Detecting Cascadia's changing shape with GPS

Teacher Manual

"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 related 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 the 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

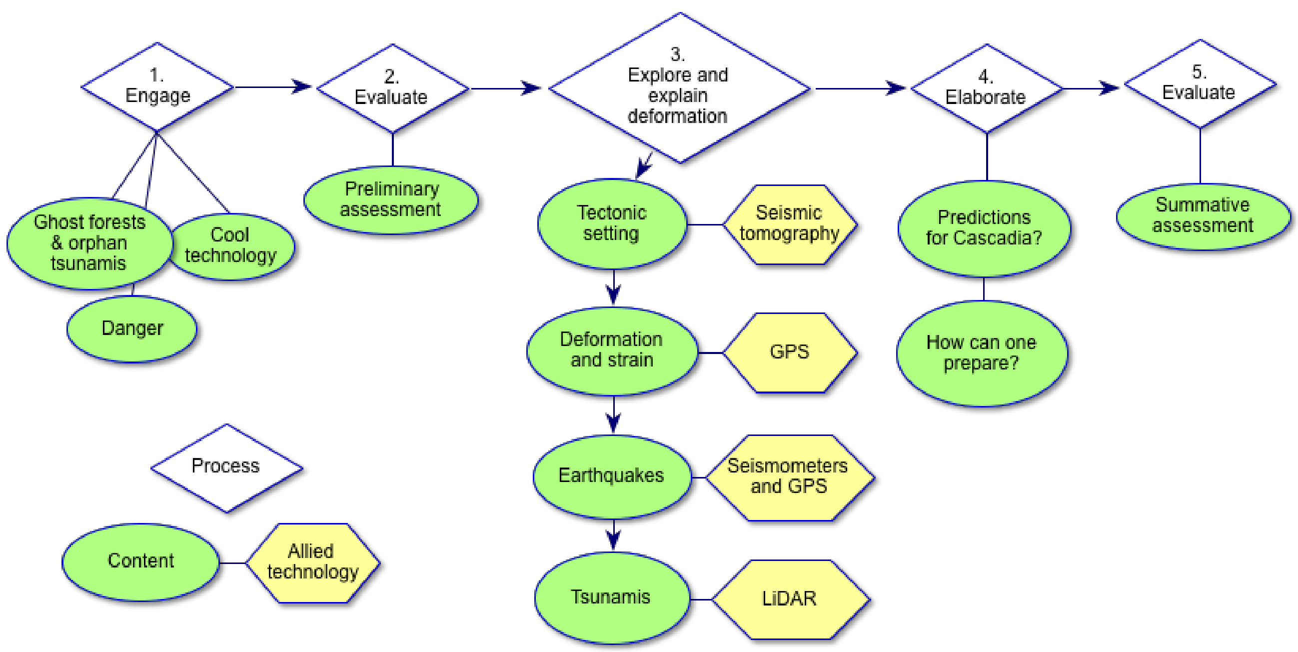
Grade Levels 6 – 12 (modifications will be needed for 6th and 7th)

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.

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



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.

Organization The general sequence is laid out in the figure on the previous page. 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.

Next Generation Science Standards (NGSS)

Performance Expectations	Students who demonstrate understanding can
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.

General Procedure The flowchart on the first page 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

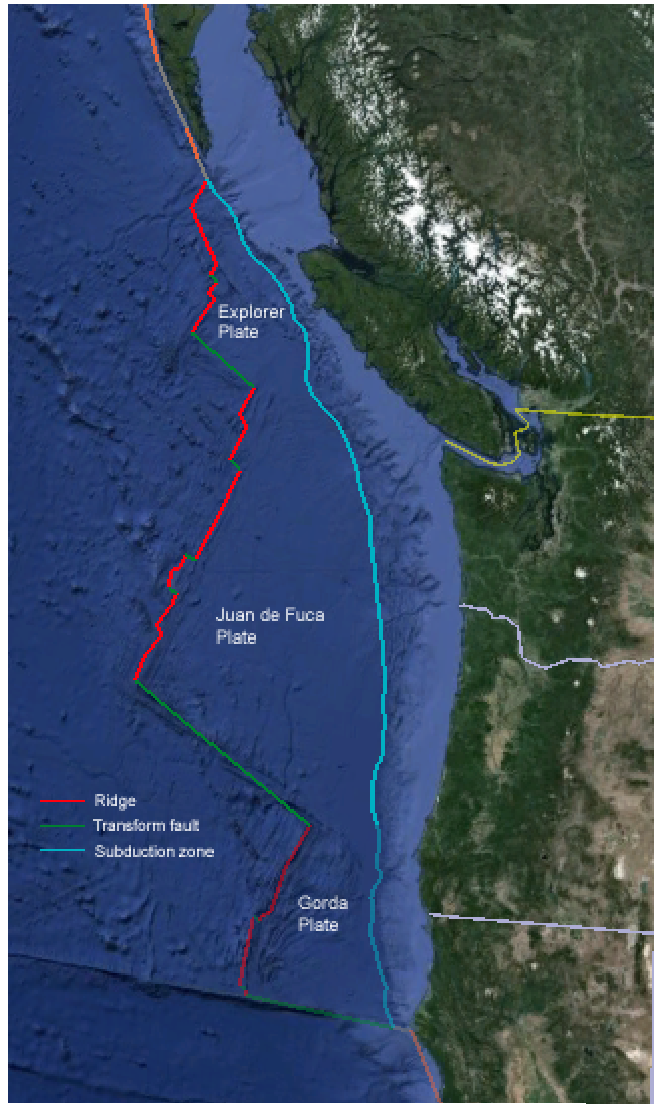


Figure 2. Plate boundaries in Cascadia. Adapted from Google Earth.

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.

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

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

Engage Option 1: A Detective Story—The Orphan Tsunami
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. This can be completed as a quick jigsaw activity or via media.   **Teaching Tips**   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.")   Additionally, the American Museum of Natural History (AMNH) tells the same story in "Ghosts of Tsunamis Past," an on-line article for non-scientists. (Search for "AMNH tsunamis.")

Engage Option 2: 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 (resources for each strand can be found in the Engage Lesson packet)
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.   When an earthquake occurs seismic waves radiate from the epicenter like waves on a pond. It is these waves we feel as earthquake shaking and cause damage to structures. The technology exists to detect moderate to large earthquakes so quickly that an alert can be delivered to locations outside the area where the earthquake begins before shaking arrives.   Both the United States and Japan have operational early-warning systems. This strand explores how they operate and their effectiveness.
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. This strand explores how scientists are modeling both earthquakes and tsunamis in a variety of ways in order to better understand them.

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, smartphones 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.

Engage Option 3: Streamlining This Section

If you have limited time or merely 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.

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 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.

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 3.

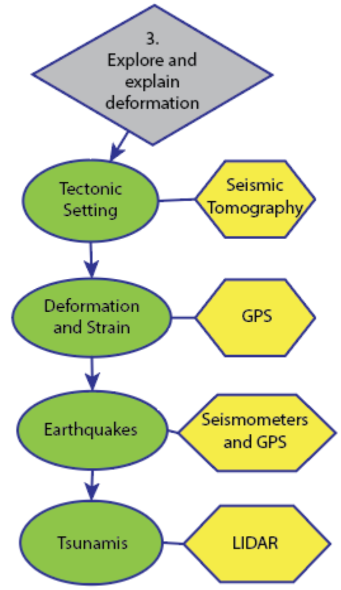


Figure 3. Content map.

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. 4a 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 Cascadia Subduction Zone (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.

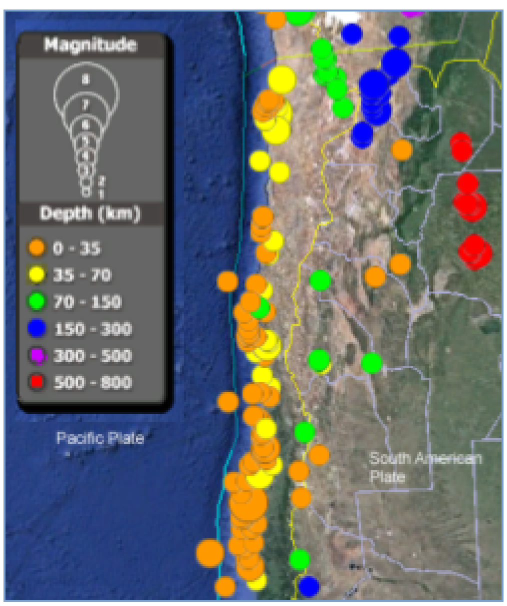


Figure 4a. Chile. Earthquakes > M = 6 from 1993 - 2012 and all quakes for one week in September 2013.

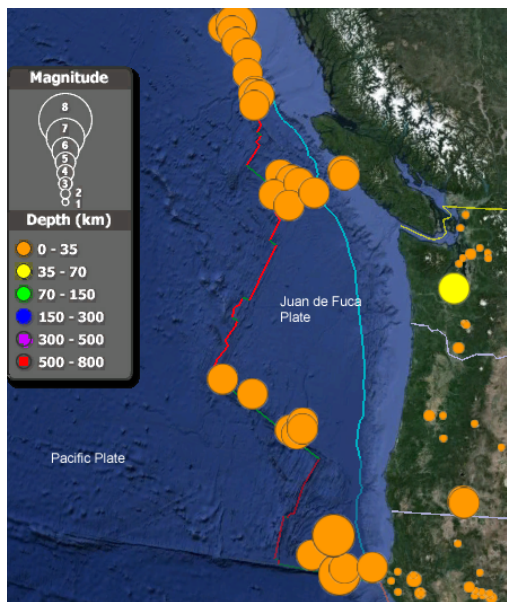


Figure 4b. Cascadian quakes, as in Figure 13a. Figures are from Google Earth.

Teaching Tip: *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 (https://www.google.com/earth/versions/) installed—it is free and downloadable (the online version will not work for this purpose). Also download Dynamic Earth (https://serc.carleton.edu/sp/library/google_earth/examples/49004.html) 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." ● "Cascadia Subduction Zone: The Big One" 7:58. 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 "Cascadia Subduction Zone OSU") ● A simulation of how the Juan de Fuca plate came to be (https://animations.geol.ucsb.edu/2_infopgs/IP3RegTect/dNoPacific.html) 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" (https://www.iris.edu/hq/files/programs/education_and_outreach/aotm/22/1b.EarthquakesVolcanoesInThePacificNW.pdf) 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" (https://www.iris.edu/hq/files/programs/education_and_outreach/aotm/5/2.Subduction_Rebound_Background.pdf) 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." (https://www.usgs.gov/publications/cascadia-subduction-zone-two-contrasting-models-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.")

A1. 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.

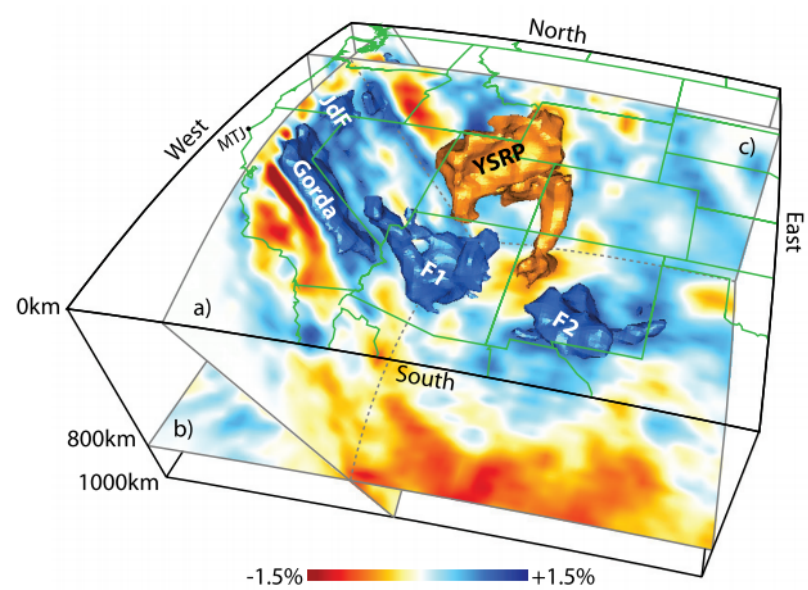


Figure 5. Seismic tomographic image of Cascadia showing the subducting Juan de Fuca (JdF) and Gorda Plates as blue slabs. YSRP is the plume of heat under Yellowstone N.P. Obrebski, *et al.*, 2010.

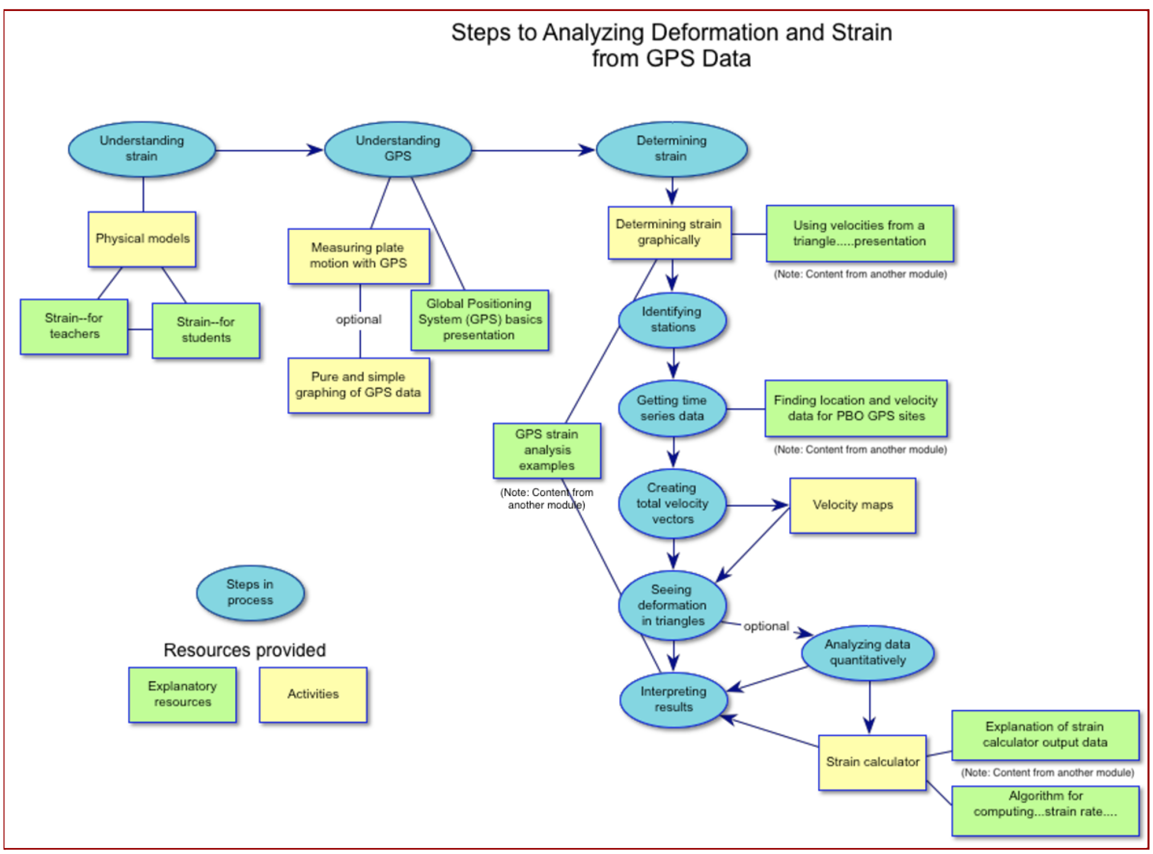
Analogous to a CT scan for an injury, seismic tomography combines images that slice virtually through Earth to reveal deep structures. The slices are made in a national project, the USArray, which is a flock of 400 seismometers stepping across the country over ten years. Collectively, the seismometers 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. 5).

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" (http://cascadiageo.org/documentation/literature/cascadia_papers/obreski_etal_2010_slab_plume.pdf) is the original research article, "Yellowstone: what lies beneath," (http://all-geo.org/highlyallochthonous/2010/08/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.")

EarthScope explains seismic tomography in a four-page article (https://www.iris.edu/hq/files/programs/education_and_outreach/lessons_and_resources/docs/es_tomography.pdf) for the public. (Search for "IRIS seismic tomography.")

B. 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 on the previous page shows the sequence of steps (blue bubbles), activities (yellow boxes), and resources to explain concepts (green boxes). 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.

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.

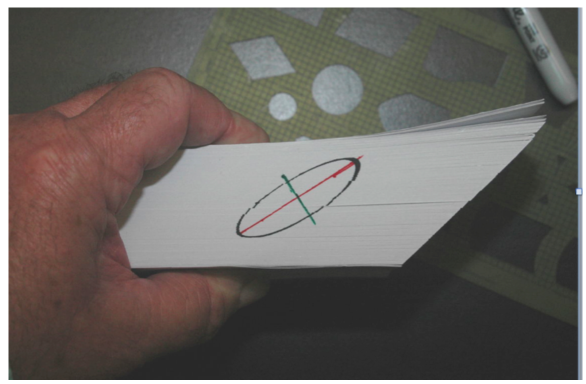


Figure 6. Deck of cards that has been sheared as an example of simple strain. The ellipse was a circle before shearing. Cronin, 2012.

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. 7).

Figure 7. A Jurassic belemnite from the Alps that has been strained--stretched into segments. Coin is 2 cm in diameter. WeFT, 2007.

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.

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

Activity A: Measuring plate motion with GPS: Icelandhysical models of strain

Students learn how a GPS works. They interpret data from plots showing the position of the station over time, or "time series plots" (Fig. 8). 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."

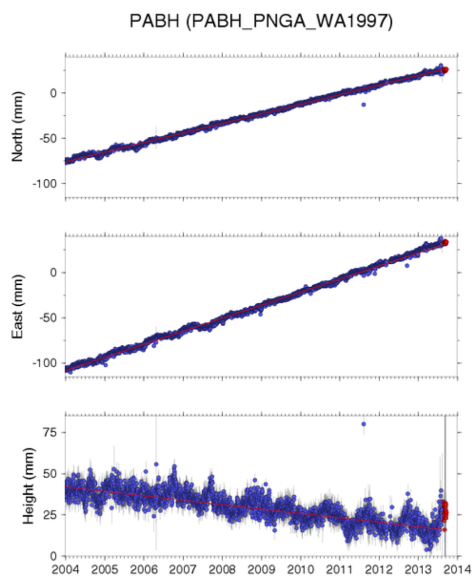


Figure 8. Time series plot from PABH, a GPS station in coastal Washington.

Activity 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.

Resources - Activity B

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.

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.

Activity 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.

Activity 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. 9).

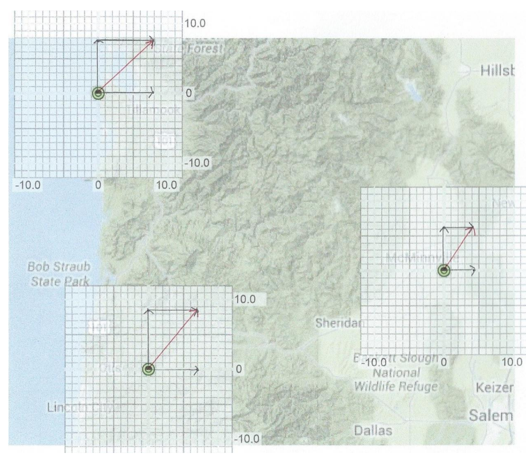


Figure 9. Part of Oregon, overlain by grids with velocity vectors from GPS stations. The red arrow is the sum of the north-south and east-west vectors.

Activity 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

These resources, from the module GPS, Strain, and Earthquakes, were developed for a majors-level geology course. 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. These are included in the Geodesy Tools for Societal Issues (GETSI) collection on SERC.

- *Unit 2: Mashing it up: physical models of deformation and strain (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 process.

- *Unit 3: Getting started with GPS data (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.

- *Unit 4: GPS and infinitesimal strain analysis (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."

- *Unit 5: 2014 South Napa Earthquake and GPS strain (GPS strain analysis examples)*

  This is an exercise with a worked example of the 2014 South Napa earthquake with shear strain. The first example is absolutely relevant to Cascadia. Instructor notes discuss the geology of the region. The student exercise relies solely on the strain calculator. This example might help you get the lay of the land.

- *Unit 6: Applying GPS strain and earthquake hazard analyses to different regions (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.

B1: Technology allied with deformation and strain—GPS

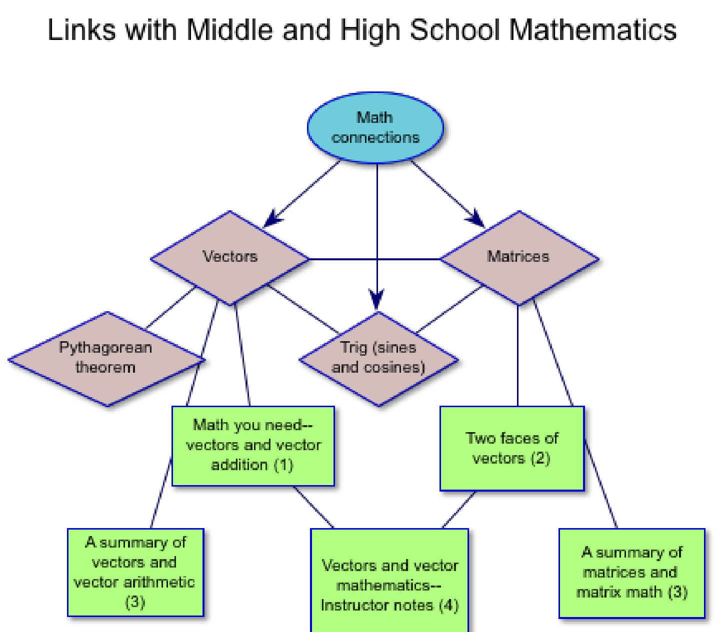
GPS is handy when lost and frustrated in a car in an unfamiliar city. Bossy and annoying as the droid in your dashboard might be, it can get you where you want to go. GPS is also handy when hiking or noting a spot at which you've taken scientific observations or measurements. In studies of plate tectonics,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

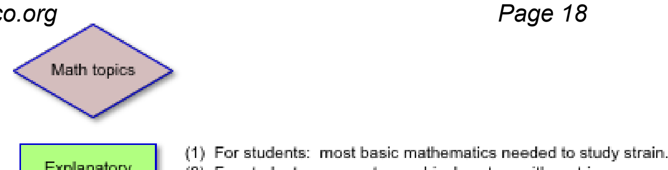
Resources
"EarthScope Overview." (https://www.youtube.com/watch?v=Uc0JZnO9Axg) 5:05. An overview of a national project, EarthScope, to discover what lies under the United States. Instruments placed across the country measure and monitor changes in Earth's crust. They also allow us to see into the Earth 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" (https://youtu.be/zzFXS7f3thA) 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.)

B2: Mathematics allied with deformation and strain

These lessons use middle school mathematics. Students can determine strain graphically (Fig. 9). 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

that

Figure 10. Math topics with applications in determining deformation and strain.

science and mathematics. Think how powerful could be for them…relating the math they're learning to scientific research they're conducting.

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.

C. 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 11. 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.

Activity
A. Your students can explore the 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, 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 (https://www.pnsn.org/tremor) 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 (https://www.pnsn.org/earthquakes/historic-catalog). 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 (https://www.usgs.gov/programs/earthquake-hazards/faults) 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 (https://www.pnsn.org/) 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." (https://crew.org/wp-content/uploads/2016/04/cascadia_subduction_scenario_2013.pdf) 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?" (https://youtu.be/NMNNr2CyekA) 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." (https://www.nature.com/articles/news.2010.270) (*Nature News*) and "Odds Are About 1-In-3 That Mega Earthquake Will Hit Pacific Northwest in Next 50 Years, Scientists Say" (https://www.sciencedaily.com/releases/2010/05/100524121250.htm) (*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." (https://pubs.er.usgs.gov/publication/pp1661F) (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" (https://www.iris.edu/hq/files/programs/education_and_outreach/aotm/22/1b.EarthquakesVolcanoesInThePacificNW.pdf) and "Subduction Zone—Plate Interaction" (https://www.iris.edu/hq/files/programs/education_and_outreach/aotm/5/2.Subduction_Rebound_Background.pdf) from IRIS. (Search for "IRIS geologic setting northwest" and "IRIS subduction zone.")

Resources - Earthquakes in General

For a perspective on earthquakes, volcanoes, and plate motions, try UNAVCO's Velocity Viewer (Fig. 12). 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.")

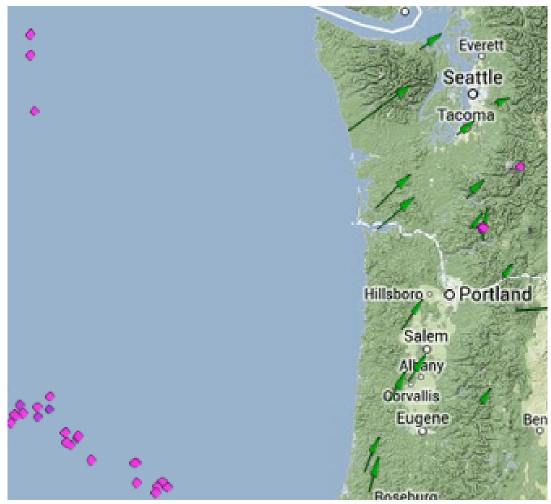


Figure 12. Velocity Viewer showing GPS data as vectors and earthquakes as circles.

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. The 3D view is particularly useful when exploring the relationship between subduction zone types and location/depth/magnitude of the earthquake. (Search for "IRIS EPO" and select the Earthquake Browser.)

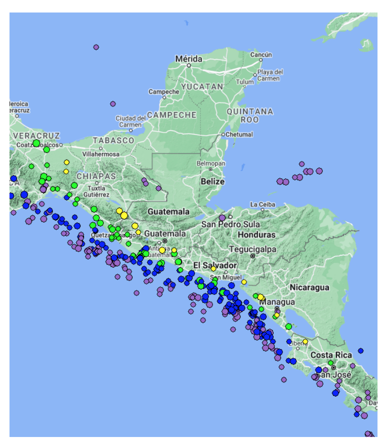
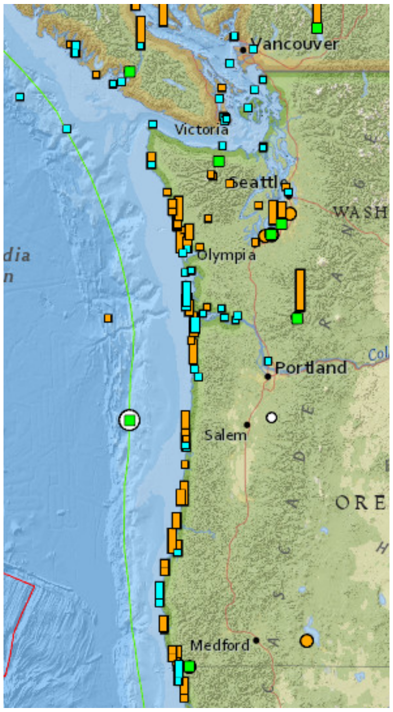


Figure 13. Earthquake browser from IRIS.



For earthquakes, tsunamis, and volcanoes, the National Geophysical Data Center Natural Hazards Viewer (https://www.ncei.noaa.gov/maps/hazards/) 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. 14). (Search for "NGDC hazards viewer.")

Figure 14. NGDC Hazards Viewer. Earthquakes are shown as circles; tsunami wave heights as bars; and tsunami sources as squares.

Tohoku, Japan 2011 as a Well-Documented Analog

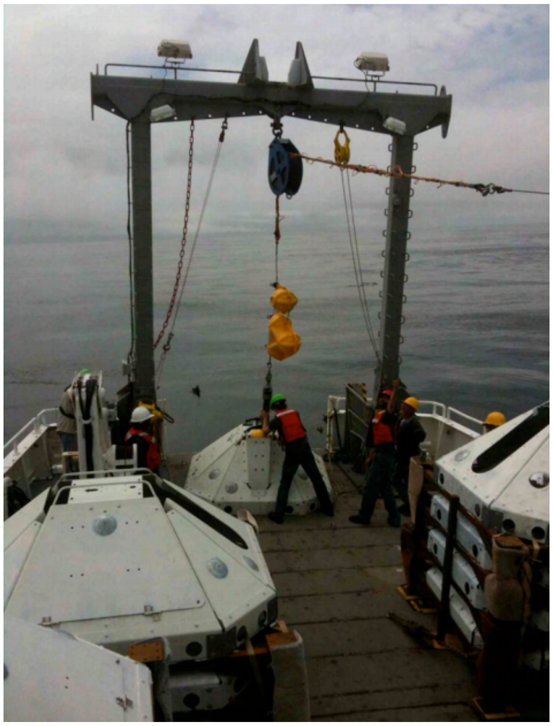
A background article about the 2011 Tohoku earthquake from the University of Portland and IRIS Education and Outreach's Teachable Moments explains the earthquake in its regional setting and describes hazards. It also includes a seismogram from Portland. (Search for "IRIS Tohoku notice" and link to the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

C1: 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.

Resources	
"EarthScope Overview," (https://youtu.be/Uc0JZnO9Axg) 5:05, is a video about how the EarthScope project with numerous seismometers and GPS that allowed us to scope out what lies under the United States. (Search for "EarthScope Overview video.")	
	In an amphibious twist, the Cascadia Initiative (https://cascadia.uoregon.edu/) 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. 15.) College students filmed their shipboard experiences emplacing instruments, watching whales, recording bubbling plumes of methane in these videos on their YouTube channel: Cascadia Initiative (Search for "Cascadia Initiative" and "Cruisin' Cascadia.") Figure 15. A seismometer hoisted for placement on the seafloor in commercial fishing grounds. Tolstoy, M. and A. Trehu, 2011.

D. 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.

<table>
<tr><th></th><th>Activity</th></tr>
<tr><td>Option 1</td><td>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 16. Tsunami evacuation zone from Fort Worden State Park, WA. West, 2013.</td></tr>
<tr><td>Option 2</td><td>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?"</td></tr>
</table>

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" (https://youtu.be/ZXxDUkGMNLs) (Search for "surviving tsunami science nation.")
A video on the basics of tsunamis, warning signals, and what to do (https://www.youtube.com/watch?v=tUN_UTY0GNo) 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." (https://oceantoday.noaa.gov/tsunamistrikedestruction/) 2:55. Footage of tsunami. (Search for "tsunami strike destruction.")

- "Tsunami Strike: Japan Part II: Propagation." (https://oceantoday.noaa.gov/tsunamistrikepropagation/) 2:04. Footage and modeling. (Search for "tsunami strike propagation.")
- "Tsunami Strike: Japan Part III: Warning Systems." (https://oceantoday.noaa.gov/tsunamistrikewarning/) 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" (https://youtu.be/_oPb_9gOdn4) 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.")

D1. 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.

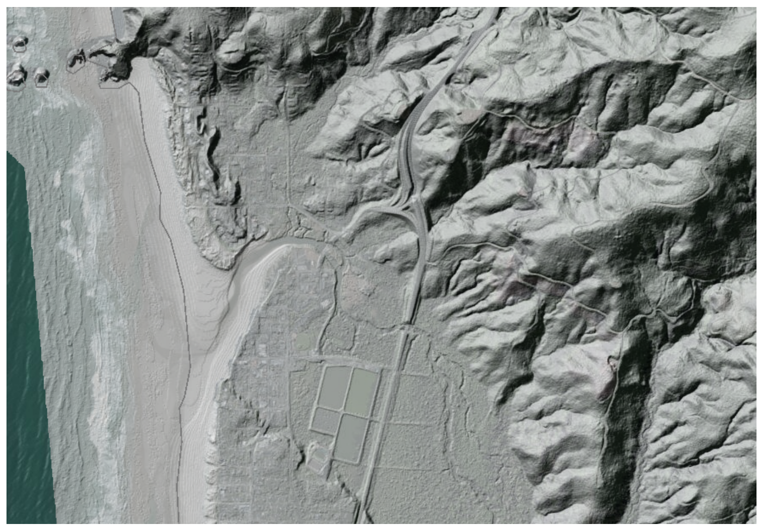


Figure 17. LiDAR image of Seaside, Oregon. If this were online, you could zoom in and see fleas jumping in the sand.

Resources

"Discovering and Mapping Natural Hazards with LiDAR" (https://lidarmag.com/2012/07/27/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 (https://oceanservice.noaa.gov/facts/lidar.html) 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 YouTube video shows how LiDAR works https://youtu.be/_t6TUYjfPYo) 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 (https://coast.noaa.gov/digitalcoast/training/lidar-101.html) 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 (https://coast.noaa.gov/digitalcoast/training/intro-lidar.html). 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 (https://www.oregongeology.org/lidar/) 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 (http://pugetsoundlidar.ess.washington.edu/) 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 (https://opentopography.org/) 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.

Part 4. 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?

Activity A. Class Discussion

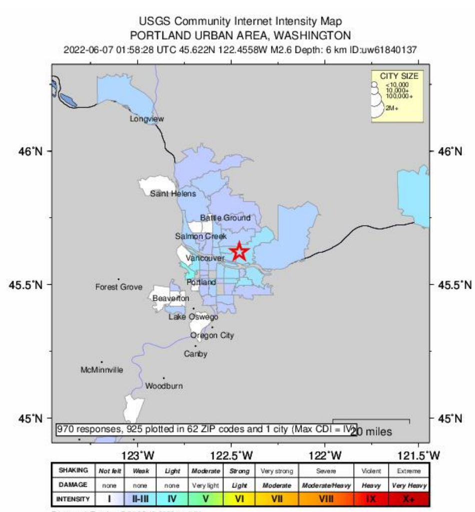
Ask your students, "What do you think will happen in Cascadia? Why do you think so?" Seek evidence. Expect them to support their statement with evidence. (This could also be a fine homework assignment or small group discussion.)

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 (https://www.usgs.gov/programs/earthquake-hazards/prepare) offers materials. FEMA's Ready (https://www.ready.gov/earthquakes) 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) http://www.cert-la.com/EmergPrepBooklet.pdf), 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?

Activity B. Did You Feel It? — Citizen Science via the USGS



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 USGS")

Activity C. The Great Shake Out

Participate in the Great ShakeOut, as a class, school, family, community group, or individual. ShakeOut is an international earthquake preparedness event held on 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 a seismic zone, to register and follow through. Depending on your location, there may be state specific ShakeOut resources available via the official website. (Search for "shakeout.")

Figure 18. 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]

<u>Earth Science Literacy Principles</u>

Big Idea 1: Data and Observations lead to Understanding Earth	1.1 Predict hazards 1.3 Experiment and collect multiple kinds of evidence 1.2 Many science disciplines come to bear on understanding 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 Advances in technology refine understanding
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