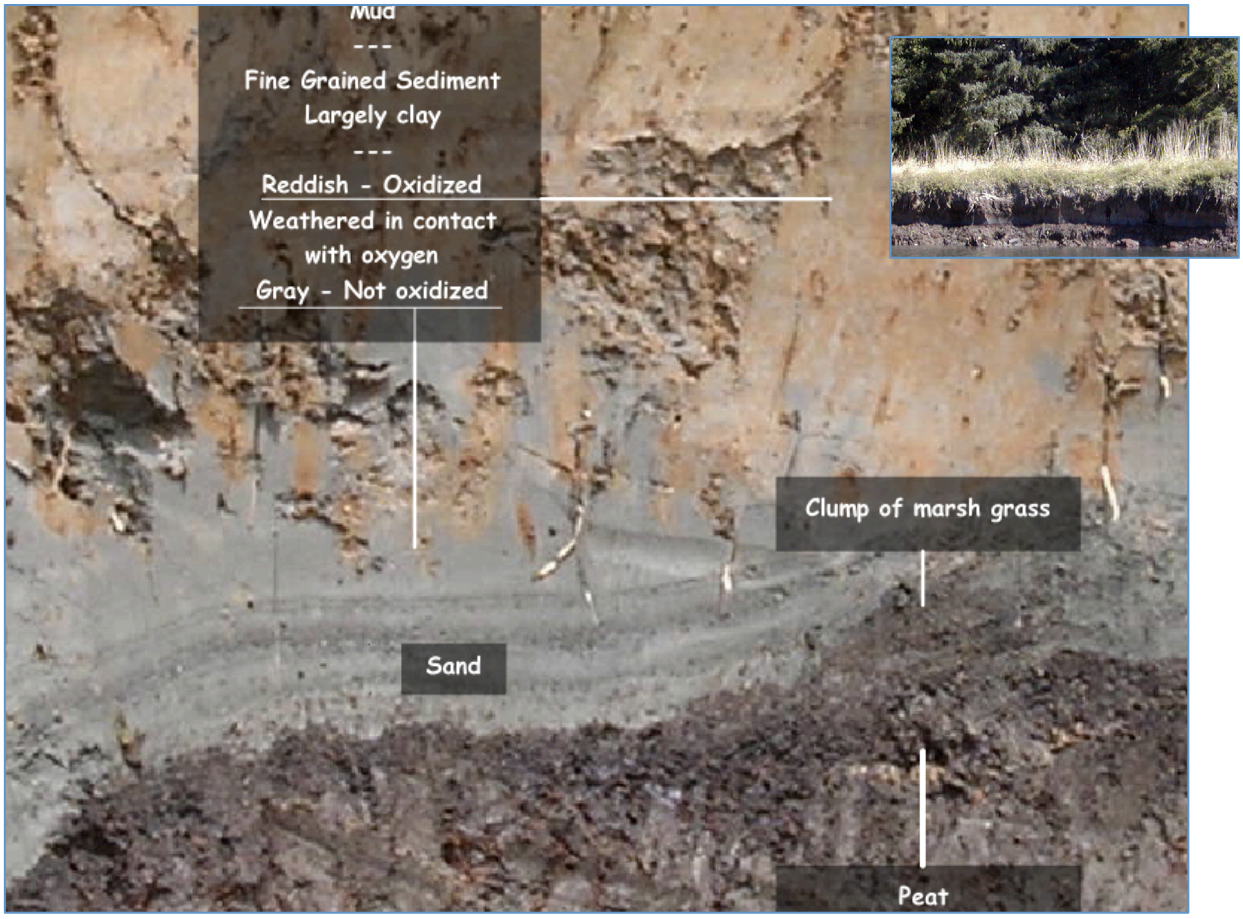


Figure 6. River bank deposits of tsunami sands lying above peaty marsh soils on the Niawiakum River, southwestern Washington. Inset shows the river bank. Granshaw, 2009.

Jigsaw D. Historical records. In Japan, close to 46,000 earthquakes were documented between 416 and 1872. While compiling earthquake records in the 1940's, Musha Kinkichi, recognized that peculiar flooding occurred simultaneously in two spots. These two records were combined later with documents from several villages mentioning a tsunami or unusual flooding, "something like a high tide" that struck January 27, 1700. The village of Kuwagasaki lost 13 houses destroyed by waves and 20 by fire. Villagers headed to the hills, though, and no one was hurt (Fig. 7). The government stepped in with an emergency allotment of rice for 159 famished people and lumber to build temporary shelters. Elsewhere in coastal Japan, salt-evaporation kilns were damaged; a ship full of rice capsized; and rice paddies, villages, a government storehouse, and a castle's moat were flooded. Because writers felt no preceding earthquake, they did not know what to make of this "orphan tsunami."

Give your students these clues (Appendix B) and see what they make of them: For ten minutes, give a quarter of your students a different clue to study. Then pull from these groups to make teams with diverse expertise. Ask teams to spend fifteen to twenty minutes reporting what each member has learned and discussing the clues. Can they think of an explanation that ties the pieces together?

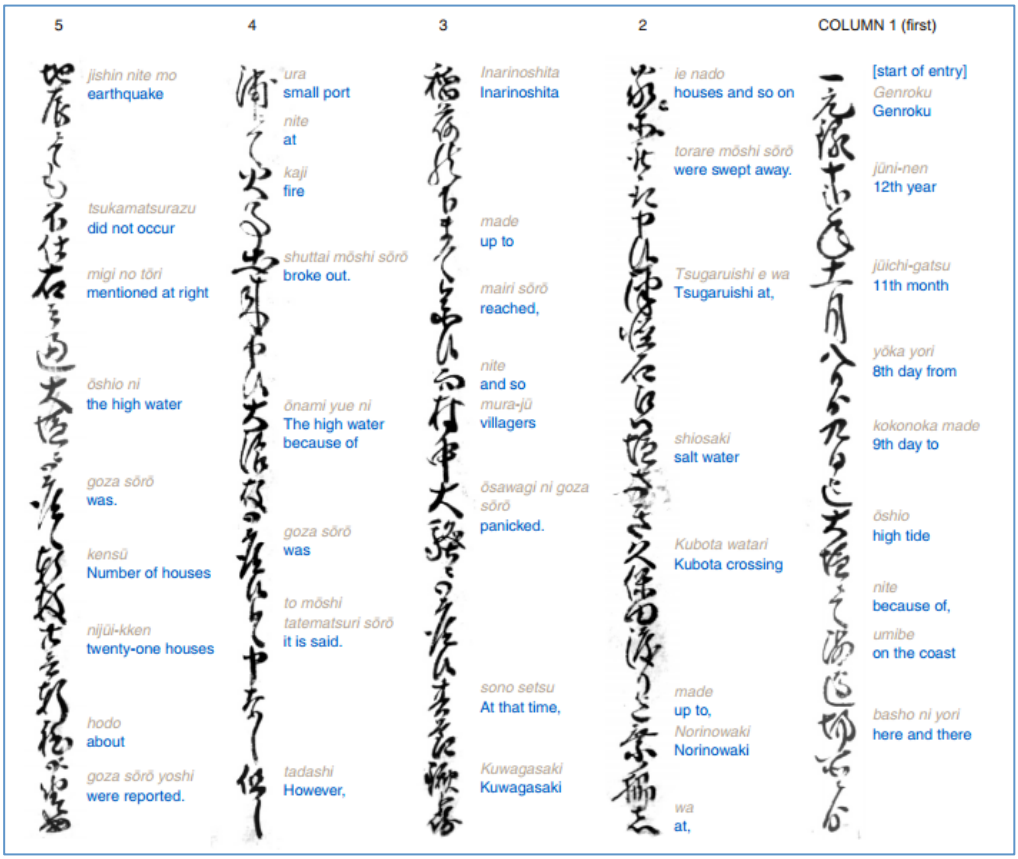


Figure 7. A diary describing houses swept away by an "orphan tsunami," January, 1700. Atwater, 2005.

Discuss the mystery with your students. You can explain the story that was carefully pieced together by Brian Atwater and colleagues in 2005 of a massive earthquake (M ~ 9) along the Cascadia Subduction Zone (CSZ), triggering a tsunami. From historical and modern earthquake and tsunami records, scientists inferred the source, magnitude, and timing of this most recent Cascadian mega-thrust earthquake. Also, since geoscientists unraveled the mystery of ghost forests and orphan tsunamis, other geoscientists have cored sediments offshore Cascadia and extended and refined the history. In the last 10,000 years, 41 quakes magnitude 8 or greater have occurred.

2. As a shorter introduction, at the end of the jigsaw activity, or for absent students, consider playing a 7:48 piece on National Public Radio's Morning Edition that featured Atwater. "Unearthing Proof of a Tsunami in the Pacific Northwest" assembles the clues and introduces emergency preparedness. However, it omits mention of Native peoples' oral histories and traditions. (Search for "NPR tsunami proof.")

3. The American Museum of Natural History tells the same story in "Ghosts of Tsunamis Past," an on-line article for non-scientists. (Search for "AMNH tsunamis.")

Resources:

As background for you, watch Atwater explaining how scientists deciphered the 1700 earthquake. Seven YouTube videos cover a lecture Atwater gave as a Distinguished Lecturer for IRIS and the Seismological Society of America. (Search for "YouTube orphan tsunami Atwater.")

Smithsonian.com covers the story in "Future Shocks." This four-page article is for non-scientists. Because it also discusses risks of movement on other Seattle area faults, which might or might not be tied to the CSZ, this article will be a good read for you but might confuse students. (Search for "Smithsonian future shocks.")

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Engage Option 2: The allure of danger

Earthquakes, some of which produce tsunamis, relieve crustal strain arising from subduction. **You could show your students one of the videos that follow in a film fest, as homework in a flipped class, or one a day as a trailer while you wind down your previous unit.** The following are vintage film clips or modern simulations of earthquakes and tsunamis. Videos come from the four largest earthquakes ever recorded: Chile in 1960 (M = 9.5), Alaska in 1964 (M = 9.2), Sumatra in 2004 (M = 9.1), and Japan in 2011 (M = 9.0). All spawned devastating tsunamis, and all were subduction zone megathrust earthquakes.

Resources:

A comprehensive video that shows shaking from the Tohoku, Japan 2011 earthquake and its ensuing tsunami. Footage includes the view from a Japanese Coast Guard ship and a view of a wave from the air. Simulations model the rise and fall of seismic waves through Japan as measured by GPS. If you show only one video, show this one from National Geographic's Environmental News: Rare Video: Japan Tsunami. 3:34. (Search for "environmental news Japan tsunami.")

Raw destruction from the Japanese tsunami, courtesy of BBC. The tsunami overturns fishing boats and drives one under a bridge while people film the spectacle from high balconies. 1:56. (Search for "BBC moment tsunami.")

From NOAA, footage of the Japanese tsunami. "Tsunami Strike: Japan Part 1: Destruction." 2:55. (Search for "tsunami strike destruction.")

"Japan Earthquake: before and after" -- photos of many locations in Japan, from ABC News. Swipe your mouse over aerial photos to see the effects of the Tohoku earthquake and tsunami. This website is a simple and dramatic way to dig into details of images. (Search for "Japan quake before after photos ABC Australia.")

Some students will be intrigued by vintage movies. A CBS News video, "Recalling the 1960 Chile Quake," shows black and white video of the largest earthquake recorded--eleven minutes of shaking and a terrible tsunami. This was made after the 27 February, 2010 quake (M = 8.8). 1:50, plus an advertisement. (Search for "CBS recall Chile quake.")

"Cataclysm: Volcano, Tidal Waves Devastate Pacific Area," presents a Universal Studio newsreel from 27 May 1960 of the Chilean earthquake and tsunami. 1:44. (Search for "cataclysm newsreel.")

A shocking 8 mm movie from a ship in Valdez, Alaska being slammed by shaking, burning, and flooding from the Good Friday, 1964, tsunami. "The Big Picture: Alaskan Earthquake," from the Department of Defense. 5:03. (Search for "Alaskan earthquake big picture.")

Video linking Native American stories with modern research and modeling about tsunamis in Coos Bay and Cannon Beach, Oregon from Cascadia earthquakes. The video by Oregon Public Broadcasting includes clips about designing City Hall in Cannon Beach to shelter

people from a tsunami. "Oregon Field Guide: Tsunami." 10:02. (Search for "Oregon guide tsunami update.")

AOL.on Education's "The Great Sumatra-Andaman Earthquake Disaster." This is a matter-of-fact video chronicling the tragic 2004 tsunami. This video focuses on the tsunami only; footage shows numerous examples of the waves and their effect on people and property. 4:17, with a 30 second advertisement. (Search for "AOL Sumatra earthquake 2004.")

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Engage Option 3: Fresh, high-test technology

The technology that scientists use to document and analyze Earth's hiccups could engage some students. Ideas for three strands follow.

1. Earthquake early warning systems

Predicting earthquakes is still in the future. We can, however, detect earthquakes and transmit warnings to people who live away from the epicenter. Japan, for instance, has a system that alerts people via cell-phones, TV, radio, and computers. In the 2011 Tohoku earthquake, citizens in Tokyo had 80 seconds to prepare for the shaking.

You can show your students the warning system in action with a video from TV coverage of the Japanese Parliament as it was interrupted by the early warning system. "Earthquake and Tsunami Alarm Systems of Japan March 11, 2011." 3:41 (Search for "Japan earthquake tsunami alarm YouTube.")

After showing the video, ask your students for their ideas about how the earthquake early warning system might work and then how they might devise one using GPS. They can then view the first 2:50 of "GPS and Earthquake Early Warning. "GPS and Earthquake Early Warning." 6:56 total. (Search for "UNAVCO educational resources" and scroll to the video.)

Figure 8. Japan's early warning system in action with the Tohoku quake. Elliott, 2011.

Resources:

"Earthquake early warning in action," from the American Geophysical Union's *The Trembling Earth* blog, explains that early shaking detected by seismometers triggers an alert with estimates of the probable intensity, how long until shaking begins, and magnitude. The signal is transmitted by electromagnetic waves that travel at the speed of light—300,000 km/sec--whereas seismic waves travel a few kilometers per second. Thus, a cell-phone call will reach someone before a P-wave does. (Search for "trembling early warning action Japan.")

"The USGS and partners work to develop an earthquake early warning system for California" describes benefits of a system and how one is being tested in the ShakeAlert program. Examples of potential benefits are the ability to slow trains, open elevator doors, and halt medical procedures. (Search for "USGS partners warning.")

Some high-resolution GPS stations deliver data in real-time. When they jump, signals can be processed in about two minutes and a warning sent out. A national program of federal agencies, universities, UNAVCO, and other institutions has created the Real-time Earthquake Analysis for Disaster (READI) Mitigation Network to employ GPS as an earthquake and tsunami warning system. Testing began in April 2012. NBC News.com describes the program in laymen's language with "NASA tests GPS network to monitor earthquakes" in *OurAmazingPlanet*. NASA gives more detail with its news release, "NASA tests GPS monitoring system for big U.S. earthquakes." (Search for "NBC READI NASA" and "NASA GPS earthquake news.")

2. Simulating, modeling, or animating earthquakes and tsunamis

The power to show large-scale phenomena is one of the beauties of computers. Seeing simulations of Earth events could appeal to students with a penchant for modeling and simulation. An example is a simulation of seismic waves from the Tohoku quake rippling across the United States provided by the Incorporated Research Institutions for Seismology (IRIS). Red dots represent stations rising, blue dots show stations falling. The intensity of the color indicates how high the station rose or how low it fell. (Search for "USArray GMV Honshu.")

Research GPS stations in Japan provided evidence of the great quake almost instantaneously. This model shows both horizontal and vertical jumps of the land. (Search for "grapenthin Sendai displacements.")

Scientists use computers to model tsunamis as well. One example is a model of the tsunami generated by the 1960 Chilean earthquake, by Nobuo Shuto of Tohoku University, Japan. NOAA provides a color simulation of the same event. A third example, from the Pacific Tsunami Warning Center, gives another perspective. Students who are animated by computer applications could compare and contrast the three simulations. What makes a simulation effective? Why would you choose one style over another? Which conveys the most information? Which would be fastest (and least expensive) to design? (Search for "modeling 1960 Chile tsunami," "NOAA Chile animation 1960," and "PacificTWC Chile animation.")

3. Playing with seismometers and citizen science.

Seismometers have evolved since a pendulum knocked a ball into a frog's mouth (Fig. 9). With the right apps, smart phones and tablet computers can be seismometers. They contain accelerometers that detect motion along the three dimensions of space. If you have an iPhone on a desk with the seismometer app open AND an earthquake occurs, your phone will measure Earth's motion.

Your students can experiment with these devices. They can lie on the floor with the device on their chest and watch their heart beat. Returning to geology, they can then place the device on a table, rap the tabletop and jostle each side. This will replicate the use of classic sets of three seismographs (Fig. 10) where each instrument measures motion in a single dimension. You will need an app such as iSeismometer or iSeismograph HD.

Figure 9 A replica of a Chinese seismometer from the first century A.D. Shizhao, 2004.

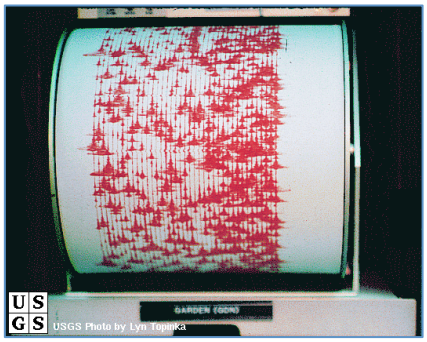

Figure 10. Old-school seismograph or seismometer. Topinka, date unknown.

Researchers at the University of California, Berkeley, are working to turn smart phones into a network of seismometers to collect and automatically send shaking and location data to their server. With full development of their app, the information garnered can connect into an early warning system and Geographic Information System (GIS) to analyze soils, building design, proximity to faults, and shaking. All will be critical to hazard and risk analysis…and warning. BBC News explains in "Smartphones to be pocket seismometers" how researchers test apps with a shake table (Fig. 11) as well as their plans for a seismic citizen science project in the Bay Area. (Search for "BBC smartphone seismometer.")

Figure 11. Smartphones being tested as seismometers on a shake table. Amos, 2012.

Engage Option 4: Streamlining this section

Choose among the mystery of ghost forests and orphan tsunamis, drama and danger inherent to subduction zones, or modern technology to captivate your students. Culling the best to limit time spent might be the real challenge. To streamline this introductory engagement phase, choose one or two short videos that will interest your students—perhaps a comprehensive or quirky one. Suggestions are:

- "Unearthing Proof of a Tsunami in the Pacific Northwest." 7:48. (Search for "NPR tsunami proof.")
- National Geographic's Environmental News: Rare Video: Japan Tsunami. 3:34. (Search for "environmental news tsunami.")
- "Oregon Field Guide: Tsunami." 10:02. (Search for "Oregon guide tsunami update.")
- "Cataclysm: Volcano, Tidal Waves Devastate Pacific Area," 1:44. (Search for "cataclysm Pacific tidal.")
- And, play with a smart device—their coolness factor engages.

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Part 2. Preliminary Assessment

Before you dive into instruction, you will want to know what your students already know, what they know little about, and in what ways they misunderstand things. Taking the time for this preliminary assessment will save time in the long run and will focus your instruction. It can also act as a baseline for identifying what your students learn from the lessons.

Formats for assessing their prior knowledge could include:

- Think-Pair-Share in which students think about a question, share their responses with a classmate, and report the combined response. This engages *all* students.
- Concept maps—electronic or with sticky notes on paper. Concept maps tell you what your students know now and let students to see how their knowledge evolves. This engages all students if done individually or most students if done collectively in small groups.
- Whole class discussion. Quick and dirty, but students can hide behind their reluctance to participate.
- Writing from a prompt—an image, a video, a quotation, or a question. Engages all students but will be time-consuming for you to read.

Preliminary assessment for this module should include something about plate tectonics in the Pacific Northwest, earthquakes and tsunamis, deformation, and GPS. You don't need to evaluate all of these at one time. You can, for instance, open a class with a short video and/or question to learn what your students know about a topic and focus them on your class. Circulate as students work on the assessment. For Think-Pair-Share, discussion, or writing, questions could be from among the following:

- What do you know about subduction zones—or convergent margins?
- Describe plate tectonics in the Pacific Northwest? (They may not know the term "Cascadia.") Or, draw what you understand about plate tectonics in Washington and Oregon.
- Have you ever been to that part of the country? What was your experience? What was interesting about it?
- What do you think you know about earthquakes? Tsunamis?
- Have you ever experienced an earthquake? What was it like? What happened?
- Describe what you understand about how faults and folds form.
- In the video we watched, what caught your attention?
- Describe how you understand GPS units to work.

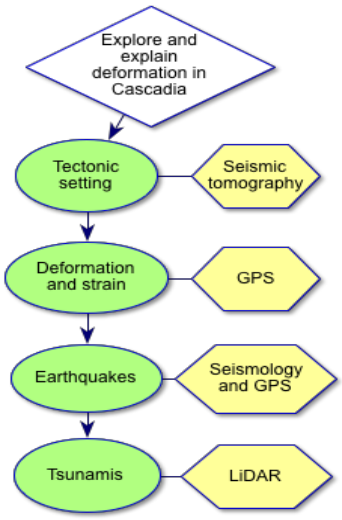
If you have students build concept maps, logical topics are plate tectonics, earthquakes, tsunamis, deformation, and GPS.

To streamline the preliminary assessment, do Think-Pair-Shares about subduction zones, earthquakes and tsunamis, and GPS.

[Back to module overview.]

Part 3. Explore and Explain

The meat of the matter: teaching and learning about subduction, deformation, earthquakes, and tsunamis, with Cascadia as our homegrown subduction zone. This section briefly presents the conventional big topics of plate tectonics, earthquakes, and tsunamis in the context of Cascadia. Suggestions emphasize on-line resources from which to help visualize data or processes.



New to this module are materials that help to explain why the quakes are so strong. They teach about deformation and strain, and they get the most attention in this section. As the Juan de Fuca plate dives under North America, Cascadia crumples. It is deformed and strained until the crust breaks in an earthquake (or folds, at depth). And, in some cases, tsunamis form. Hence, the order within this section, as shown in Figure 12. (Click on a shape to navigate.)

Figure 12. Content map.

A. Tectonic setting:

Students need a sense of how plate tectonics plays out in Cascadia. First, the plates. For many tectonic plates, students can pick out plate boundaries from earthquake data. That works well, for instance, in Chile, where earthquake foci get deeper inland, away from the trench at the subduction zone. That's not the case with Cascadia (Figs. 13a and b). In Cascadia, there is a dearth of earthquakes along the trench, an observation that lies at the heart of this module.

Additionally, there is no trench visible at the CSZ. Sediments keep it full—rapid uplift of mountains, lots of rain to wash sediment downstream, and a relatively slow rate of spreading and subduction have cooperated to fill the trench.

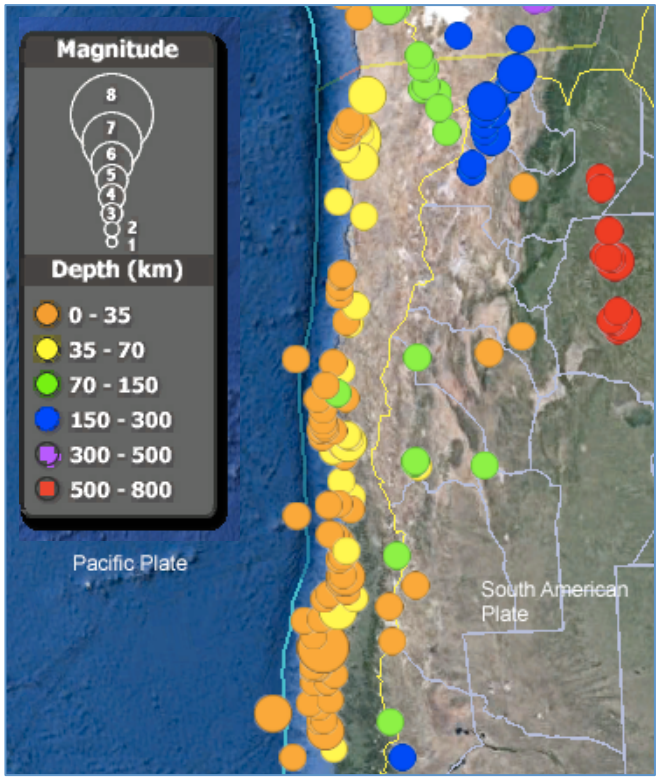


Figure 13a. Chile. Earthquakes > M = 6 from 1993 - 2012 and all quakes for one week in September 2013.

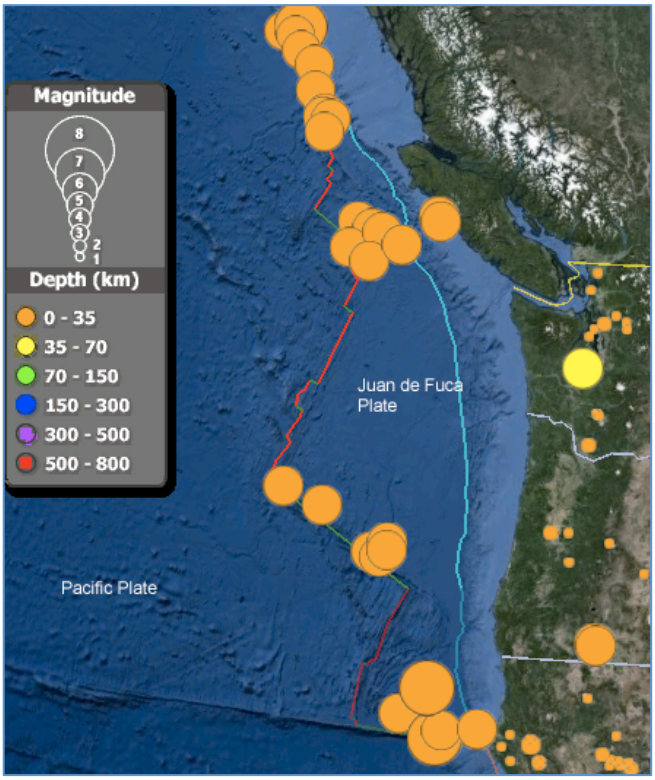


Figure 13b. Cascadian quakes, as in Figure 13a. Figures are from Google Earth.

(Students might well ask, "If that's the case, how do we know where the subduction zone is?" A legitimate question. You can ask them for their ideas. Ask, for instance, "Besides patterns of earthquakes, what tells us where subduction is happening?" Or, "How do we know *that* subduction occurs?" The simplest answer now is that we can see the slab angling under the continent. A network of seismometers allows us to construct images of deep structures. See page 17 for resources on seismic tomography.)

Activities:

Option 1. As a dynamic way to have students explore Cascadian tectonics, you can have them use Google Earth to see a classic ocean-continent subduction zone such as Chile and compare Cascadia to it. Computers will need to have Google Earth installed—it is free and downloadable. Also download Dynamic Earth files from the Science Education Resource Center. Have students explore the Plate Boundary Models and Seismicity layers. The layer "Volcanoes of the World…." fleshes out the data but is not necessary. (Search for "Google Earth" and "Dynamic Earth SERC.")

When students zoom in towards Chile, point out the spreading ridge at the divergent margin on the west side of the Nazca plate and the oceanic trench at the subduction zone on its east side. Ask your students to note where the Nazca/South American plate boundary lies with respect to the deep water of the trench. Also, ask them to describe how the depth of the earthquakes changes from west to east across the Andes.

Then have them zoom into Cascadia. How is the Juan de Fuca plate like the Nazca plate? And how is the North American plate like the South American plate? Describe the seafloor at the subduction zone. Compare and contrast the pattern of earthquakes.

This could be done individually, as pairs, or as a class discussion.

Option 2. Alternatively, you can introduce the tectonic setting with media:

The first five slides of the presentation, "Episodic Tremor and Slip: the Case of the Mystery Earthquake."

"EarthScope in Cascadia." 5:51. The video includes simulations of Cascadian plate motions. This is a good, quick overview of the tectonic setting and how we measure the activity of plate tectonics. (Search for "EarthScope in Cascadia movie.")

A simulation of how the Juan de Fuca plate came to be over the last 80 million years as the Pacific plate slipped under the North American plate. The narrative explains the simulation in direct and lively language. (Search for "UCSB animation Farallon.")

A simulation of a subducting plate causing an earthquake clarifies how the crust deforms before an earthquake and springs back during one. The video shows the role of GPS in measuring changes. "How Does Land Jump in an Earthquake." 0:49. (Search for "land jump earthquake.")

Resources:

For background on the plate tectonics of Cascadia, the first part of "Generalized Geologic Setting of the Pacific Northwest" is useful. This article from IRIS is a general summary, with individual topics ranging from tectonics to four kinds of earthquakes to the subduction zone earthquake and tsunami of 1700. Another article, "Subduction Zone—Plate Interaction" from IRIS, compares the CSZ to the Sumatra-Andaman region. In both articles, stop reading when you get to "Episodic Tremor and Slip." Although the intended audiences are teachers,

students with a background in plate tectonics and who have wrestled with earthquake data could appreciate having their ideas neatly tied up with a bow by these articles. (Search for "IRIS geologic setting northwest" and "IRIS subduction zone.")

The dip of the subducting Juan de Fuca slab varies, as seen in gravity data in "Cascadia Subduction Zone: Two contrasting models of lithospheric structure." This brief article shows two cross-sections of the subduction zone that are derived from geological, geophysical, and borehole data—they are not just cartoon drawings. (Search for "USGS CSZ lithospheric.")

[Back to module overview.]

B. Technology allied with the tectonic setting—seismic tomography:

Scientists' understanding of plate tectonics has always been advanced by developments in technology. A classic example is that of Harry Hess using Sonar, developed to hunt submarines in World War II, to map the Pacific's seafloor, leading to the idea of seafloor spreading. Now we have an array of seismometers and high-precision GPS units spanning our continent. We can combine earthquake data with computer modeling to see the bowels of Earth with seismic tomography.

Analogous to a CT scan for an injury, seismic tomography combines images that slice virtually through Earth to reveal deep structures. The slices are made in a national project, the USArray, which is a flock of 400 seismometers stepping across the country over ten years. Collectively, the seismometers indicate areas that transmit seismic waves slower or faster than expected. By assuming that their velocity is tied to the temperature and materials through which waves travel, researchers can deduce features such as the subducting Juan de Fuca slab (Fig. 14).

This project has also led to interesting connections among Cascadia, the vast Columbia River basalts, and the hotspot underlying Yellowstone National Park. While "Slab-plume interaction beneath the Pacific Northwest" is the original research article, "Yellowstone: what lies beneath," is a blog that explains the science in less technical language. The blog has many of the same images as the research paper. (Search for "Obrebski slab" and "Yellowstone lies beneath.")

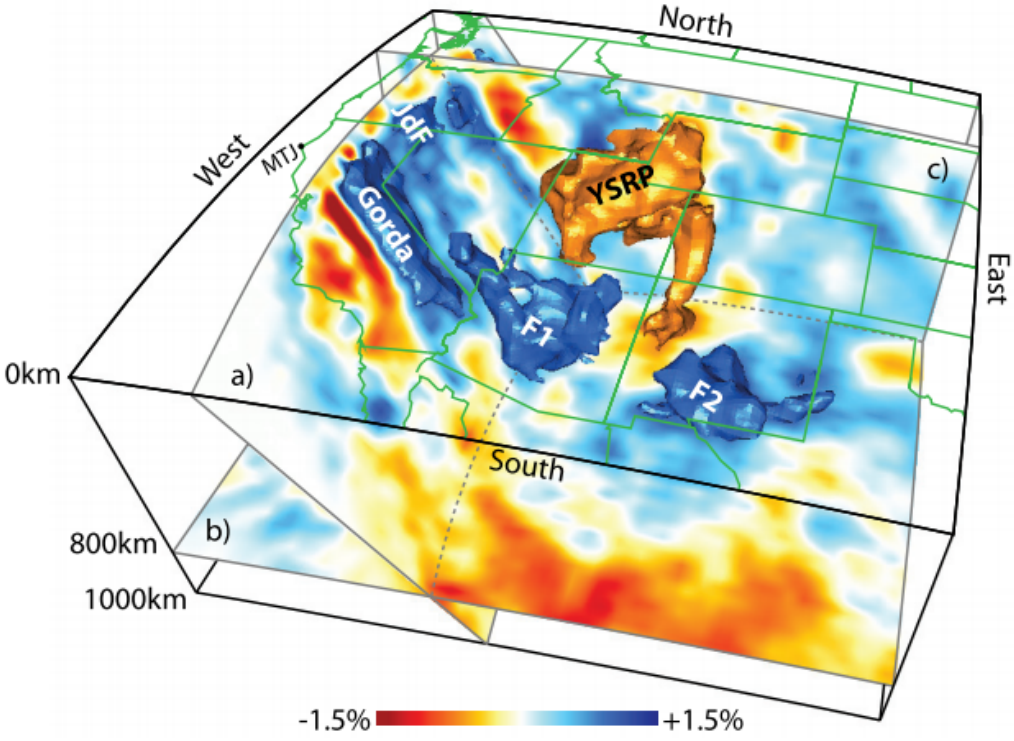


Figure 14. Seismic tomographic image of Cascadia showing the subducting Juan de Fuca (JdF) and Gorda Plates as blue slabs. YSRP is the plume of heat under Yellowstone N.P. Obrebski, *et al*., 2010.

EarthScope explains seismic tomography in a four-page article for the public. (Search for "IRIS seismic tomography.")

[Back to module overview.]

C. Deformation and strain:

Plate tectonics is standard fare in earth science and geology courses. Deformation and strain are not. Yet, students can witness and understand the crustal deformation wrought by subduction zones using GPS data and simple graphical methods. This section presents a series of new lessons to teach about the changing shape of Earth's crust, changes measured by precise GPS instruments. The map that follows shows the sequence of steps (blue bubbles), activities (yellow boxes), and resources to explain concepts (green boxes). Clicking on the shapes takes you to a blurb describing the activity. Each activity has a fully developed lesson plan, with options to streamline or to develop the concept fully. Student sheets and background reference materials are included.

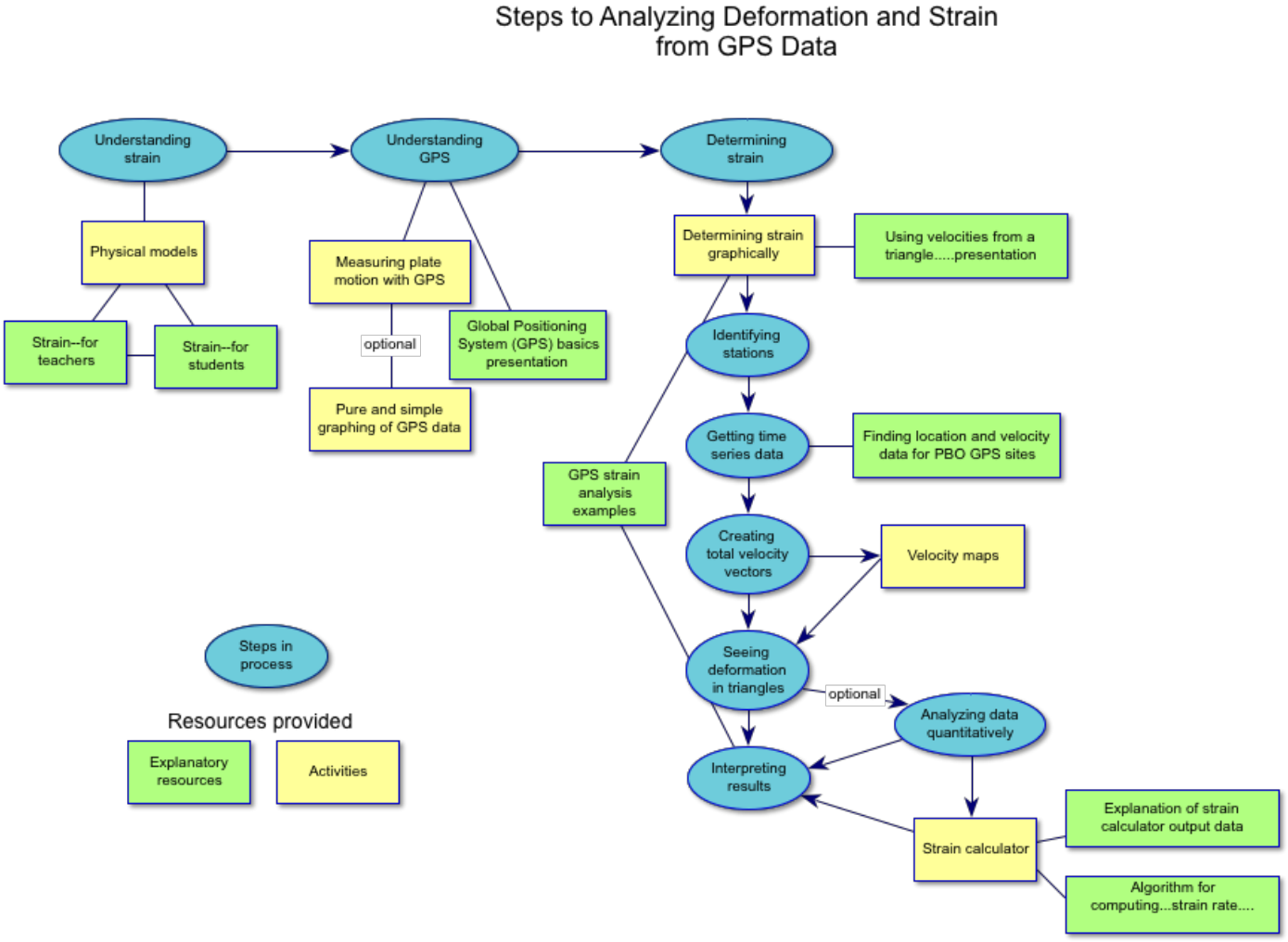


Figure 15. Sequence of lessons on deformation and strain. Click on a shape to navigate.

1. **Understanding strain:** By exploring physical models, students gain an intuitive understanding of what strain is. They learn that strain is a component of deformation. It refers to the change in shape of a block, its distortion. A block might also be moving ("translating") and rotating as a whole. Deformation encompasses translation, rotation, *and* strain.

Activity: Physical models of strain

Students explore one-dimensional strain using bungee cords and compressional springs in two activities. Then they explore two-dimensional strain using an athletic tee shirt. The final activities demonstrate pure strain with Silly Putty® and simple strain with a deck of cards.

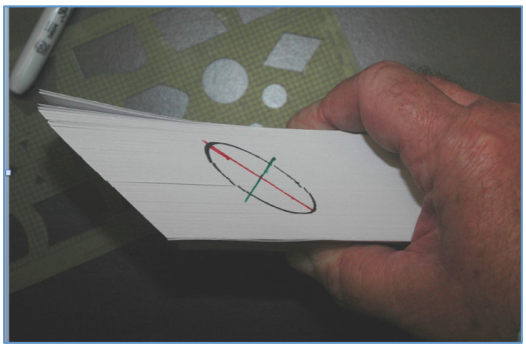


Figure 16. Deck of cards that has been sheared as an example of simple strain. The ellipse was a circle before shearing. Cronin, 2012.

Resources:

About Strain: a summary for teachers

This article explains strain for you as a backdrop for all of these activities. It parallels "Physical models of strain." Each section begins by looking at rocks or the crust to see the effect of strain over time. For instance, the first example shows fossils (belemnites, shaped like bullets) that have broken into segments under tension (Fig. 17).

About Strain: a summary for students

This is like the primer for teachers but is written for students. You can think of it as the textbook to accompany your instruction.

Figure 17. A Jurassic belemnite from the Alps that has been strained--stretched into segments. Coin is 2 cm in diameter. WeFT, 2007.

[Back to deformation map.]

2. **Understanding GPS:** These materials teach students about GPS apparatus and the data they generate.

Activities:

A. Measuring plate motion with GPS

Students learn how a GPS works. They interpret data from plots showing the position of the station over time, or "time series plots" (Fig. 18). They draw the data as velocity vectors, to scale, on a map and add the vectors graphically to create a total horizontal velocity vector. In the latter part of the activity, students apply their skills to data from Iceland and discover that the Mid-Atlantic Ridge is rifting the island. They also cement and demonstrate their understanding of vectors with an abstract application. There are instructions for you, lab sheets for your students, and a PowerPoint presentation. The activity also has an optional prequel, "Pure and simple graphing of GPS data."

B. Introduction to graphing GPS data (extra support)

This activity is a scaffold for students who cannot yet graph earth science data skillfully or confidently. In order to understand graphs, students first make graphs. They begin by graphing simple fictitious data and progress to graphing real—and messier--data from several GPS stations in the western United States. By hand-drawing these graphs, students gain skills needed to understand GPS time series graphs. At the end, students graph north-south vs. east-west motion of GPS stations over five years in order to see that graphs can also display data as a kind of map. With these last graphs, students also draw and interpret velocity vectors. Materials include a lesson plan, student lab sheets, and a PowerPoint presentation.

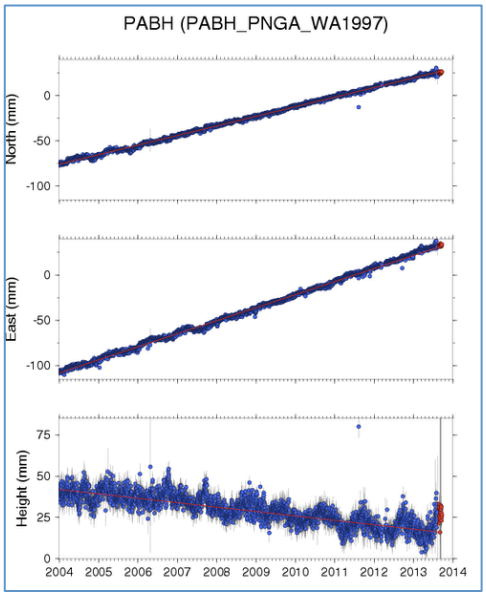


Figure 18. Time series plot from PABH, a GPS station in coastal Washington.

Resource:

Introduction to Global Positioning System (GPS) basics

This PowerPoint presentation introduces what GPS is, how it works, and how to start reading and interpreting data output from GPS stations. It can provide background for you; you will want to consider how much of it will suit your students' needs.

[Back to deformation map.]

3. Determining strain: Students determine strain, rotation, and translation for a triangle of Earth's crust. In brief, they gather GPS data as time series plots, graph the stations' motion as vectors, add those vectors to create total velocity vectors, talk about what they think they see, analyze the vectors graphically, and interpret the results. Ultimately, they can pair their graphically-derived results with results from a spreadsheet-based calculator.

Activities:

A. Determining strain graphically--students & teachers

We know that Earth deforms, and in this activity, students explore the deformation graphically within an area bounded by three GPS stations. They use a map, velocity data from GPS stations, and graph paper. They literally see translation and rotation of the triangle, and they see crustal distortion within the triangle of stations. The activity can culminate in students using a spreadsheet-based calculator to determine strain quantitatively.

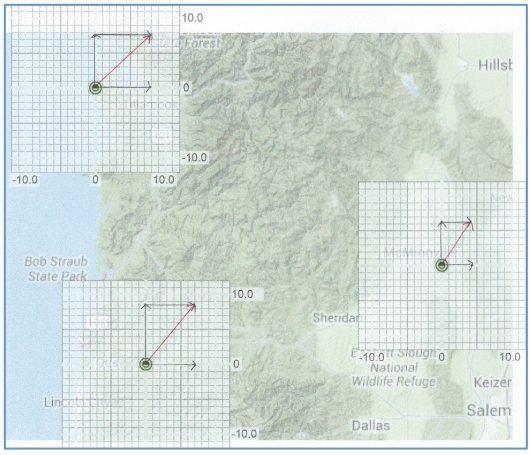


Figure 19. Part of Oregon, overlain by grids with velocity vectors from GPS stations. The red arrow is the sum of the north-south and east-west vectors.

B. Velocity maps--students & teachers

This activity fits within "Determining strain graphically." Your students plot vectors that represent horizontal

time series data and add them to make a total horizontal vector. They do this for three GPS stations (Fig. 19).

C. Strain calculator (optional)

Students plug time series data from three GPS stations into an Excel spreadsheet and generate relative length and orientation of strain axes and other parameters (taught in structural geology courses). They are black-box calculations that quantify graphical results; students can plot the axes on their graphs to see how "expert analysis" compares to their graphical version.

Resources:

All of these resources were developed for a structural geology course for geoscience majors. Some have components for instructors as well as for students. Despite the original intended audience, they might have value for you as examples and background information. (Search for "UNAVCO strain majors materials.")

GPS strain analysis examples

This is an exercise with worked examples of the Olympic Peninsula, WA, with compressional strain; the Wasatch fault, UT, with extensional strain; and the San Andreas Fault, CA, with shear strain. The first example is absolutely relevant to Cascadia. Instructor notes discuss the geology of the regions. The student exercise relies solely on the strain calculator. These examples might help you get the lay of the land.

Using velocities from a triangle of GPS sites to investigate crustal strain

A PowerPoint presentation for college students and other adults shows the essence of the graphical analysis.

Finding location and velocity data for PBO GPS sites

A worked example from Oregon Coastal ranges of finding GPS data and determining total horizontal vectors with the Pythagorean theorem. This activity was adapted for parts of this module.

Explanation of strain calculator output data

A three-page text that explains results of the strain calculator. Although originally written for college geology majors, advanced high school students who have worked through this activity could use this to make sense of their results.

Algorithm for computing infinitesimal strain rate between three non-colinear GPS stations, given their N-S and E-W velocities, with a worked example

This intense document explains the steps needed for you or your students to code your own infinitesimal strain calculator – for the challenge and to make the calculator less of a "black box."

[Back to module overview.] [Back to deformation map.]

Technology allied with deformation and strain—GPS

GPS is handy when lost and frustrated in a car in an unfamiliar city. Bossy and annoying as the droid in your dashboard might be, it can get you where you want to go. GPS is also handy when hiking or noting a spot at which you've taken scientific observations or measurements. In studies of plate tectonics, GPS allows unprecedented analysis. It allows scientists to measure

the position of a spot daily to the millimeter. A network of GPS stations does more. To learn about large national projects using GPS to measure crustal changes, look at these resources:

"EarthScope Overview." 5:05. An overview of a national project, EarthScope, to discover what lies under the United States. Instruments placed across the country measure and monitor changes in Earth's crust. They also allow us to see into the Earth using seismic tomography. The project is composed of a GPS network, another of seismometers, and a borehole through the San Andreas Fault. (Search for "EarthScope Overview video.")

"Plate Boundary Observatory Movie" shows the installation of a GPS station and explains their purpose. Why a network of GPS stations? "…to capture subduction live, in real time…." 1:37. (Search for "UNAVCO Cascadia-PBO mov." The movie is the small inset in the article about the Cascadia Project.)

Mathematics allied with deformation and strain

These lessons use middle school mathematics. Students can determine strain graphically (Fig. 19). They can use a scale to find the arrow's length and a protractor or directional compass to find its compass direction or azimuth.

However, you have the opportunity to weave together science and math. For example, students could use the Pythagorean theorem (taught in Pre-Algebra) in addition to graphing. They could use sines and cosines (late in Algebra 1 or in Geometry) or they can delve into vectors as matrices (Algebra II or beyond). The map below shows connections your students *could* make between science and mathematics. Think how powerful that could be for them…relating the math they're learning to scientific research they're conducting.

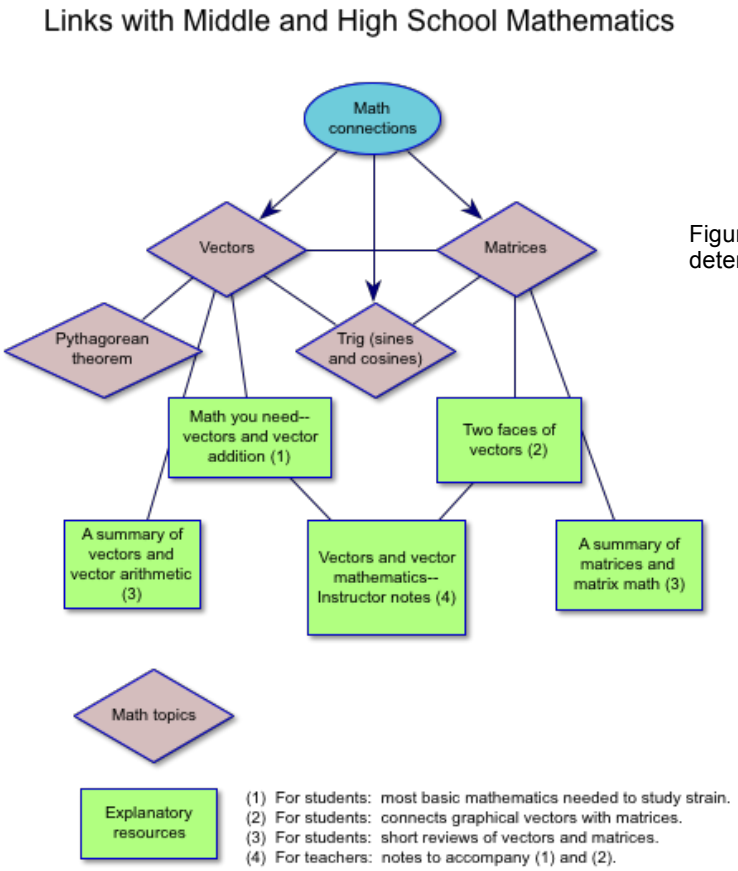


Figure 20. Math topics with applications in determining deformation and strain.

Resources:

Math you need—vectors and vector addition

Written for students, this two-page text explains what a vector is and how to add vectors by putting the head of one vector against the tail of another and drawing a new arrow that connects the first one's tail to the second one's head (Fig. 19). Students can analyze strain graphically knowing only this.

Two faces of vectors – vectors in science and math

Written for students, this article takes students as far as they want to go in connecting science and math in the context of strain. Mathematically adept students can run ahead on their own with a sequence spelled out for them. Topics include using the Pythagorean theorem to find the length of the total vector; measuring the vector's azimuth with a protractor or compass; calculating the vector's azimuth with sines and cosines; adding vectors analytically; and manipulating vectors as matrices. Recommendations for Khan Academy videos are included so that students can learn independently.

A summary of vectors and vector arithmetic

Written for students, this is a primer on three-dimensional vectors. It includes operations on vectors through dot and cross products. This primer would be appropriate for science students who are in Algebra II or higher.

A summary of matrices and matrix math

This article parallels the summary of vectors, focusing instead on applications of matrices to science. It, too, might be of interest to students in Algebra II or higher.

Vectors and vector mathematics—Instructor notes

For you, this article is the companion to the previous two. It relates math to steps in the activities and gives tips about equipment (e.g. conventional protractors vs. circular ones). Furthermore, it might coax you to explore the math connections for your own pleasure.

[Back to module overview.]

Earthquakes:

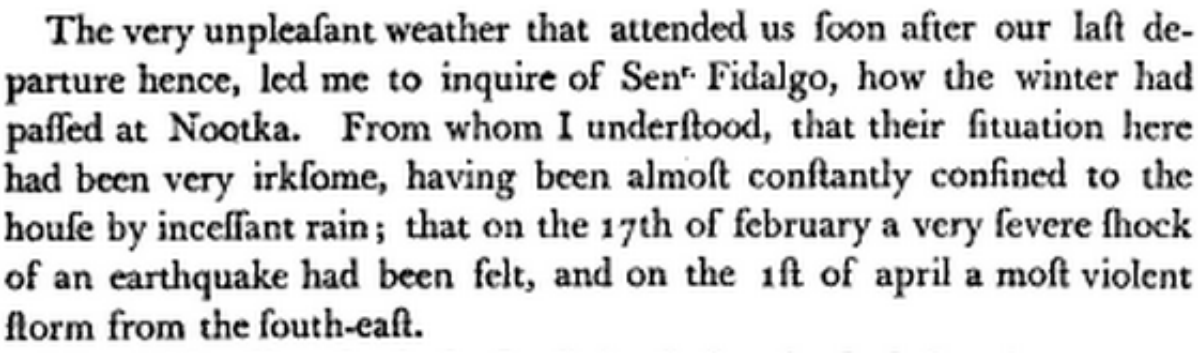

The very unpleaſant weather that attended us ſoon after our laſt departure hence, led me to inquire of Senr. Fidalgo, how the winter had paſſed at Nootka. From whom I underſtood, that their ſituation here had been very irkſome, having been almoſt conſtantly confined to the houſe by inceſſant rain; that on the 17th of february a very ſevere ſhock of an earthquake had been felt, and on the 1ſt of april a moſt violent ſtorm from the ſouth-eaſt.

Figure 21. A clipping from Captain George Vancouver's 1793 journal, the first recorded earthquake in Cascadia.

Captain George Vancouver is credited with the first written mention of an earthquake in Cascadia. This was a run-of-the-mill quake, not a megathrust quake. Cascadia earthquake patterns are worth comparing to other subduction zones in terms of scarcity, distribution across the region, and style. In addition to earthquakes, GPS and seismic studies reveal peculiar slow seismic events.

Activities:

A. Your students can explore seismicity of several subduction zones. Chile exemplifies what we expect for seismicity where an oceanic plate subducts under a continent. Using the resources listed in the "Earthquakes in general" section below or about Google Earth on page 15, ask your students to compare and contrast Chile to Cascadia. You could expect them to consider the number of quakes and their patterns across an area and into the depths of the Earth.

B. They can also compare and contrast those two settings to Japan, the site of the 2011 Tohoku quake. Although the orientation of the subducting plate mirrors the CSZ, your students will know about the quake (for a few years after this was written in 2013), and it is the best-measured quake in history.

C. The CSZ has an array of GPS and seismic stations to measure subtle changes in the shape and position of the crust. Together, those instruments have detected unusual events in which deep parts of the subduction zone fault periodically slip over days. These "Episodic Tremor and Slip" events increase the strain on the shallower part of the fault that slips in megathrust quakes. You can see the events at the Pacific Northwest Seismic Network's site. (Search for "PNSN Interactive Tremor Map.") An activity, "Episodic Tremor and Slip," teaches your students about these oddball events. It includes guidance for you, a lab sheet, and a PowerPoint presentation.

D. Captain Vancouver's log is the first example among many in the Historic Catalog of the Pacific Northwest Seismic Network. Have students with a penchant for history browse the catalog looking for interesting entries. Note that because the CSZ last ruptured in 1700, it is *not* represented in this catalog. However, reports of damage from the April 13, 1949 and April 29, 1965 earthquakes are. Both originated on a deep portion of the subducting plate. (Search for "catalog historic northwest seismicity.")

Resources:

Earthquakes in Cascadia

You can see modern (Quaternary) faults on an interactive map by the U.S. Geological Survey. Clicking on the faults links to information about them. You can trace the CSZ as the long north-south fault on the western edge of the offshore faults. (Search for "Quaternary faults web mapping.")

The Pacific Northwest Seismic Network is a rich source of data about seismicity of all sorts in Washington and Oregon. The front page shows recent earthquakes, and the link to seismograms takes you to records from individual stations. (Search for "PNSN.")

The Cascade Region Earthquake Group developed "Cascadia Subduction Zone Earthquakes: A magnitude 9.0 earthquake scenario." The 22-page article about earthquakes in the Pacific Northwest explains in everyday language the probable effects of shallow, deep, and subduction zone earthquakes. The scenario focuses on the last and uses the 2004 Sumatra and the 1964 Alaska Good Friday quakes as analogs. (Search for "CREW subduction scenario.")

"What can GPS tell us about future earthquakes?" compares causes for the 2011 Tohoku earthquake to the tectonic setting in Cascadia. 4:13. Data comes from GPS stations, especially Cape Meares, Oregon, which moves 10.5 mm/year to the northeast. At that rate, the coast has moved 3.3 meters inland since 1700. The video features Plate Boundary Observatory GPS data displayed in clear simulations. (Search for "GPS future earthquakes.")

For comprehensive earthquake information by state, connect to the U.S. Geological Survey's Earthquake Hazards Program for Oregon, Washington, and California. (Search for "USGS [state name] earthquake hazards.")

"Risk of giant quake off American West coast goes up." (*Nature News*) and "Odds Are About 1-In-3 That Mega Earthquake Will Hit Pacific Northwest in Next 50 Years, Scientists Say" (*Science Daily*) are articles in the popular press about the likelihood of more megathrust quakes. Both articles stem from research on cores drilled in offshore sediments. The work is documented in a technical Professional Paper (1661-F) from the U.S. Geological Survey, "Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone." (Search for "Nature News American West quake," "Science Daily mega earthquake," and "USGS 1661 F.")

Explanations of Episodic Tremor and Slip are in "Generalized Geologic Setting of the Pacific Northwest" and "Subduction Zone—Plate Interaction" from IRIS. (Search for "IRIS geologic setting northwest" and "IRIS subduction zone.")

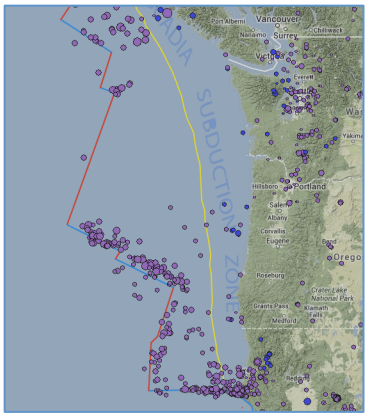


Figure 22. Earthquake browser from IRIS.

Earthquakes in general

An elegant and simple website to sort out earthquakes, IRIS's Earthquake Browser, can be modified to show earthquakes of various magnitudes, depths, and time of occurrence. Students can zoom into particular regions and then view data in 3D. (Search for "IRIS EPO" and select the Earthquake Browser.)

For earthquakes, tsunamis, and volcanoes, the National Geophysical Data Center Natural Hazards Viewer shows all in a Geographic Information System. You can toggle layers on and off, search for data, and click on specific events to learn more. Symbols indicate the impact on people (Fig. 23). (Search for "NGDC hazards viewer.")

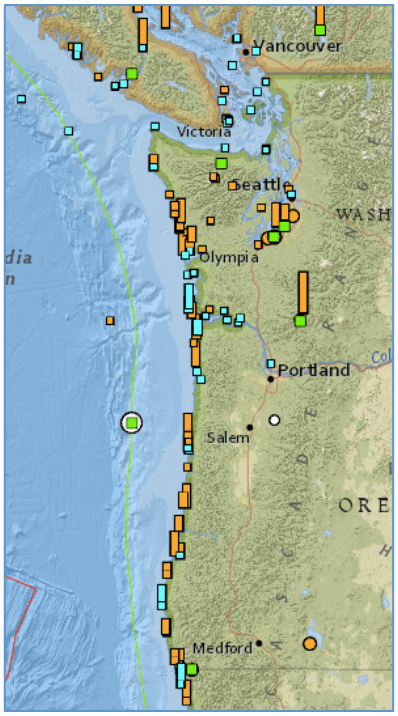


Figure 23. NGDC Hazards Viewer. Earthquakes are shown as circles; tsunami wave heights as bars; and tsunami sources as squares.

UNAVCO's Jules Verne Voyager, Jr. allows your students to see earthquake epicenters, plate boundaries, volcanoes, and the velocities of plates shown as vectors. For the last, choose North America from the Add Velocity menu. You can choose observed plate motions or modeled ones. The modeled ones go into the oceans—where there are no GPS stations anchored 10 meters into the ground, for obvious reasons. Modeled data shows the Juan de Fuca plate plowing into North America (Fig. 24). Jules Verne Voyager, Jr. allows limited zooming in. (Search for "UNAVCO Jules Jr.")

For another perspective on earthquakes, volcanoes, and plate motions, try UNAVCO's Velocity Viewer (Fig. 25). This does allow you to zoom in, but it does not show model data; therefore the Juan de Fuca's plate motion is not depicted. To begin, under Data Source, choose UNAVCO GPS velocities, NAM08. (Search for "UNAVCO velocity.")

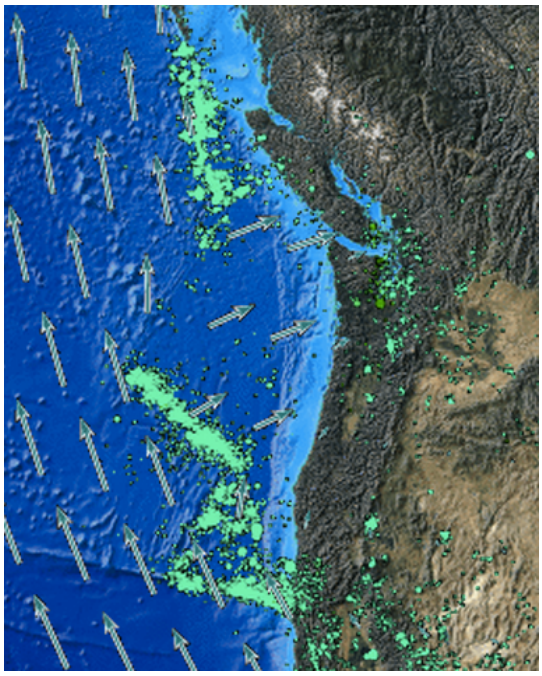


Figure 24. Jules Verne Voyager, Jr. showing earthquake epicenters and modeled plate motions.

Tohoku as a well-documented analog

A background article about the 2011 Tohoku earthquake from the University of Portland and IRIS Education and Outreach's Teachable Moments explains the earthquake in its regional setting and describes hazards. It also includes a seismogram from Portland. (Search for "IRIS Tohoku notice" and link to the presentation from the University of Portland and IRIS.)

You and your students can watch seismic waves from the Tohoku quake rippling across the United States in a visualization from IRIS. Red dots represent stations rising, blue stations falling. The intensity of the color indicates how high the station rises or how low it falls. (Search for "USArray GMV Honshu.")

For a comprehensive presentation on the Tohoku quake, consider IRIS's PowerPoint presentation, "Magnitude 9.0 Near the East Coast of Honshu, Japan." It shows photos, maps, data, and simulations in 23 colorful slides. A few of the slides are technical and thus more suitable for you than for students. (Search for "IRIS Tohoku notice" and link to the PowerPoint presentation.)

[Back to module overview.]

Technology allied with earthquakes—seismometers and GPS

Seismometers measure how much the ground shakes in an earthquake. From their signals, scientists can infer how much energy a quake released, where the earthquake originated, and properties of the materials below ground. Two major projects have joined seismology to GPS data to understand the geology of our continent on a grand scale.

"EarthScope Overview," 5:05, is a video about how a project with numerous seismometers and GPS allows us to scope out what lies under the United States. (Search for "EarthScope Overview video.")

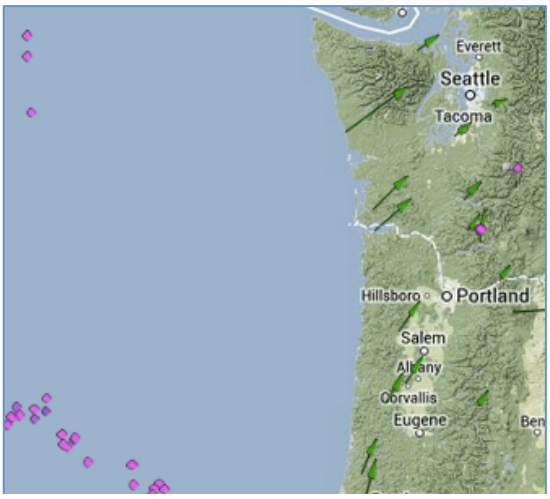


Figure 25. Velocity Viewer showing GPS data as vectors and earthquakes as circles.

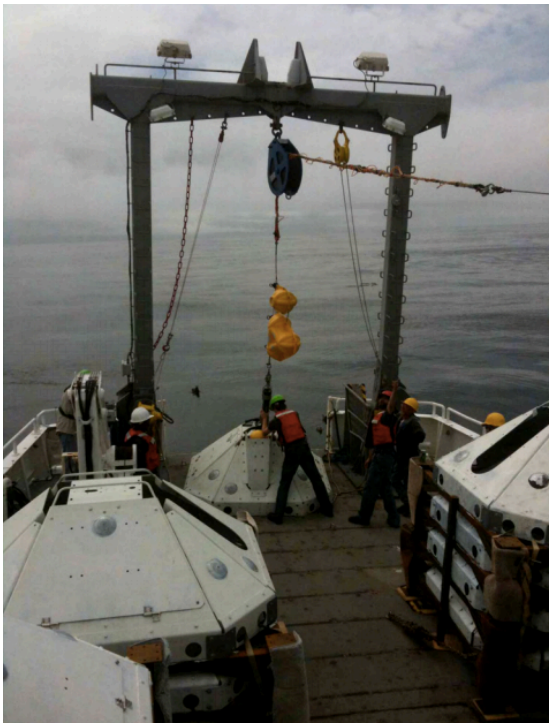


Figure 26. A seismometer hoisted for placement on the seafloor in commercial fishing grounds. Tolstoy, M. and A. Trehu, 2011.

In an amphibious twist, the Cascadia Initiative places seismometers offshore Cascadia for a year. (It also places them onshore and upgrades GPS stations.) The seismometers endure storms and trawlers, storing their data until retrieved by research vessels the next summer (Fig. 26.) Two college students filmed their shipboard experience emplacing instruments, watching whales, and recording bubbling plumes of methane in a 30 minute video, "Cruisin' Cascadia." (Search for "Cascadia Initiative" and "Cruisin' Cascadia.")

[Back to module overview.]

Tsunamis:

Tsunamis can happen with earthquakes (and landslides). As such, they are realistic threats to Cascadian shores—we know they have occurred at least 41 times in the last 10,000 years.

Activities:

1. You can show your students the videos described in the Engage section and below and ask them to list causes of tsunamis. Also, because the videos are graphic, students will have strong reactions. You can ask them to express their visceral reactions in words, drawing, music, or dance.

Figure 27. Tsunami evacuation zone from Fort Worden State Park, WA. West, 2013.

2. You and your students can also predict where tsunamis might cause floods. Ultra high-resolution LiDAR images measure elevation precisely. Resources listed below in "Technology allied with tsunamis" explain how LiDAR works and show images of Earth's surface. Have the fun of exploring the images with your students and then ask them, "If you were vacationing in Cannon Beach, Coos Bay, or Seaside, Oregon, where would you seek higher ground? And, what route would you take to get there?"

Resources:

The National Science Foundation shows a short video that models a tsunami striking Seaside, Oregon. Both physical and computer models predict what could happen to the city and its residents. The message is to climb to higher ground, or to "evacuate vertically" by climbing to higher floors in buildings. This is shown in Science Nation's "Surviving a Tsunami: Vertical Evacuation." (Search for "surviving tsunami science nation.")

A video on the basics of tsunamis, warning signals, and what to do, from NOAA. (Search for "teacher tsunami basics.") 6:37.

Three videos with footage from the March 11, 2011 tsunami that struck Japan after the Tohoku earthquake:

"Tsunami Strike: Japan Part 1: Destruction." 2:55. Footage of tsunami. (Search for "tsunami strike destruction.")

"Tsunami Strike: Japan Part II: Propagation." 2:04. Footage and modeling. (Search for "tsunami strike propagation.")

"Tsunami Strike: Japan Part III: Warning Systems." 3:07. Footage and examples of technology used to predict and warn about tsunamis. (Search for "tsunami strike warning.")

The National Geographic video "Tsunami: Tsunami 101" explains tsunamis with footage of the 2004 Sumatra-Indonesia tsunami. It describes the Pacific Tsunami Warning Center's role in protecting people on the Pacific Rim. 3:27. The video begins with a commercial. (Search for "tsunami 101.")

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Technology allied with tsunamis--LiDAR:

Light Detection and Ranging, LiDAR, uses lasers for measuring and mapping Earth's surface to within 15 centimeters vertically from an airplane. The method is time- and cost-efficient. And LiDAR gives us superpowers—it can see through vegetation. With LiDAR, planners can pick out features such as old landslides and fault traces hidden by lush Douglas fir forests and blackberry/nettle thickets. Accurate measurements of elevation also allow them to predict areas likely to flood from a tsunami.

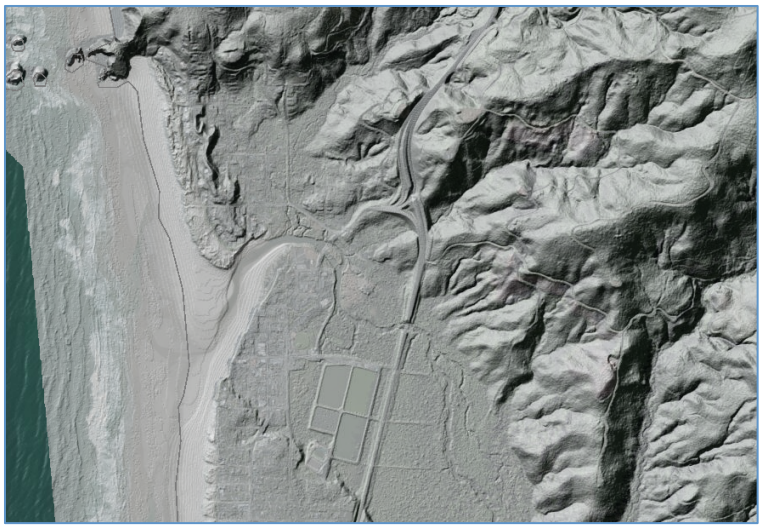

Figure 28. LiDAR image of Seaside, Oregon. If this were online, you could zoom in and see fleas jumping in the sand.

Resources:

"Discovering and Mapping Natural Hazards with LiDAR" is a magazine article describing how Oregon uses LiDAR to identify landslides and to plan for inundation by tsunamis. Oregon makes LiDAR available online through its LiDAR Data Viewer. (Search for "LiDAR magazine natural hazards.")

How LiDAR works

A brief explanation of LiDAR from the National Ocean Service, because LiDAR can be used to map coastal waters as well as land. This is particularly useful when planning for tsunamis. (Search for "NOS LiDAR.")

A video shows how LiDAR works and its applications. Idaho State University scientists combine LiDAR and aerial imagery to have a complete and accurate view of a dynamic system (the Snake River). 2:50. (Search for "LiDAR video Idaho State.")

A much longer article explaining LiDAR from elsewhere in the National Oceanic and Atmospheric Administration. (Search for "NOAA LiDAR 101.")

NOAA's Digital Coast provides a comprehensive online (free) hour-long course on LiDAR, Introduction to LiDAR. Content includes how LiDAR works, applications, data quality, products and sources, and how to download data from Digital Coast to use with GIS software. (Search for "NOAA introduction LiDAR.")

Sources of LiDAR data

All of Oregon's coast has been mapped with LiDAR and is available through the Department of Geology & Mineral Industries' web viewer. (Search for "DOGAMI LiDAR.")

Washington's Puget Sound LiDAR Consortium provides images in Washington. For the area you want to explore, select a Topographic Image Index Map. Download the file and choose the .tif image. It will open as a photograph that you zoom in on for details. Some of Washington's LiDAR data takes persistence and patience to obtain. (Search for "Puget LiDAR.")

OpenTopography makes LiDAR data from all over the country available—some data is ready to use on Google Earth. Other areas must be converted to a Google Earth compatible file. See Appendix C for instructions. Alternatively files can be opened in full-blown GIS software such as ArcGIS. (Search for "OpenTopo.")

Other sources such as the National Map, NOAA's Digital Coast, and the U.S. Geological Survey's CLICK site offer LiDAR data that can be used with ArcGIS.

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Making it real to students—what can they do?

Now that your students understand intellectually the effect of the CSZ on deformation, earthquakes, and tsunamis, it is time to send the message home. Make the CSZ real to students everywhere. Get them thinking in advance about how they will respond to a large quake and/or tsunami in their backyards or in someone else's. How can they be safe and how can they help their countrymen and women?

Activities:

1. Class discussion. Ask your students, "What do you think will happen in Cascadia? Why do you think so?" Seek evidence. Expect them to support their statement with evidence. (This could also be a fine homework assignment or small group discussion.)

Then ask, "Do you know anyone or know of anyone famous who lives in Cascadia? What are your concerns for these people? How could a large quake affect them?" You could start this as a small group or Think-Pair-Share discussion to engage all students, or you could ask them to write their thoughts or list their concerns.

Finally, ask your students what they can do to prepare. For students who live in Cascadia, this has immediacy. You can ask, "What can you and your family do to be prepared?" "How can you learn what you *should* do? Who would know? Who are your local emergency managers? How can you find out what they suggest or expect?" (For resources on how to answer those questions, search online for "earthquake preparedness," or ask your students to. Several sites pop up with useful links: The U.S. Geological Survey's Earthquake Hazards Program offers materials. FEMA's Ready site is built around natural disasters of many sorts with recommendations about what to do before, during, and after an earthquake. The Los Angeles Fire Department, fully aware from experience of what could happen, has a pamphlet for the public about being prepared.)

Even if you don't live in Cascadia, you could have an earthquake. And, even if the ground is perpetually quiet where you live, the humanitarian crisis and economic effects from a subduction zone quake in Cascadia will probably affect you. You could ask your students how they would respond to such a humanitarian crisis. How could they help in the short and long terms? What factors make a disaster relief organization effective and efficient?

2. Participate in the Great ShakeOut, as a class, school, family, community group, or individual. ShakeOut is a national earthquake preparedness event the third Thursday in October. Participants drop, cover, and hold on for 60 seconds at a specific time (e.g. 10:17 a.m. October 17, 2013.) Encourage those you know, even if you are in an aseismic zone, to register and follow through. (Search for "shakeout.")

3. If you do feel an earthquake, contribute your experience to science. The U.S. Geological Survey collects details about whether dishes rattled, your bed slid, chimneys toppled, and the like. Citizens contribute valuable information about the intensity of quakes through the Did You Feel It website. (Search for "DYFI.")

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Figure 29. Practicing the drop, cover, and hold on move in the Great ShakeOut.

Part 5. Summative Assessment

Did your students learn what you wanted them to learn? Have they met your objectives? You can ask them to return to the questions you asked in the preliminary assessment and have them describe what they learned. How are their answers different? Do they think or feel differently about earthquakes, tsunamis, Cascadia, the human effects of plate tectonics, and technology?

If you asked them originally to make a concept map, now have them revise it using a different color so that they can see their new knowledge or changed understanding. Similarly, if you gave them a writing prompt, give them the prompt again and, after they've written, hand back their original responses for comparison.

And, of course you can grade the lab sheets for activities.

Appendix A: Relevant excerpts from *A Framework for K-12 Science Education* as cited in the *Next Generation Science Standards* and *Earth Science Literacy Principles*

1: Science & Engineering Practices in the NGSS:

4. Analyzing and interpreting data;
5. Using mathematics and computational thinking;
6. Constructing explanations (for science) and designing solutions (for engineering);
7. Engaging in argument from evidence; and
8. Obtaining, evaluating, and communicating information.

2: Crosscutting Concepts:

Patterns: HS-ESS1-5;
Cause and effect: HS-ESS3-1;
Scale, proportion, and quantity: MS-ESS2-2;
Energy and matter: HS-ESS2-3; and
Influence of science, engineering, and technology on society and the natural world: HS ETS1-3.

3: Disciplinary Core Ideas:

PS2.A: Forces and Motions: All positions of objects and the directions of forces and motions must be described in an arbitrarily chosen reference frame and arbitrarily chosen units of size. In order to share information with other people, these choices must also be shared. [Grade 8]

PS4.A: Wave Properties: Geologists use seismic waves and their reflection at interfaces between layers to probe structures deep in the planet. [Grade 8]

ESS1.C: The History of Planet Earth: Tectonic processes continually generate new ocean floor at ridges and destroy old floor at trenches. [Grade 12]

ESS2.A: Earth's Materials and Systems: All Earth processes are the result of energy flowing and matter cycling within and among the planet's systems. This energy is derived from the sun and Earth's hot interior. The energy that flows and matter that cycles produce chemical and physical changes in Earth's materials and living organism. [Grade 8]

ESS2.A: Earth Materials and Systems: Evidence from deep probes and seismic waves, reconstruction of historical changes in Earth's surface and its magnetic field, and an understanding of physical and chemical processes lead to a model of Earth with a hot but solid inner core, a liquid outer core, a solid mantle and crust. Motions of the mantle and its plates occur primarily through thermal convection, which involves the cycling of matter due to the outward flow of energy from Earth's interior and gravitational movement of denser materials toward the interior. [Grade 12]

ESS2.B: Plate Tectonics and Large-Scale System Interactions: Plate tectonics is the unifying theory that explains the past and current movements of the rocks at Earth's surface and provides a framework for understanding its geologic history. Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. Maps of ancient land and water patterns, based on investigations of rocks and fossils, make clear how Earth's plates have moved great distances, collided, and spread apart. [Grade 8]

ESS2.B: The radioactive decay of unstable isotopes continually generates heat energy within Earth's crust and mantle, providing the primary source of heat that drives mantle convection. Plate tectonics can be viewed as the surface expression of mantle convection. [Grade 12]

ESS3.B: Natural Hazards: Mapping the history of natural hazards in a region, combined with an understanding of related geologic forces can help forecast the locations and likelihoods of future events. [Grade 8]

ESS3.B: Natural Hazards: Natural hazards and other geologic events have shaped the course of human history; [they] have significantly altered the sizes of human populations and have driven human migrations. [Grade 12]

ETS1.B: Developing Possible Solutions: When evaluating solutions, it is important to take into account a range of constraints, including cost, safety, reliability, and aesthetics, and to consider social, cultural, and environmental impacts. [Grade 12]

Earth Science Literacy Principles

Big Idea 1: Data and Observations Lead to Understanding	1.1 Predict hazards. 1.2 Many science disciplines come to bear on understanding Earth. 1.3 Collect multiple kinds of evidence. 1.4 Use indirect measurements. 1.5 Understand the past to forecast the future. 1.6 Improve data and observations to refine models. 1.7 New technology leads to breakthroughs.
Big Idea 2: Ancient Earth	2.1 Earth's materials record its history. 2.4 Continental and oceanic crust differ. 2.7 Change can be gradual or catastrophic.
Big Idea 3: Earth as a System	3.2 Energy and matter cycle through Earth's systems. 3.6 Earth's systems are dynamic.
Big Idea 4: Dynamic Earth	4.1 The geosphere changes. 4.2 Earth is cooling; heat flow drives internal motions. 4.3 Convection drives plate tectonics. 4.4 Tectonic plates move. 4.5 Geology happens at plate boundaries. 4.6 Rocks cool from magma and get recycled. 4.7 Landscapes evolve, reflecting tectonic processes.
Big Idea 5: Water	5.6 Water shapes landscapes.
Big Idea 7: Earth's Resources	7.2 Geology determines population centers.
Big Idea 8: Natural Hazards	8.1 Earth processes can be dangerous. 8.2 Hazards shape human history. 8.4 Hazards can be sudden or gradual. 8.5 Local hazardous events can have global effects.

8.6 Earth scientists' predictions are improving.
8.7 Humans' actions can reduce risk.
8.8 Earth science literacy is vital to reducing risks.

Big Idea 9: Humans' Impact

9.9 Earth science literacy promotes sound stewardship, policy, and cooperation.

Appendix B: Jigsaw pieces for Part 1. Engage; Option 1.

Jigsaw Piece 1: Ghost Forests in Washington and Oregon

Figure 7. "Ghost forest" in the Copalis River, Washington. Atwater, *et al*., 2005.

The tree stumps you see in the photo have a story to tell. You could think of them as corpses in a mystery. They provide a clue that you will report to your classmates who are reading other clues. As a group you will try assemble the clues to solve the mystery, a real mystery. Only in 2005 did scientists and historians put together the pieces and figured out what these trees and other information imply. Your job is to explain these "ghost forests."

The ghost forests are stands of dead western red cedar trees at the Washington coast. While the ones in the picture are in a tidal marsh of the Copalis River, there are other examples in Washington. Western red cedar trees cannot live knee-deep in salty water; the water killed them.

As a detective, what would you try to learn about these corpses?

Would you, for instance, like to know when they died? Scientists figured that out. They used two methods. In the 1980s, they used carbon-14 dating, a method used on objects that contain carbon, including plants, bones, teeth, and archeological objects. This method indicated that the trees died between 1695 and 1720.

In the second method, researchers compared tree rings from slices of the ghost forest stumps and compared them to living trees in the same area. Fortunately cedar trees on land can live a long time. As trees grow, their diameters expand with alternating light and dark bands. Early in the growing season, new cells are light. Later in the year, they are dark. Especially good growing years yield relatively wide bands. The pattern of narrow and wide bands appears in trees across a region and can be matched from tree to tree.

Figure 8. Tree rings from a freshly cut tree. Arnoldius, 2006.

Here's how it works. With a living tree, scientists work from the bark to the inside of the tree, looking at the pattern of light and dark bands. As they work inwards through the wood, they go back in

time, one ring per year. As you can see in the figure below, you can think of the pattern as a bar code. Scientists match sections of tree ring patterns from ghost and living trees, count the rings on the living trees, and know when the ghost trees died.

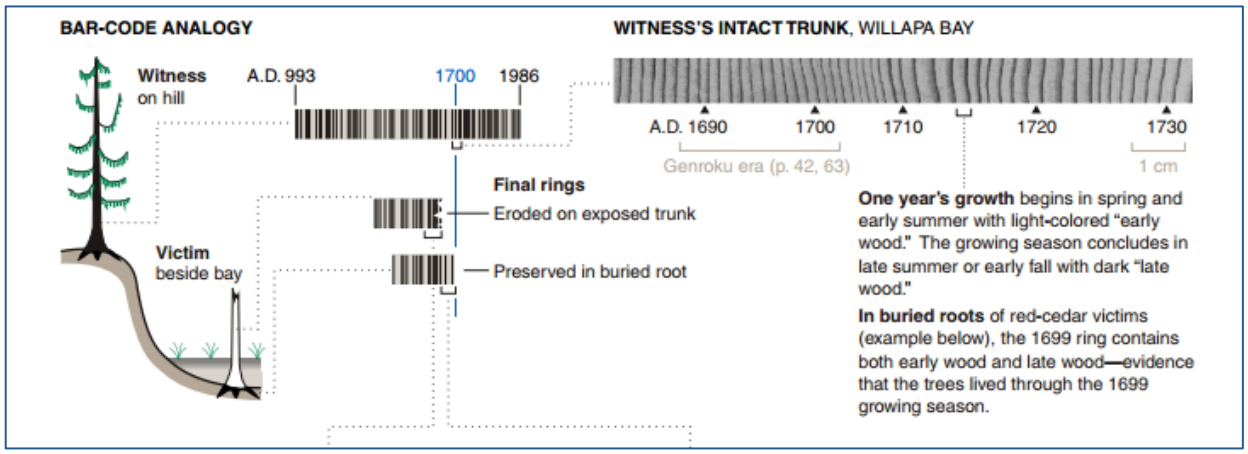


Figure 9. Witness trees living above sea level used to date dead trees at or below sea level. Atwater, *et al.,* 2005.

Originally, scientists worked from stumps that had been exposed to the weather for hundreds of years. Some outermost rings had obviously worn off. When they excavated tree roots with the bark still on them (in 1996), they knew they had the entire history of the trees. In seven of eight trees, scientists learned that the trees died after the growing season of 1699. The trees died in the winter of 1700. The eighth tree hung on into the 1700 growing season and then died.

You now know when the trees died. What about why they died? How could forests of trees that live on dry ground end up in salty water at high tide? You'll discuss this with your teammates—they each have a different clue in this mystery.

Picture credits:

Figure 1. Atwater, Brian F.; Satoko, M.- R.; Kenji, S.; Yoshinobu, T.; Kazue, U.; and Yamaguchi, D.K. 2005. *The Orphan Tsunami of 1700.* U.S. Geological Survey Professional Paper 1707, p. 16.

Figure 2. Arnoldius. 2006. http://commons.wikimedia.org/wiki/File:Tree_rings.jpg Retrieved 3 October 2013 from Wikimedia Commons.

Figure 3. Atwater, Brian F.; Satoko, M.- R.; Kenji, S.; Yoshinobu, T.; Kazue, U.; and Yamaguchi, D.K. 2005. *The Orphan Tsunami of 1700.* U.S. Geological Survey Professional Paper 1707, p. 97.

Jigsaw Piece 2: Eye-Witness Accounts

Figure 1. Mask from the Swai'xwe tribe, British Columbia. American Museum of Natural History.

If you danced wearing this mask, the feathers and other dangles on this mask from British Columbia would twitch and flutter along with you. Their motion represents what the artisans who made the mask knew to be their people's history—a shaking earth and whirling atmosphere. The mask and picture below speak of cultural tradition based on tribal experiences.

Native people in British Columbia, Washington, Oregon, and northern California have passed stories of massive flooding and ground shaking through generations. For example, Chief Louis Nookmis, was interviewed in 1964, at age 84. "These are stories from my grandfather's father about events that took place four generations before his time…over 200 years ago…the land shook…a big wave smashed into the beach." Estimates for the time of the event are between 1640 and 1740. (Ludwin, 2005, p. 142.)

And, "They had practically no way or time to try to save themselves. I think it was at nighttime that the land shook. … I think a big wave smashed into the beach. The Pachena Bay people were lost. … But they who lived at Ma:lts'a:s, "House-up-Against-Hill" the wave did not reach because they were on high ground. … Because of that they came out alive. They did not drift out to sea with the others." (Ludwin, 2005, p. 142, 143.)

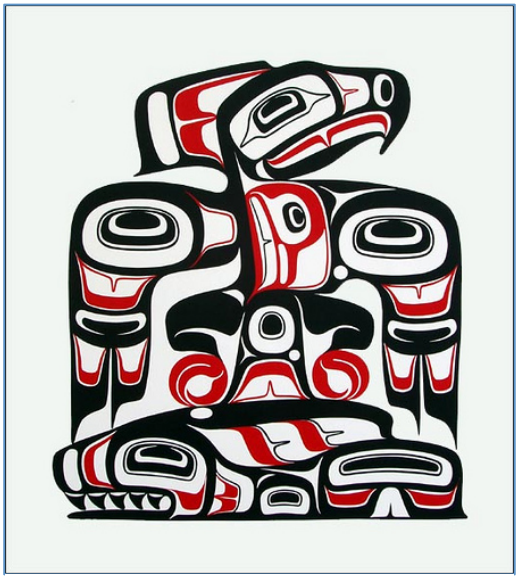


Figure 2. Thunderbird and whale image. Pacific Northwest Seismic Network.

The cultural tradition of battles between the Whale and the Thunderbird tells metaphorically of catastrophic geological events. The tradition appears in stories, artifacts, and paintings on buildings. The thunderbird grabs the whale from the ocean, flies towards his perch, and drops the whale on the ground. In other stories the whale pulls the thunderbird under—the victor and vanquished vary.

A medicine man of the Hoh tribe on the Olympic Peninsula of Washington said (in 1934), "My father also told me that following the killing of this destroyer [the thunderbird? whale?]…there was a great storm and hail and flashes of lightning in the darkened, blackened sky and a great and crashing "thunder-noise" everywhere. He further stated that there were also "a shaking, jumping up and trembling of the earth beneath, and a rolling up of the great waters." (Ludwin, 2005, p. 144.)

These stories and legends are documented along the coast from Vancouver Island to northern California. However, native peoples from elsewhere do not share these tales.

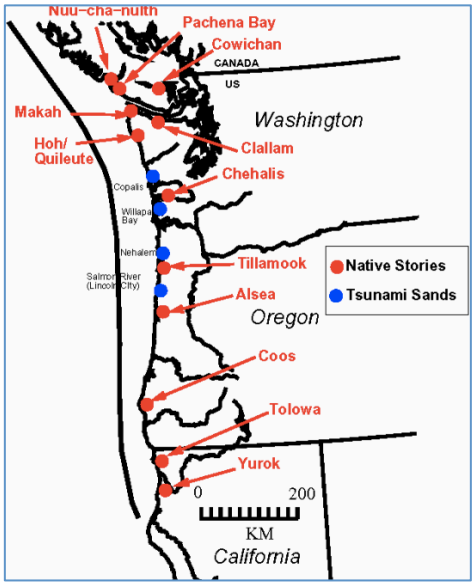


Figure 3. Places with an oral history of earthquakes or tsunamis. Ludwin, 2008.

Some stories refer to earthquake; others to floods, and as you have read, some refer to both. Your task is to pass along the oral history to your team. Let them know that people who lived along the Pacific Northwest coast report catastrophic geological events in their oral history, art, dance, and metaphors.

Picture credits:

Figure 1. Ludwin, Ruth S. 2008. "Pacific Northwest Earthquakes: Evidence in Native Myth and Tradition." http://www.earthquakeconference.org/Presentations/Ludwin-PNW%20Earthquakes%20Native%20Myth%20and%20Tradition_%20NEC%2008.pdf Retrieved 11 October 2013.

Figure 2. Puget Sound Seismic Network. http://www.pnsn.org/outreach/native-american-stories/thunderbird-and-whale/thunderbird-and-whale-overview Retrieved 11 October 2013.

Figure 3. Ludwin, Ruth S. 2008. "Pacific Northwest Earthquakes: Evidence in Native Myth and Tradition." http://www.earthquakeconference.org/Presentations/Ludwin-PNW%20Earthquakes%20Native%20Myth%20and%20Tradition_%20NEC%2008.pdf Retrieved 11 October 2013.

Jigsaw Piece 3: Physical Evidence

You will present physical evidence to your teammates in your effort to solve a mystery. Geologists noticed patterns of sediments when they dug along the coast of Washington and Oregon. Only in 2005, did they have enough insight into what caused the patterns to be comfortable publishing their story. Will your team come to the same conclusion?

Here are examples of what geologists saw:

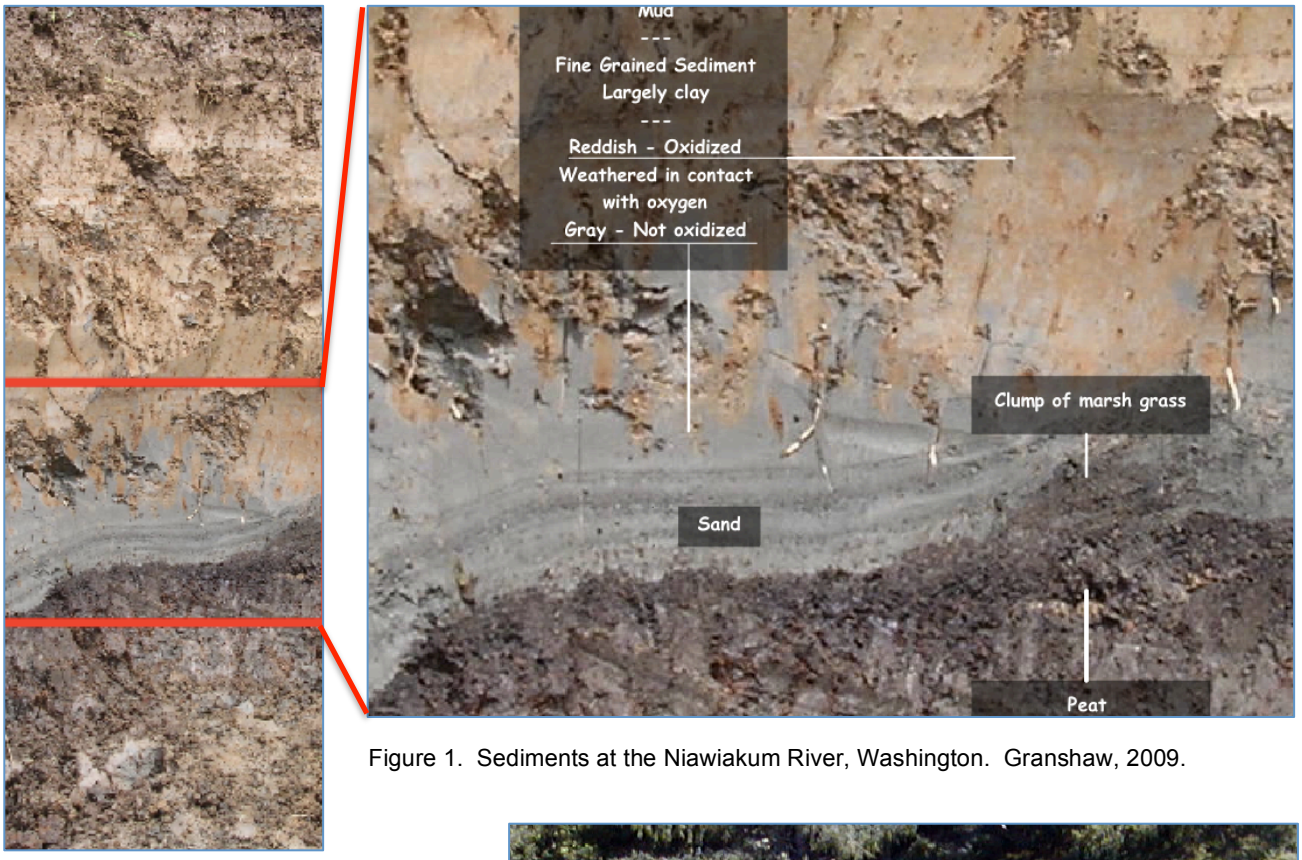


Figure 1. Sediments at the Niawiakum River, Washington. Granshaw, 2009.

Figure 2. Geologists dug into this mud and sand bank along the river to see the sediments in Figure 1. Granshaw, 2009.

Farther south, this sequence lies along the Salmon River's bank. Again, there is a dark zone (topsoil) with sand above it, and tidal mud on top. (Where tides sweep in and out, the water often deposits fine, gooey, stinky mud.) Native Americans cooked at this site.

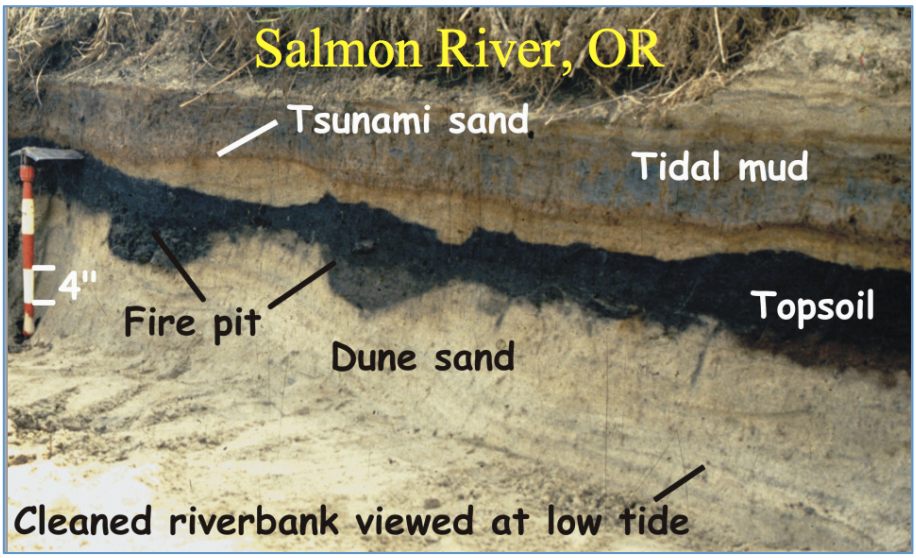


Figure 3. A riverbank along the Salmon River, Oregon. Ludwin, 2008.

These deposits of mud over sand over soil are found from northern Vancouver Island to northern California. What do they mean? In Chile (in 1960) and Alaska (1964), massive earthquakes occurred, triggering tsunamis that swept across the Pacific Ocean. Tsunamis from earthquakes also swept through Sumatra and Indonesia in 2004 and Japan in 2011.

Figure 4 shows sediments from a bank in Chile. Notice the pattern? We know that the sand layer is from the 1960 tsunami. We know that in Chile that the earthquake dropped what had been dry land so that it was underwater and that a tsunami swept across it, depositing sand on top of the soil. Then, tides deposited silt and mud over the sand. We know this because Juan Vera and Maria Silva watched the tsunami cover their field.

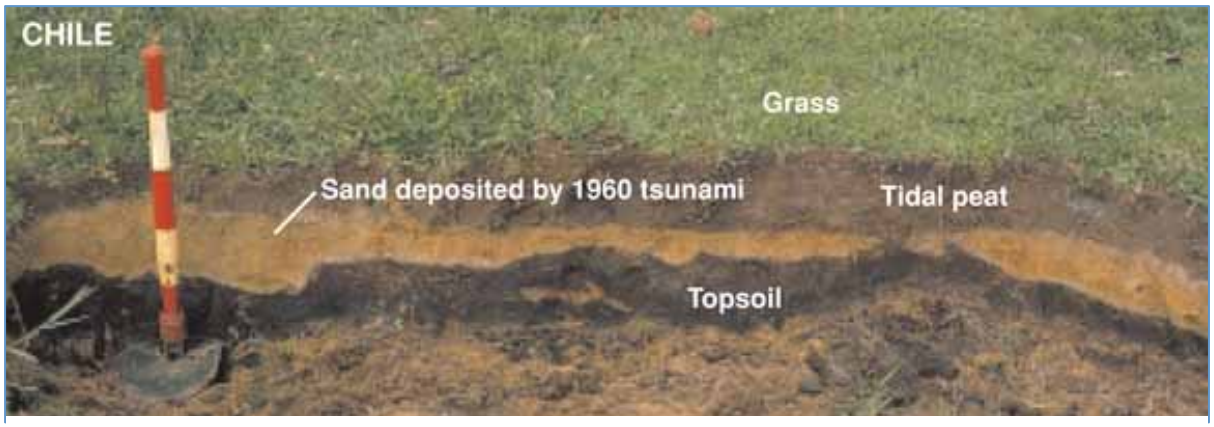


Figure 10. Tsunami sand covering topsoil from a farm's field. Near Rio Maullin, Chile. Photographer unknown.

Look again at the riverbanks from Washington and Oregon. What do you think they show? And, as a detective solving a mystery, how will you present your evidence?

Picture credits:

Figures 1 and 2. Granshaw, F. 2009. Teachers on the Leading Edge workshop. https://media.up.edu/Physics/TOLE/VFEs/a_TOTLE_VFE.swf Retrieved 4 October 2013.

Figure 3. Ludwin, Ruth S. 2008. "Pacific Northwest Earthquakes: Evidence in Native Myth and Tradition." http://www.earthquakeconference.org/Presentations/Ludwin-PNW%20Earthquakes%20Native%20Myth%20and%20Tradition_%20NEC%2008.pdf Retrieved 11 October 2013.

Figure 4. Unknown. "May1960: Surviving a Tsunami—Lessons from Chile, Hawaii, and Japan." National Weather Service's Jetstream—Online School for Weather. http://www.srh.noaa.gov/jetstream/tsunami/survive.htm. Retrieved 15 October 2013.

Jigsaw Piece 4: Historical Records

Japanese officials have documented earthquakes and tsunamis since 416 A.D. There were almost 46,000 earthquakes from 416 to 1872. Clearly, Japanese residents know earthquakes, and they know that tsunamis sometimes follow earthquakes. Do you remember the March 11, 2011 massive earthquake (magnitude 9.0) and terrifyingly sudden and deadly tsunami? The pair of events caught the attention of the world, just as a pair did in 2004 in Sumatra; 1964, in Alaska; and 1960 in Chile.

Figure 1. Japanese tsunami evacuation sign. Waterman, 2013.

One Japanese record look like this:

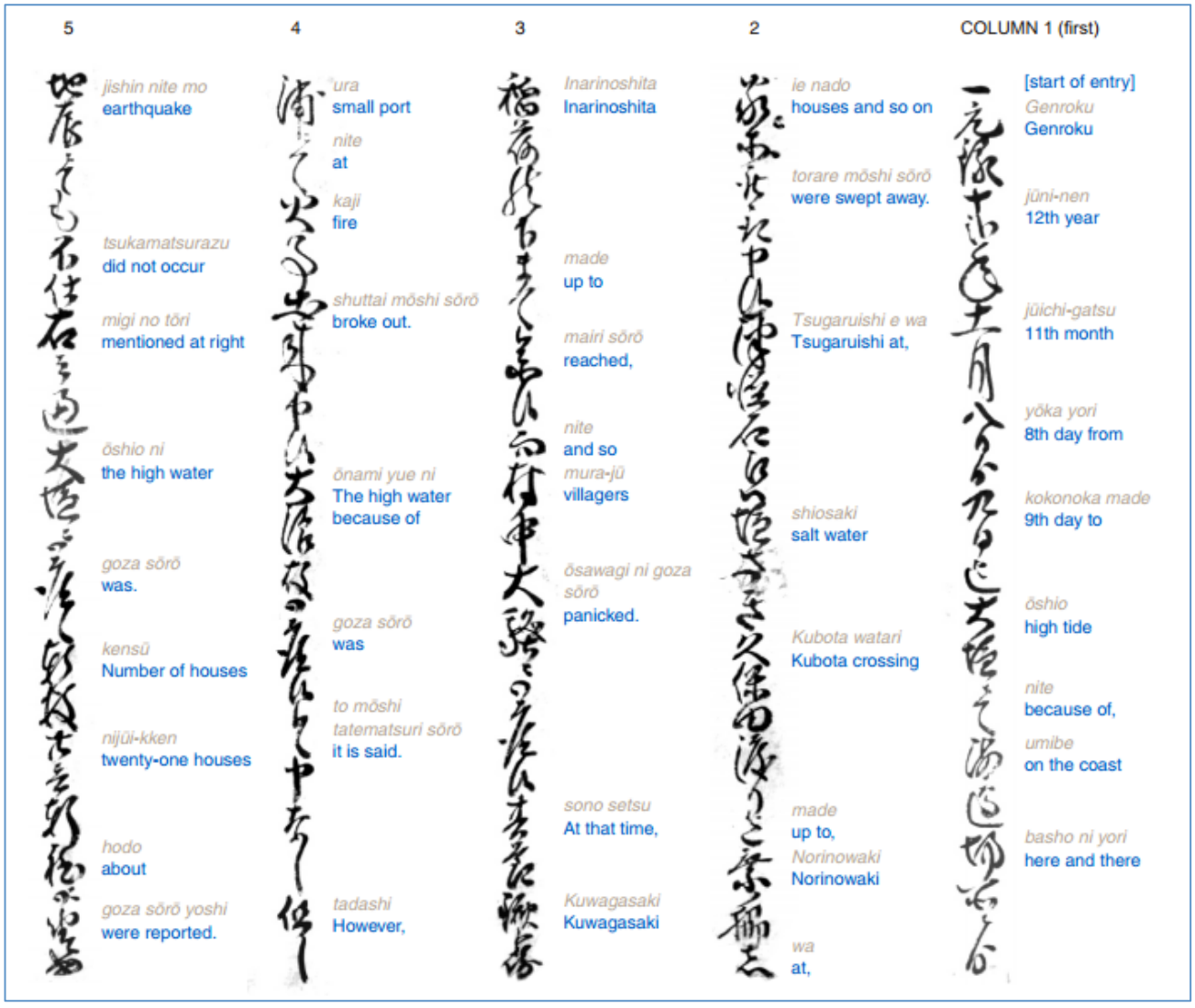


Figure 2. Record from Miyako Bay, Japan. Atwater, *et al.,* 2005.

Read columns downwards, starting on the right side. What is the general gist of this diary entry? It's an important clue to a mystery you and three classmates will try to solve. You each have very different clues. One has information about corpses, another has eye-witness reports, a third has physical evidence, and *you* bring history to the table.

The reference to the date of high water translates to January 27, 1700. The villages were all along the coast. Another record says:

Figure 3. Report from the village of Miho of "something like a very high tide," coming as seven waves. Atwater, *et al*., 2005.

Reports of tsunamis on this date came from several villages in Japan. The government stepped in with an emergency allotment of rice for 159 famished people and lumber to build temporary shelters. Elsewhere, salt-evaporation kilns were damaged; a ship full of rice capsized; and rice paddies, villages, a government storehouse, and a castle's moat were flooded. Because writers felt no preceding earthquake, they did not know what to make of this "orphan tsunami."

We know that earthquakes (and sometimes landslides) cause tsunamis. When an earthquake jars the bottom of the sea along a fault, water is lifted—or dropped—and sets off as a wave that goes around the world. The wave doesn't seem significant to a ship on the ocean, but it can grow to alarming heights as it hits shore.

As you have read, the Japanese villagers knew to seek high ground after earthquakes. But what if there orphan tsunami happens? How would someone know to climb to safety? Scientists and engineers have developed ocean buoys to detect the long-wavelength waves of tsunamis and can now warn people to leave low ground, *now*! Japanese road signs send people to safety (Fig. 1.) So do American road signs (Fig. 4).

Figure 4. Tsunami warning signs from Fort Worden, Washington. West, 2013.

When you gather with your colleagues to discuss clues, what will you tell them about orphan tsunamis?

Picture credits:

Figure 1. Waterman, Elly. 2013. http://commons.wikimedia.org/wiki/File:Tsunami_waarschuwingsbord_in_Beppu_Japan.JPG via Wikimedia Commons. Retrieved 15 October 2013.

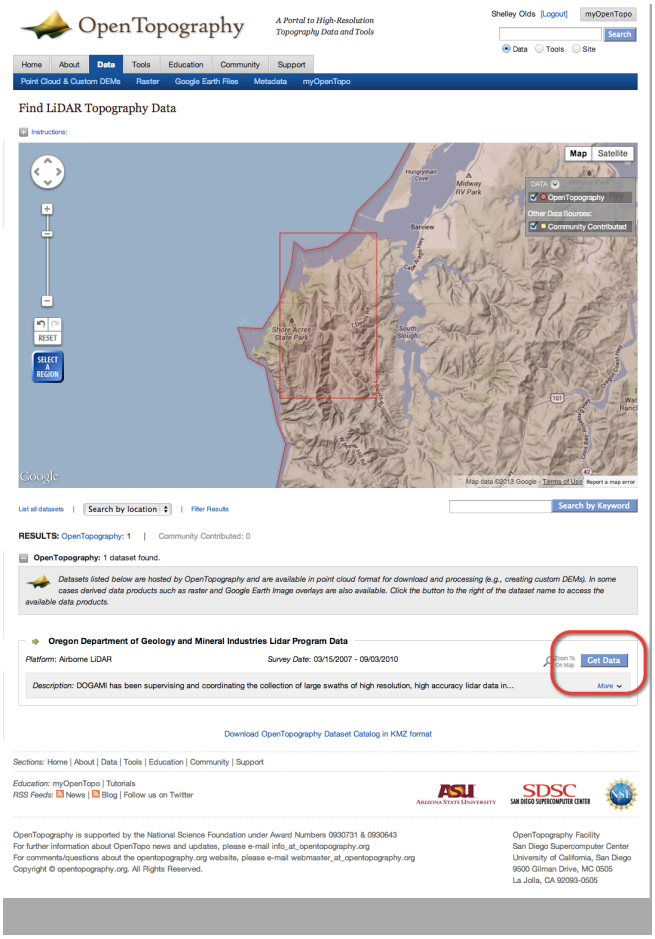
Figure 2. Atwater, Brian F.; Satoko, M.- R.; Kenji, S.; Yoshinobu, T.; Kazue, U.; and Yamaguchi, D.K. 2005. *The Orphan Tsunami of 1700*. U.S. Geological Survey Professional Paper 1707, p 52.

Figure 3. Atwater, Brian F.; Satoko, M.- R.; Kenji, S.; Yoshinobu, T.; Kazue, U.; and Yamaguchi, D.K. 2005. *The Orphan Tsunami of 1700*. U.S. Geological Survey Professional Paper 1707, p 78.

Figure 4. West, N. 2013.

Appendix C: How to get LiDAR images into Google Earth

1. Start on http://opentopography.org/
2. Click on **Find Data**
3. The map shows all of the LiDAR data available. The red dots are areas with LiDAR data that can be saved as Google Earth KML files.
4. Zoom in and use the **Select a region** button to highlight an area to get the LiDAR.
5. Scroll the page to below the map then click on **Get Data.**
6. On the new page, if you receive a warning, then create a new, smaller **select a region.** (Create an account—it's free! And you can create larger LiDAR files)



7. **To create a LiDAR image for Google Earth,** choose these settings:

   A. Choose Return Classification: Click on **Ground.**

   B. Point Cloud Results: unclick all boxes.

   C1. DEM Generation (Local Gridding): unclick all boxes

   C2. DEM Generation (TIN): click on **Calculate TIN**; keep everything else the same.

   D. Derivative Products: unclick the box.

   E. Visualization: click on **Generate hillshade images and Google Earth files from DEMs;** keep everything else the same.

8. Click on **Submit** and wait a few minutes for the results page.

9. Click on the Google Earth KMZ files – save, then open in Google Earth. Some browsers will open the file directly into Google Earth.

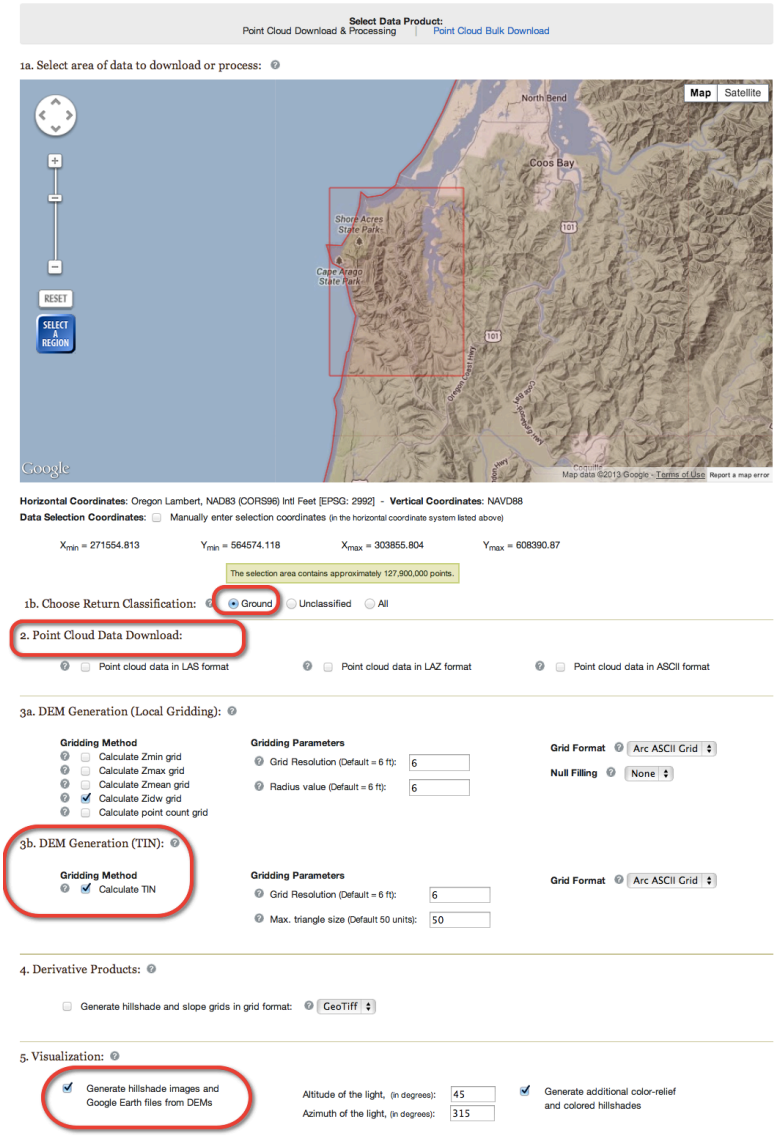


Image sources for body of text

Figure 3. Atwater, B. 2005. *The Orphan Tsunami of 1700*. U.S. Geological Survey Professional Paper 1707, p. 16.

Figure 4. Atwater, B. 2005. *The Orphan Tsunami of 1700*. U.S. Geological Survey Professional Paper 1707, p. 97.

Figure 5. Ludwin, et al. 2005. "Dating the 1700 Cascadia Earthquake: Great Coastal Earthquakes in Native Stories." Seismological Research Letters, v. 76, no. 2., pp. 143, figure 3.

Figure 6. Granshaw, F. 2009. Teachers on the Leading Edge workshop. https://media.up.edu/Physics/TOLE/VFEs/a_TOTLE_VFE.swf Retrieved 4 October 2013.

Figure 7. Atwater, B. 2005. *The Orphan Tsunami of 1700*. U.S. Geological Survey Professional Paper 1707, p. 52.

Figure 8. Elliott, Austin. April 11, 2011. "Earthquake early warning in action," The Trembling Earth. AGU Blogosphere. http://blogs.agu.org/tremblingearth/2011/04/22/earthquake-early-warning-in-action/ Retrieved 25 September 2013.

Figure 9. Shizhao. 2004. http://en.wikipedia.org/wiki/File:EastHanSeismograph.JPG Retrieved 26 August 2013 from Wikimedia Commons.

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Figure 17. User:WeFt. 2007. http://commons.wikimedia.org/wiki/File%3ARostre_de_b%C3%A9lemnite_fractur%C3%A9_par_d%C3%A9formation_04.jpg via Wikimedia Commons. Retrieved 16 November 2012.

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