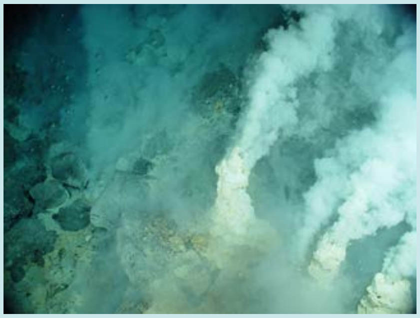


Champagne Vent, MTMNM.
Photo credit: NOAA Submarine Ring of Fire 2004 Exploration and the NOAA Vents Program

Grade Level

- 7-12

Timeframe

- Four 45-minute periods, or two 90-minute periods

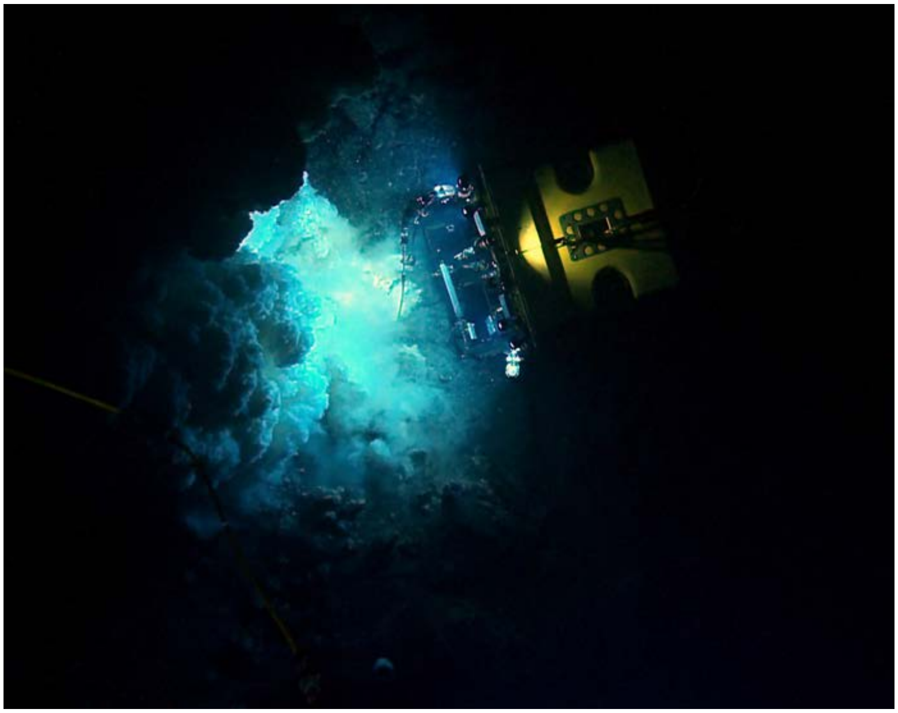
Materials

- Student worksheets (1 x student)
- Colored pencils (2 x student)
- Airhead candy, sticks of gum, or chewy granola bars, (3 x per groups of 2-3 students).

Key Words

- Bathymetry
- Geotherm
- Island arc volcanoes
- Mariana Trench
- Rift
- Serpentine mud volcanoes
- Solidus

Marianas Trench Marine National Monument: Tectonic Evolution



ROV Jason inspects the NW Rota-1 seamount during a 2009 expedition. Photo credit: NOAA PMEL

Activity Summary

The massive tectonic forces that shape our planet are sometimes hard for students to understand. This lesson seeks to have students build their own understanding of how the convergent plate boundary at the Mariana Trench creates the unique benthic environments found throughout the area, many of which are now protected as part of the Marinas Trench Marine National Monument (MTMNM). The lesson begins with students sharing what they know and want to learn about the Mariana Trench region. Next, students orient themselves to the region by observing and describing the bathymetric features that occur in the vicinity of the Mariana Trench. The students will then develop an understanding of the physical and chemical processes that result in these bathymetric features by using simple physical models, and by manipulating and interpreting data about earthquakes, geothermal and solidus gradients, and large scale tectonic movements. Finally, the student demonstrate their understanding by creating a detailed cross-section model of the entire region.

If you need assistance with this document, please contact NOAA Fisheries at (808) 725-5000.

Outline

ENGAGE – What do you know?

EXPLORE – How did THAT get there? Deep Quakes

EXPLAIN – How do you like your melt?

ELABORATE – Slow and steady destroys the plate

EVALUATE – Summary

Vocabulary

BATHYMETRY- From the Greek *bathus* ("deep") and *metron* ("measure"), bathymetry is the study of the "beds" or "floors" of water bodies, including the ocean, rivers, streams, and lakes. More commonly now this word has come to mean the study or display of underwater topography.

Learning Objectives

Students will:

1. Become familiar with the MTMNM and its benthic features.
2. Learn to trust their own observations.
3. Practice translating between different data types.
4. Learn how vertical exaggeration is used to help make graphs more understandable.
5. Explore the relationship between earthquakes and subduction zones.
6. Understand that water changes the physical and chemical characteristics of rocks.
7. Understand how heat changes the physical characteristics of rocks.
8. Understand that benthic (topographic) variations often are the result of different large scale physical and chemical geologic processes.

Background Information

The Marianas Subduction Factory:

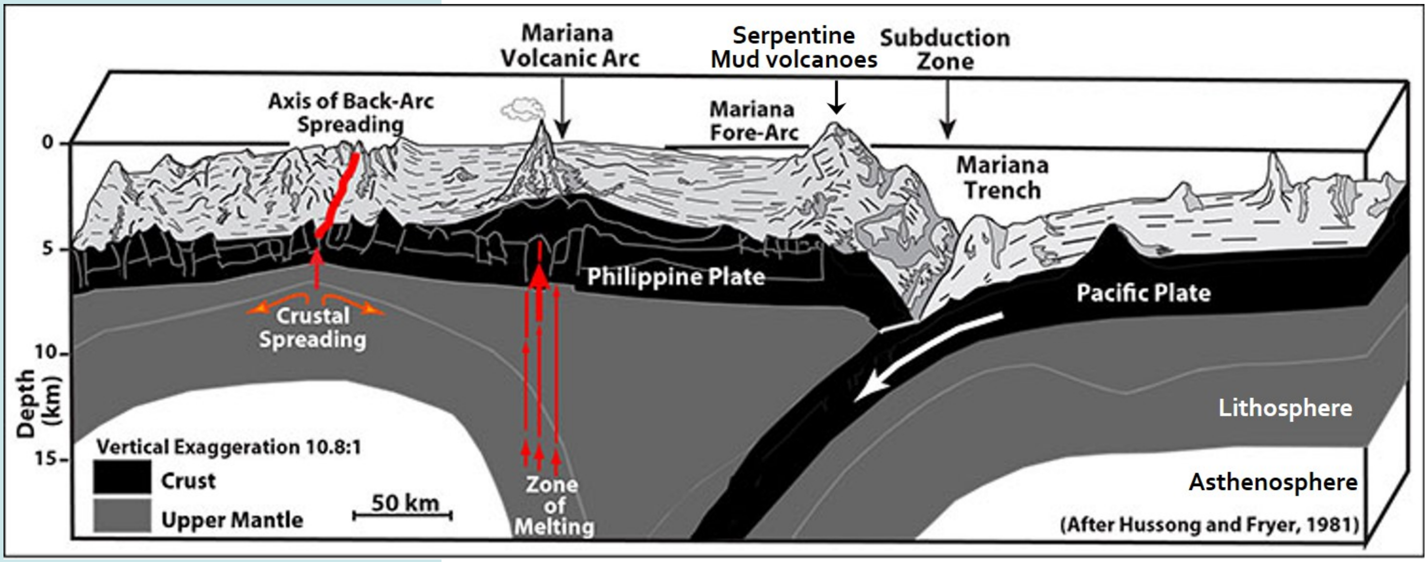


Figure 1: Overview of Mariana Trench Subduction System

BATHYMETRIC PROFILE-This is the "skyline" view of the seafloor. Usually displayed as depth below water surface vs distance along the sea-floor, in a bathymetric profile. Given the vast size of the ocean, most oceanic bathymetric profiles include substantial vertical exaggeration in order to highlight features of the ocean floor.

The Marinas Trench Marine National Monument (MTMNM) was created, in part, to help protect one of the most impressive examples of oceanic-oceanic plate convergence in the world. At the trench the very old (up to ~170 Ma) dense Pacific Plate (Stern et al. 2003) meets the younger (~50 Ma) less dense Philippine Sea Plate (Fang et al. 2011) (Figure 1). Subduction is thought to have begun about 52 Ma when the cold, dense Pacific Plate started to founder and sink along its western margin. True subduction began around 43 Ma and localized the volcanic arc close to its present location, approximately 200 km away from the trench. Two types of volcanoes common to oceanic subduction zones are

Vocabulary (continued)

DEWATER-The removal of entrained or chemically bound water from a solid material by squeezing (pressure) or heating (temperature).

GEOTHERMAL GRADIENT-The rate of temperature increase in a tectonic plate resulting from increasing pressure/depth. The profile of this temperature vs pressure/depth creates a curve known as a "geotherm".

HYPOCENTER-This is the point at depth in the Earth where strain is released, producing an earthquake. The hypocenter is synonymous with the term "earthquake focus", and the "epicenter" is the point on the surface of the Earth that is directly above the hypocenter.

MA (Ma)-abbreviation for mega-anum, or millions of years ago.

PERIDOTITE-This is an ultra-mafic, coarse grained rock that is the dominant rock type in the upper part of the Earth's mantle. The rock contains less than 45% silica and is made up mostly of the minerals olivine and pyroxene. The name derives from peridot, which is the gem name for the mineral olivine.

RIFT-In geology, a rift is a zone marked by fissuring, faulting and thinning where the Earth's crust and lithosphere are being pulled apart by extensional forces. The thinning of the lithosphere in a rift zone may decompress underlying mantle sufficiently to initiate decompression melting and magma formation.

present in the MTMNM, serpentine mud volcanoes (the only modern, active examples in the world) and a line of stratovolcanoes that parallels the trench; these are also called arc volcanoes. Both these types of volcanoes result from water being forced out of the subducting plate and filtering toward the surface through the over-riding Philippine Sea Plate.

Mud volcanoes occur near the eastern edge of the Philippine Sea Plate adjacent (0-100 km away from) the Mariana Trench (Fryer et al. 2000). These volcanoes are composed predominantly of serpentine minerals mixed with other pulverized rocks. Increasing pressure on the subducting Pacific plate squeezes out much of the water bound up in the sediments and crust. When the Pacific Plate reaches a depth of ~50 km as much as 50% of the water contained in the surface sediments may already have been removed (Rüpke et al. 2004). As this water, which is less dense than the surrounding rock, begins its ascent toward the Earth's surface through cracks and faults in the over-riding Philippine Sea Plate, it alters some of the ultra-mafic peridotite rock into serpentine minerals, which make up the rock serpentinite. This metamorphic reaction increases the volume and decreases the density of the serpentinite relative to the surrounding peridotite. The newly-formed serpentinite rises toward the surface along with the water and a slurry of unaltered rocks pulled from the walls of the faults. Over time this serpentinite erupts on the seafloor, creating enormous mud volcanoes (up to 50 km in diameter by 2 km in height) on the seafloor, which often have fluid vents issuing from their summits. These serpentinite mud volcano vents are home to some very unusual life-forms and some striking geologic and chemical phenomena. Many scientists think that conditions on and in these mud volcano vents may give us clues about how life evolved on this planet, and perhaps inform our attempts to find life on other planets. This is part of the reason that these fascinating features were specifically included as part of the Volcanic Unit of the MTMNM when it was set aside by the US government in 2009.

The stratovolcanoes in the MTMNM, also known as arc volcanoes, are found on the Philippine Sea Plate ~200 km away from the Trench. These also are related to the dewatering of the subducting Pacific Plate. When the plate reaches depths of 100 km the the pressures become so significant that minerals of the crust and mantle undergo metamorphic alteration which releases water previously bound up in their crystal structures. This newly-liberated water begins rising toward the surface through cracks and faults in the hot over-riding Philippine Sea Plate. At these pressures and temperatures, ultra-mafic peridotite in the presence of water doesn't serpentinize, but begins to melt. This process is known as flux melting and occurs because the chemical bonds that form peridotite are more easily disrupted in the presence of water and so "melting" occurs at a lower temperature for wet peridotite than it does for dry peridotite. The partial melting of the ultra-mafic peridotite creates mafic magma, similar to that erupted from Hawaiian volcanoes, which slowly rises toward the surface and forms a series of volcanoes that parallel the Trench. When the subduction zones occur between two

Vocabulary (continued)

SERPENTINE- An olive-green colored group of minerals that form from the metamorphic alteration of peridotite and pyroxene. The sometimes mottled appearance of this mineral gives rise to the Latin name *serpentinus* meaning "serpent rock". The fibrous form of this mineral, chrysotile, is the well-known asbestos material commonly used as a fire retardant in housing and insulation materials.

SERPENTINITE- Rocks composed of one or more groups of serpentine minerals which form when ultramafic rocks from the Earth's mantle (generally peridotite) are altered by hydration and metamorphic alteration.

SOLIDUS- The solidus temperature is the temperature at which a phase between liquid and solid begins/ends. Since pressure will alter the solidus temperature, a "solidus curve" is the profile of solidus temperatures at different pressures and can be very useful for predicting material behaviors.

oceanic plates, as it does beneath the Marianas, these volcanoes are known as volcanic island arcs, whereas subduction of oceanic plates beneath continental plates results in continental volcanic arcs, such as the Andes of South America or Cascades of the western USA. The Islands Unit of the MTMNM includes the waters and submerged lands around three northernmost Mariana Islands. These islands are the subaerially exposed portions of several old arc volcanoes and their unique reef habitats support marine biological communities dependent on basalt rock foundations, unlike those throughout the remainder of the Pacific. These reefs and waters are among the most biologically diverse in the Western Pacific and include the greatest diversity of seamount and hydrothermal vent life yet discovered. They also contain one of the most diverse collections of stony corals in the Western Pacific, including more than

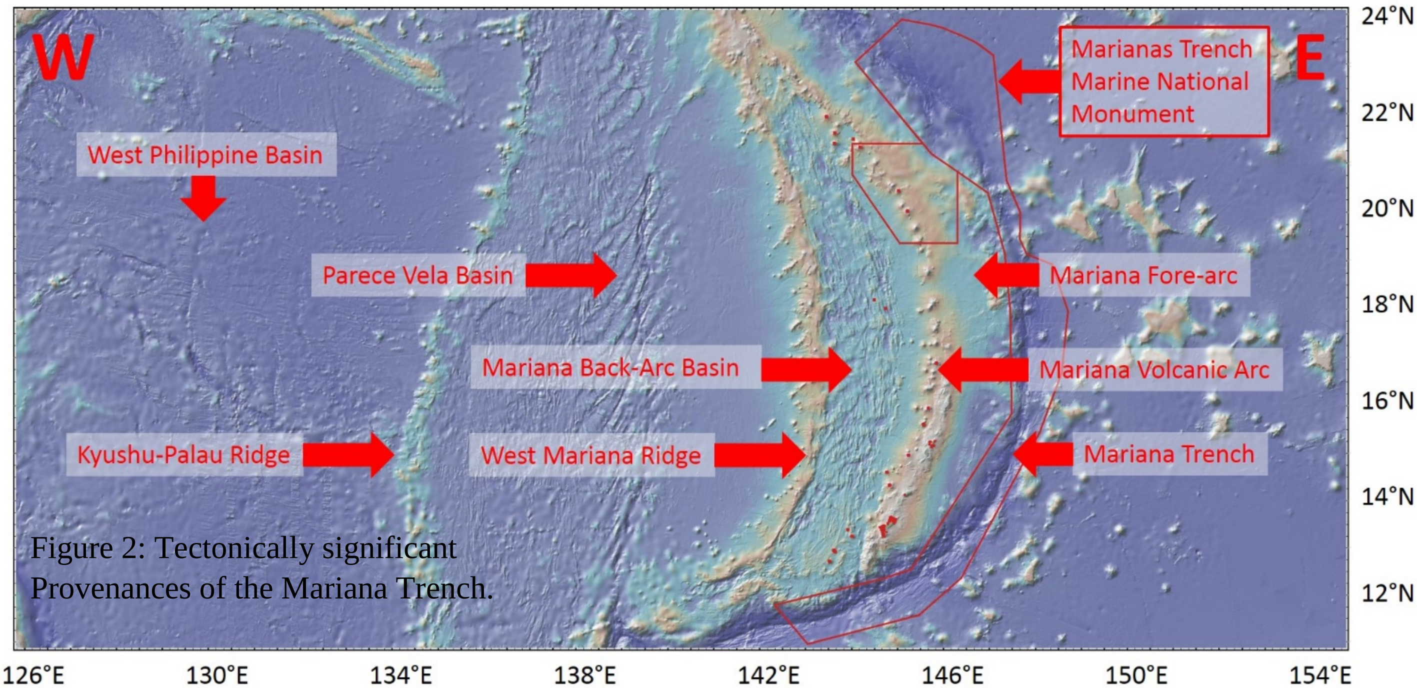


Figure 2: Tectonically significant Provenances of the Mariana Trench.

300 species, higher than any other U.S. reef area.

Around 30 Ma, rifting (or the pulling apart of a plate) began in the southern part of the Mariana volcanic arc. The heat generated by arc volcanoes weakened the plate in that location, and under extensional pressure from the west, the Philippine Sea Plate began to pull apart to form a backarc basin [*Sdrolias and Müller*, 2006]. The rift propagated northward, unzipping the plate along the line of the arc volcanoes to create the Parece Vela Basin (Figure 2). At some point after rifting began, the thinning of the crust resulted in decompression melting and the onset of sustained crustal spreading (similar to what occurs at mid-ocean ridges). Over time the spreading center gradually shifted westward away from the Marianas volcanic arc. About 25 Ma, rifting and crustal spreading began along the Izu volcanic arc to the north of the Mariana Trench region and propagated southward to form the Shikoku Basin. The opening Parece Vela and Shikoku basins became a single backarc basin around 20 Ma and crustal spreading in this huge basin continued until

Vocabulary (continued)

VERTICAL EXAGGERATION-Vertical exaggeration means that the vertical scale is larger than the horizontal scale. For example, a graph that has a 2x vertical exaggeration might have 1"=1000' in the vertical and 1"=2000' in the horizontal, a 2:1 ratio. Especially in vast ocean basins, almost all bathymetric profiles employ vertical exaggeration to highlight seafloor features.

about 15 Ma when backarc basin opening stopped. Remnants of the old Mariana arc volcanoes were carried west with the rifting and today form the Palau Kyushu Ridge. Meanwhile, volcanic activity refocused at the volcanic arc and around 10 Ma a new episode of rifting began in the south, creating the Mariana back-arc basin and the West Mariana Ridge. Crustal spreading is thought to have begun 3-4 Ma in the back-arc, and as of 2 Ma ago a new episode of rifting began in the Izu volcanic arc to the north. If these rifts follow the same pattern as seen for the combined Shikoku-Parece Vela Basin, they will at some point join and form another single large back-arc basin.

Preparation

- Read background
- Print worksheets for each student
- Print the datasheets in color for best understanding by students. Alternatively, you can print the handouts in black and white and project the color images by overhead for students to reference.
- If you will be doing the extension portions of this lesson plan, be sure you have downloaded and installed GeoMapApp on student computers. Tutorials on the use of GeoMapApp can be found at http://www.geomapapp.org/tutorials/.

Learning Procedure

Engage: Part 1 – What do you know?

To get the students thinking about the Mariana Trench and the MTMNM, begin with the two part exercise in the first section of their worksheet.

First ask the students to complete the section called "What I know" to help determine what knowledge they already have about the Mariana Trench. Most students will probably be familiar with the Challenger Deep and the Mariana Trench, but if they need some additional help to get them thinking about other things they might know, some useful guiding questions might include:

- Where is this place?
- What is this place?
- Why is this place well known?
- How did you hear about this place?

After the students complete the first section, facilitate a discussion about what they know. Finish the discussion by having the students complete the second section called "What I want to learn". You can guide this as much or as little as suits your class needs.

For some background the MTMNM, have students read the **Overview** of the Monument included with this lesson.

In addition, these fly-thru videos may help spark student interest in the Mariana Trench region (https://vimeo.com/70969375 and http://www.ngdc.noaa.gov/mgg/image/marianas.html).

Finally, students may have heard about or may be interested in the work of James Cameron and his team (http://www.deepseachallenge.com/). The website has great multimedia resources and helpful information.

Engage: Part 2 – How did that get there?

Once the students are oriented to MTMNM, they will use various types of data and their own observational skills to develop an understanding of the physical processes that form the Marianas Trench region.

The first exercise gets student to classify the bathymetry of the Marianas Trench region (datasheets; ***Figure 1: Bathymetric Map)*** into zones. Names of the features are not important at this point, merely students' observations of how the zones differ from each other.

Once students have had a chance to describe each of the zones, build a consensus diagram on an overhead (or on the board) and give the students the names of each region (as described in the Background Information) so they have a common vocabulary. After you have established this frame of reference, have the students brainstorm some reasons why each of these zones might exist.

When everyone is comfortable with the zones and descriptions, ask them to compare ***Figure 1: Bathymetric Map*** and ***Figure 2: Bathymetric Profile***. In the bathymetric profile, 0 km depth represents sea-level and the profile line is the surface of the seafloor. The shape of the seafloor profile corresponds to the bathymetric map features, so students should mark the parts of the seafloor profile that correspond to each of the zones they selected on the bathymetric map.

Once they have identified which feature in the bathymetric profile represents the Marianas Trench, have them calculate the slope of each side of the trench and graph the slope in the space provided without any vertical exaggeration. This will help them understand that though the Marianas Trench is very deep, the slope of each side of the trench is actually quite gentle. The common misconception that the Marianas Trench has steep, canyon like walls results from the tendency of cartographers to vertically exaggerate seafloor features. At the scale of ocean basins, without vertical exaggeration, seafloor features would be difficult to distinguish.

Figure 2: Bathymetric profile has a vertical exaggeration of about 200x (the vertical scale is expanded, making small changes look bigger, and the horizontal scale is compressed, making big changes look smaller).

This means that if 1 cm = 1 km on the vertical axis, on the horizontal axis 1 cm = 200 km.

This visual overview and description section make a nice homework piece. Alternatively this could be done in class with a partner.

Explore: Part 3 – Deep Quakes

Earthquake data are some of the best and most widespread data geologists have to help them understand the movement of tectonic plates. In this section, students will use earthquake data from the Marianas Trench region to better understand the movement of plates and the angle of the subducting plate.

To begin, have student write about their understanding of how earthquakes occur. Correct any misconceptions about earthquakes before moving on.

Once everyone has a clear understanding of earthquakes, have the students look at the earthquake data in ***Figure 3: Earthquake Depths.*** Each recorded earthquake is represented by a colored dot, and the dot color indicates the depth range of the hypocenter of the earthquake. On the bottom of ***Figure 3: Earthquake Depths,*** ask students to color in the range of longitudes over which the earthquakes occur at each depth (see ANWSER KEY for an example). These earthquake data highlight the interface between the two tectonic plates and the angle at which the Pacific Plate subducts beneath the Philippine Sea Plate. The accompanying questions in this section are designed to help students solidify their understanding of plate motion in a subduction zone.

Explain: Part 4 – How do you like your melt?

Now that students understand a little bit more about the relative motion of tectonic plates, this section will help them understand what happens to the Pacific Plate as it is subducted. The goal of this section is to give them some background on the temperature and pressure relationships that occur within a plate as it descends into a subduction zone. Note: On ***Figure 3: Earthquake Depths,*** you may want to have the students draw a line through their shaded regions to show the arc of the Pacific Plate as it subducts beneath the Philippine Sea Plate (see example in the ANSWER KEY).

This section begins by asking students to study a model, by Rüpke *et al*. (2004), of how sediment, crust, and mantle release water as they get deeper into a subduction zone. You may need to spend some time helping students understand the components of the graph. Note the assumption that each component (sediment, crust, mantle) is fully saturated when it leaves the surface. Water release occurs at different depths depending on the component, with water release from sediments occurring first. As this water rises up through cracks and faults in the edge of the Philippine Sea Plate it converts surrounding mantle rock into serpentine. A slurry of water, ground up low density serpentine, and chunks of unaltered mantle rocks from the walls of the faults eventually oozes out onto seafloor, creating mud volcanoes found near the edge of the Trench.

Water is more tightly bound in the crust and mantle and so is retained until the much deeper into the subduction zone (ie, further away from the point is leaves the seafloor at the bottom of the Marianas Trench). When these components do **dewater**, the water rising toward the surface through faults and cracks lowers the melting temperature of the surrounding peridotite mantle rock. Low density, hot, melted peridotite then rises toward the seafloor and erupts, forming the Mariana arc volcanoes.

By combining the data in ***Figure 3: Earthquake Depths***, and ***Figure 4: Dewatering***, students should be able to identify these relationships. The questions in the first section of Part 4 help scaffold their understanding of these relationships.

The second half of Part 4 investigates *how* water loss from the plate components helps create different kinds of features at the surface. This introduces students to the idea of a **geotherm** and a **solidus**. The plotting exercise for the geotherm and the soliduses is simple, though it may be time consuming. It is included to ensure that students are very familiar with the data before they begin making interpretations. As such, it may make a good homework piece.

As a group, read aloud the introduction to geotherms and soliduses. It may be helpful to stop and check for student understanding at this point. A cross-section diagram on the board may aid students in visualizing the relationships of tectonic plates in a subduction zone and how pressure and temperature change with depth. Key concepts are that pressure increases linearly with depth in the lithosphere, but temperature does not. Also, the melting temperature of *dry* peridotite increases linearly with pressure, but the melting temperature of *wet* peridotite does not. Once students clearly understand these pressure and depth relationships, have them use their plotted data to answer Questions 6-8 on their worksheet.

Explain: Part 5 – Slow and steady destroys the plate

Get students thinking about the importance of volcanoes by having them brainstorm ideas with a partner. Ask them to record their ideas in the space provided at the beginning of ***Part 5: Slow and steady destroys the plate,*** and then discuss student answers as a group.

To ensure that students understand how heat alters the brittle/ductile nature of tectonic plates, have them test model tectonic plates with different heating regimes. The exercise is designed to be a free form exploration. It works best if the students work in groups and have access to a freezer and a heat source, such as a heat lamp, microwave, or Bunsen burner. Airhead candy, sticks of chewing gum, or chewy granola bars work well as model tectonic plates (2-3 per group). The students should come up with ways to test how different heating regimes alter how their model tectonic plate breaks. For example they could try placing one model plate in the freezer, leaving another at room temperature, and gently warming a third with a heat lamp. After 10 minutes they test how easy it is to break each plate, and record how the plate breaks. They should see that cold plates are more brittle and tend to shatter when broken, whereas warmer plates are more ductile and tend to stretch as they break. A variation on the setup above might be to take a cold plate and to only warm a small section of the plate before breaking.

After they have developed an understanding of how heat alters the way a plate breaks, have them answer Questions 1-8 in ***Part 5: Slow and steady destroys the plate.***

Evaluate: Part 6 – Cruise summary

As a check for student understanding, have them complete the "What I learned about the Marianas Trench" section of their worksheet. For a more comprehensive summative assessment, have individuals or groups of students create a cross-sectional model showing all the processes that helped form the bathymetry in the region of the Marianas Trench. The complexity of this modeling assignment can be tailored to suit individual class needs.

Extending the Lesson

The processes described in this lesson, while spectacularly demonstrated in the MTMNM, are not unique to this area. To extend this lesson and further solidify students' understanding of the processes involved, ask students to identify other places on Earth where similar processes are taking place. Students can explore the seafloor bathymetry using the GeoMapApp tool. Ask them to identify other areas where oceanic-oceanic plate convergences are occurring. In addition you can have them identify other volcanic island arcs and back-arc spreading areas. For a further challenge, have students identify possible locations of oceanic-continental plate convergences and ask them to describe which geologic features are the same and different from oceanic-oceanic plate convergences.

There is an excellent opportunity to extend the portion of this lesson regarding vertical exaggeration. To help students develop a deeper understanding of vertical exaggeration, have them use a ruler to calculate the vertical exaggeration of Figure 2 in the datasheet. You can then have them reconstruct part of the graph (trench perhaps) at other exaggerations to see how that changes the appearance of the data.

Connections to Other Subjects

- Chemistry
- Physics
- Biology

- Technology
- Mathematics
- Cartography

Related Links

Census of Marine Life
Pacific Islands Fisheries Science Center
NOAA Marine National Monument Program
NOAA Fisheries Pacific Islands Regional Office
Papahānaumokuākea Marine National Monument
R/V Oscar Elton Sette

For More Information

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All images are from NOAA unless otherwise cited.

Thank you to all the reviewers for their feedback and assistance.

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Education Standards

Next Generation Science Standards	• MS-ESS2-3. – Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions. [Clarification Statement: Examples of data include similarities of rock and fossil types on different continents, the shapes of the continents (including continental shelves), and the locations of ocean structures (such as ridges, fracture zones, and trenches).] [Assessment Boundary: Paleomagnetic anomalies in oceanic and continental crust are not assessed.] • MS-ESS3-1. – Construct a scientific explanation based on evidence for how the uneven distributions of Earth's mineral, energy, and groundwater resources are the result of past and current geoscience processes. [Clarification Statement: Emphasis is on how these resources are limited and typically non-renewable, and how their distributions are significantly changing as a result of removal by humans. Examples of uneven distributions of resources as a result of past processes include but are not limited to petroleum (locations of the burial of organic marine sediments and subsequent geologic traps), metal ores (locations of past volcanic and hydrothermal activity associated with subduction zones), and soil (locations of active weathering and/or deposition of rock).] • 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. [Clarification Statement: Emphasis is on the ability of plate tectonics to explain the ages of crustal rocks. Examples include evidence of the ages oceanic crust increasing with distance from mid-ocean ridges (a result of plate spreading) and the ages of North American continental crust increasing with distance away from a central ancient core (a result of past plate interactions).] • 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. [Clarification Statement: Emphasis is on how the appearance of land features (such as mountains, valleys, and plateaus) and sea-floor features (such as trenches, ridges, and seamounts) are a result of both constructive forces (such as volcanism, tectonic uplift, and orogeny) and destructive mechanisms (such as weathering, mass wasting, and coastal erosion).] • HS-ESS2-5. –Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes. [Clarification Statement: Emphasis is on mechanical and chemical investigations with water and a variety of solid materials to provide the evidence for connections between the hydrologic cycle and system interactions commonly known as the rock cycle. Examples of mechanical investigations include stream transportation and deposition using a stream table, erosion using variations in soil moisture content, or frost wedging by the expansion of water as it freezes. Examples of chemical investigations include chemical weathering and recrystallization (by testing the solubility of different materials) or melt generation (by examining how water lowers the melting temperature of most solids).]
Ocean Literacy Principles	• 1 – The Earth has one big ocean with many features. • 1B – Ocean basins are composed of the seafloor and all of its geological features (such as islands, trenches, mid-ocean ridges, and rift valleys) and vary in size, shape and features due to the movement of Earth's crust (lithosphere). Earth's highest peaks, deepest valleys and flattest plains are all in the ocean. • 5E – The ocean provides a vast living space with diverse and unique ecosystems from the surface through the water column and down to, and below, the seafloor. Most of the living space on Earth is in the ocean. • 5G - There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps, rely only on chemical energy and chemosynthetic organisms to support life. • 6G - Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. Individual and collective actions are needed to effectively manage ocean resources for all.

Marianas Trench Marine National Monument: Overview

There are a few places on Earth so unique and unusual that they warrant special attention and protection. The Marianas Archipelago, though only partially explored, is one of these places. Located east of the Philippines in the Western Pacific Ocean, this region encompasses both geological and biological environments seen nowhere else on Earth. Recognizing the uniqueness of this area, President George W. Bush in 2009 used the Antiquities Act of 1906 to establish the Marianas Trench Marine National Monument. The importance of this region was described in the presidential proclamation as follows:

"Over approximately 480 nautical miles, the Mariana Archipelago encompasses the 14 islands of the United States Commonwealth of the Northern Mariana Islands and the United States Territory of Guam that sit atop the Mariana Ridge in an area known as the Mariana Volcanic Arc. The Mariana Volcanic Arc is part of a subduction system in which the Pacific Plate plunges beneath the Philippine Sea Plate and into the Earth's mantle, creating the Mariana Trench. Six of the archipelago's islands have been volcanically active in historic times, and numerous seamounts along the Mariana Ridge are volcanically or hydrothermically active. The Mariana Trench is approximately 940 nautical miles long and 38 nautical miles wide within the United States Exclusive Economic Zone and contains the deepest known points in the global ocean.

The Mariana Volcanic Arc contains objects of scientific interest, including the largest active mud volcanoes on Earth. The Champagne vent, located at the Eifuku submarine volcano, produces almost pure liquid carbon dioxide. This phenomenon has only been observed at one other site in the world. The Sulfur Cauldron, a pool of liquid sulfur, is found at the Daikoku submarine volcano. The only other known location of molten sulfur is on Io, a moon of Jupiter. Unlike other reefs across the Pacific, the northernmost Mariana reefs provide unique volcanic habitats that support marine biological communities requiring basalt. Maug Crater represents one of only a handful of places on Earth where photosynthetic and chemosynthetic communities of life are known to come together.

The waters of the archipelago's northern islands are among the most biologically diverse in the Western Pacific and include the greatest diversity of seamount and hydrothermal vent life yet discovered. These volcanic islands are ringed by coral ecosystems with very high numbers of apex predators, including large numbers of sharks. They also contain one of the most diverse collections of stony corals in the Western Pacific. The northern islands and shoals in the archipelago have substantially higher large fish biomass, including apex predators, than the southern islands and Guam. The waters of Farallon de Pajaros (also known as Uracas), Maug, and Asuncion support some of the largest biomass of reef fishes in the Mariana Archipelago. These relatively pristine coral reef ecosystems are objects of scientific interest and essential to the long-term study of tropical marine ecosystems."

-Presidential Proclamation 8335, January 12, 2009

The Marianas Trench Marine National Monument (Monument) protects approximately 95,216 square miles of submerged lands and waters in three separate units: the Islands Unit, which includes the waters and submerged lands of the three northernmost Mariana Islands; the Volcanic Unit, which includes the submerged lands within 1 nautical mile of 21 designated volcanic sites; and the Trench Unit, which includes the submerged lands extending from the northern limit of the Exclusive Economic Zone of the United States in the Commonwealth of the Northern Mariana Islands (CNMI) to the southern limit of the Exclusive Economic Zone of the United States in the Territory of Guam.

The Monument is managed by the Secretary of the Interior, in consultation with the Secretary of Commerce, though any fishery-related activities in the waters of the Islands Unit are primarily managed by the National Oceanic and Atmospheric Administration (NOAA). Additionally, the Marianas Trench and Volcanic Units have been included within the National Wildlife Refuge System, and the interior secretary delegated his management responsibility in the Monument to the Fish and Wildlife Service. Jointly the Secretaries have established a Marianas Trench Monument Advisory Council (Council) to provide advice and recommendations on the development of management plans and management of the Monument. The Council currently includes three officials of the Commonwealth of the Northern Mariana Islands government and one representative each from the Department of Defense and the U.S. Coast Guard.

Sources

Marianas Trench Marine National Monument
http://www.fpir.noaa.gov/MNM/mnm_marianas-trench.html

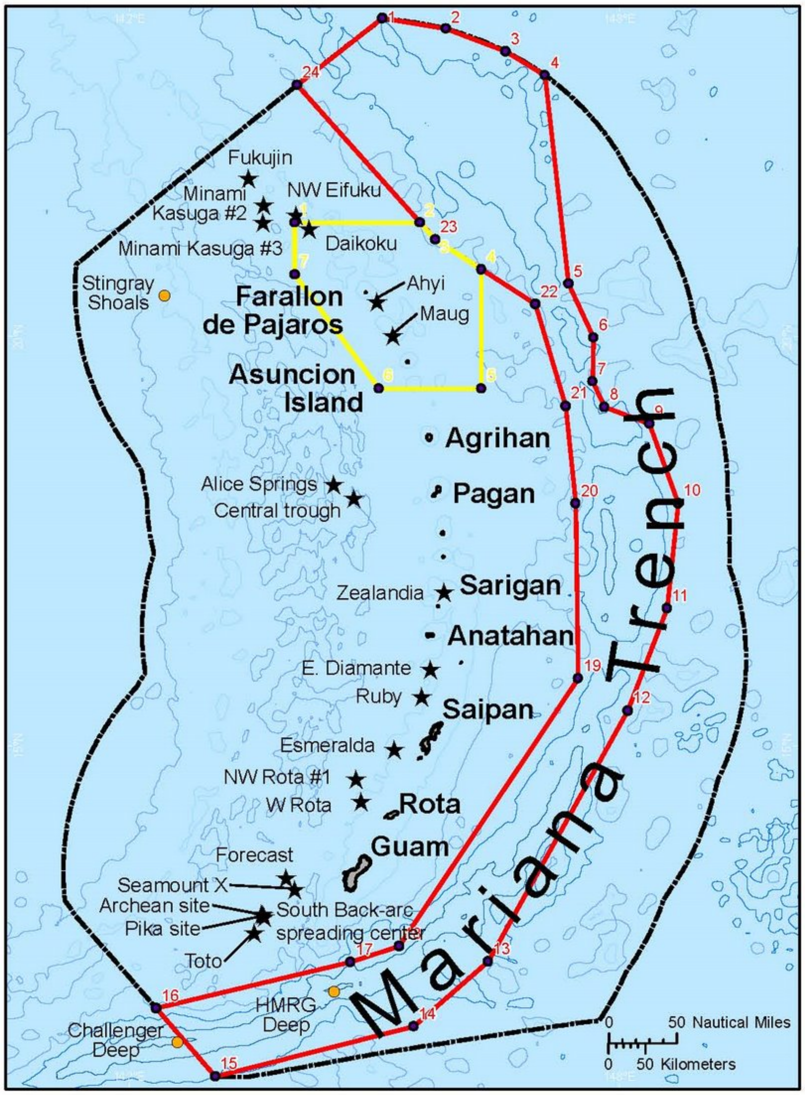
http://www.fws.gov/refuge/mariana_trench_marine_national_monument/

http://www.fpir.noaa.gov/MNM/mnm_mtmac.html

NOAA Marine National Monument Program
http://www.fpir.noaa.gov/MNM/mnm_index.html

Presidential Proclamation
http://www.fpir.noaa.gov/Library/MNM/Proclamation%208335%20-%20Marianas%20Trench.pdf

Mariana Trench
Marine National Monument



Trench Unit

Id	Longitude	Latitude
1	145° 5' 46" E	23° 53' 35" N
2	145° 52' 27.10" E	23° 45' 50.54" N
3	146° 36' 18.91" E	23° 29' 18.33" N
4	147° 5' 16.84" E	23° 11' 43.92" N
5	147° 22' 31.43" E	20° 38' 41.35" N
6	147° 40' 48.31" E	19° 59' 23.30" N
7	147° 39' 59.51" E	19° 27' 2.96" N
8	147° 48' 51.61" E	19° 8' 18.74" N
9	148° 21' 47.20" E	18° 56' 6.46" N
10	148° 42' 50.50" E	17° 58' 2.20" N
11	148° 34' 47.12" E	16° 40' 53.86" N
12	148° 5' 39.95" E	15° 25' 51.09" N
13	146° 23' 24.38" E	12° 21' 38.38" N
14	145° 28' 33.28" E	11° 34' 7.64" N
15	143° 3' 9" E	10° 57' 30" N
16	142° 19' 54.93" E	11° 47' 24.83" N
17	144° 42' 31.24" E	12° 21' 24.65" N
18	145° 17' 59.93" E	12° 33' 5.35" N
19	147° 29' 32.24" E	15° 49' 25.53" N
20	147° 27' 32.35" E	17° 57' 52.76" N
21	147° 20' 16.96" E	19° 9' 19.41" N
22	146° 57' 55.31" E	20° 23' 58.80" N
23	145° 44' 31.14" E	21° 11' 14.60" N
24	144° 5' 27.55" E	23° 2' 28.67" N

Islands Unit

Id	Longitude	Latitude
1	144° 1' 22.97" E	21° 23' 42.40" N
2	145° 33' 25.20" E	21° 23' 42.40" N
3	145° 44' 31.14" E	21° 11' 14.60" N
4	146° 18' 36.75" E	20° 49' 17.46" N
5	146° 18' 36.75" E	19° 22' 0.00" N
6	145° 3' 12.22" E	19° 22' 0.00" N
7	144° 1' 22.97" E	20° 45' 44.11" N

Vents Unit

Volcano	Longitude	Latitude
Fukujin	143° 27' 30" E	21° 56' 30" N
Minami Kasuga #2	143° 38' 30" E	21° 36' 36" N
NW Eifuku	144° 2' 36" E	21° 29' 15" N
Minami Kasuga #3	143° 38' 0" E	21° 24' 0" N
Daikoku	144° 11' 39" E	21° 19' 27" N
Ahyi	145° 1' 45" E	20° 26' 15" N
Maug	145° 13' 18" E	20° 1' 15" N
Alice Springs	144° 30' 0" E	18° 12' 0" N
Central trough	144° 45' 0" E	18° 1' 0" N
Zealandia	145° 51' 4" E	16° 52' 57" N
E. Diamante	145° 40' 47" E	15° 56' 31" N
Ruby	145° 34' 24" E	15° 36' 15" N
Esmeralda	145° 14' 45" E	14° 57' 30" N
NW Rota #1	144° 46' 30" E	14° 36' 0" N
W Rota	144° 50' 0" E	14° 19' 30" N
Forecast	143° 55' 12" E	13° 23' 30" N
Seamount X	144° 1' 0" E	13° 14' 48" N
South Backarc	143° 37' 8" E	12° 57' 12" N
Archaean site	143° 37' 55" E	12° 56' 23" N
Pika site	143° 38' 55" E	12° 55' 7" N
Toto	143° 31' 42" E	12° 42' 48" N

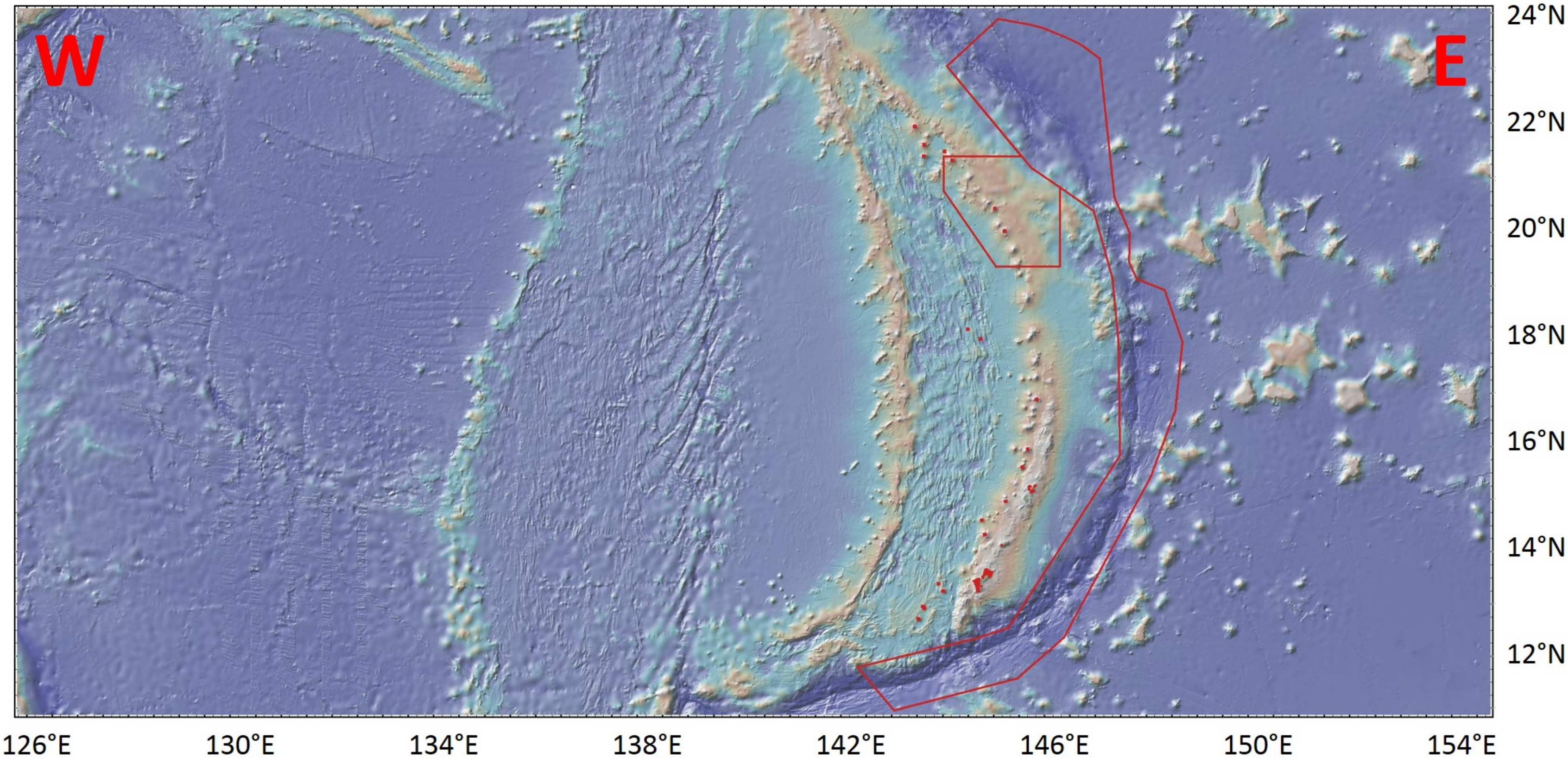
Sources:
NOAA Coral Reef Conservation Program
NMFS Coral Reef Ecosystem Division
NESDIS NGDC
NOS/CCMA Biogeography Branch
OAR Pacific Marine Environmental Lab

-10000 m
-8000 m
-6000 m
-4000 m
-2000 m

★ Active Hydrothermal Submarine Volcanoes
Trench Unit (59,732 nm²)
Islands Unit (12,388 nm²)
EEZ

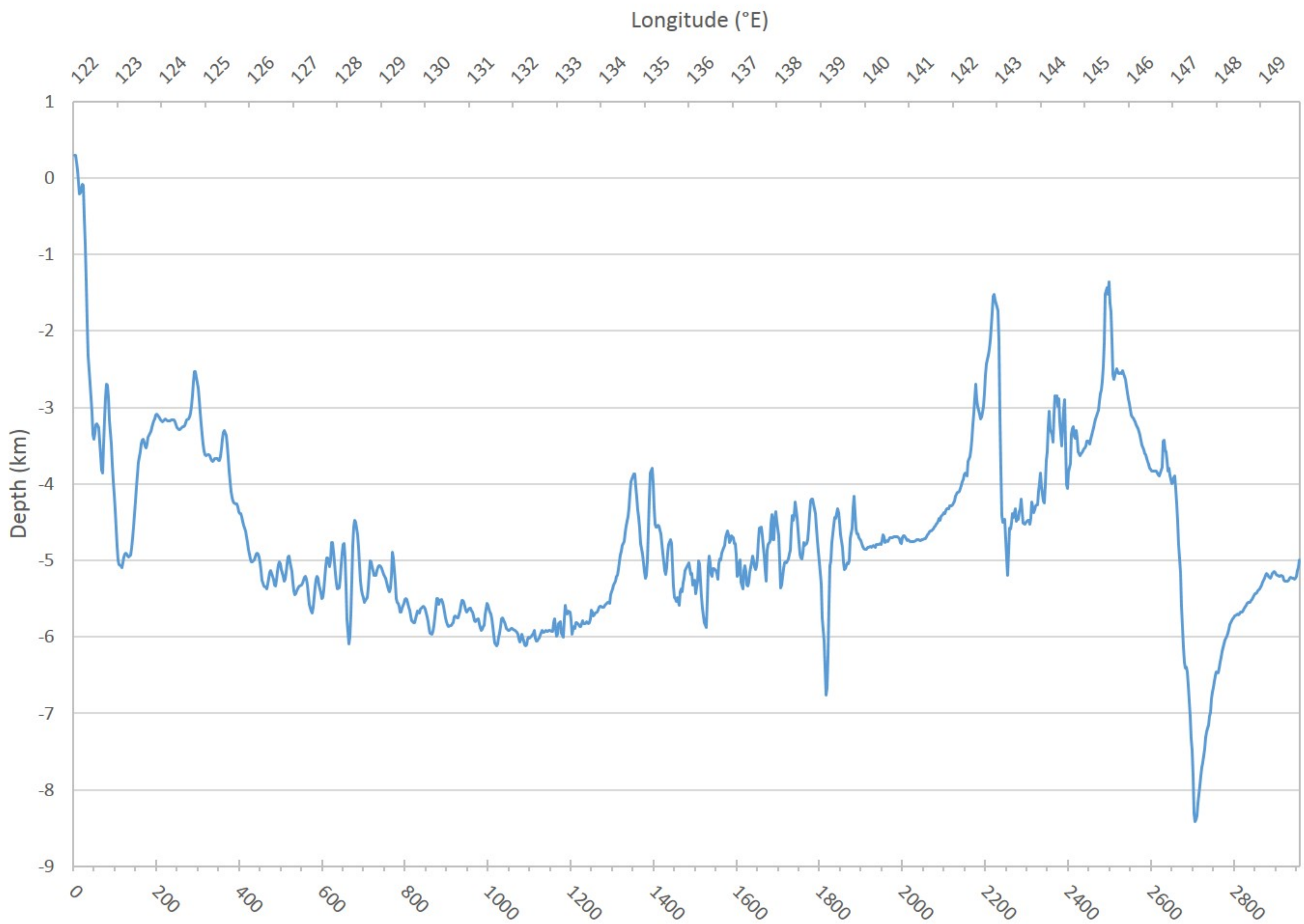
Marianas Trench Marine National Monument: Datasheets

Figure 1: Bathymetric Map



Source: GeoMapApp

Figure 2: Bathymetric Profile



Source: GeoMapApp

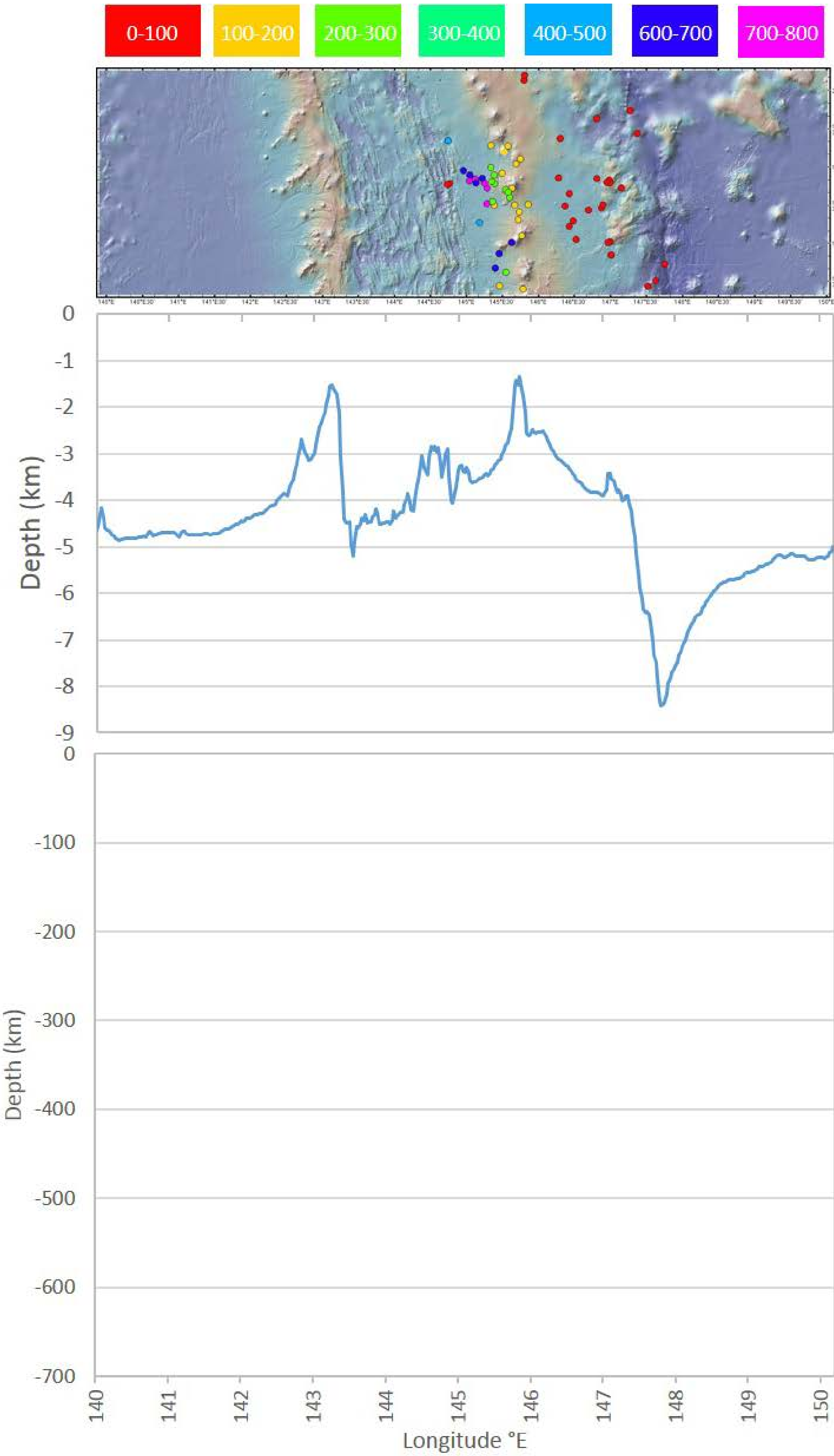
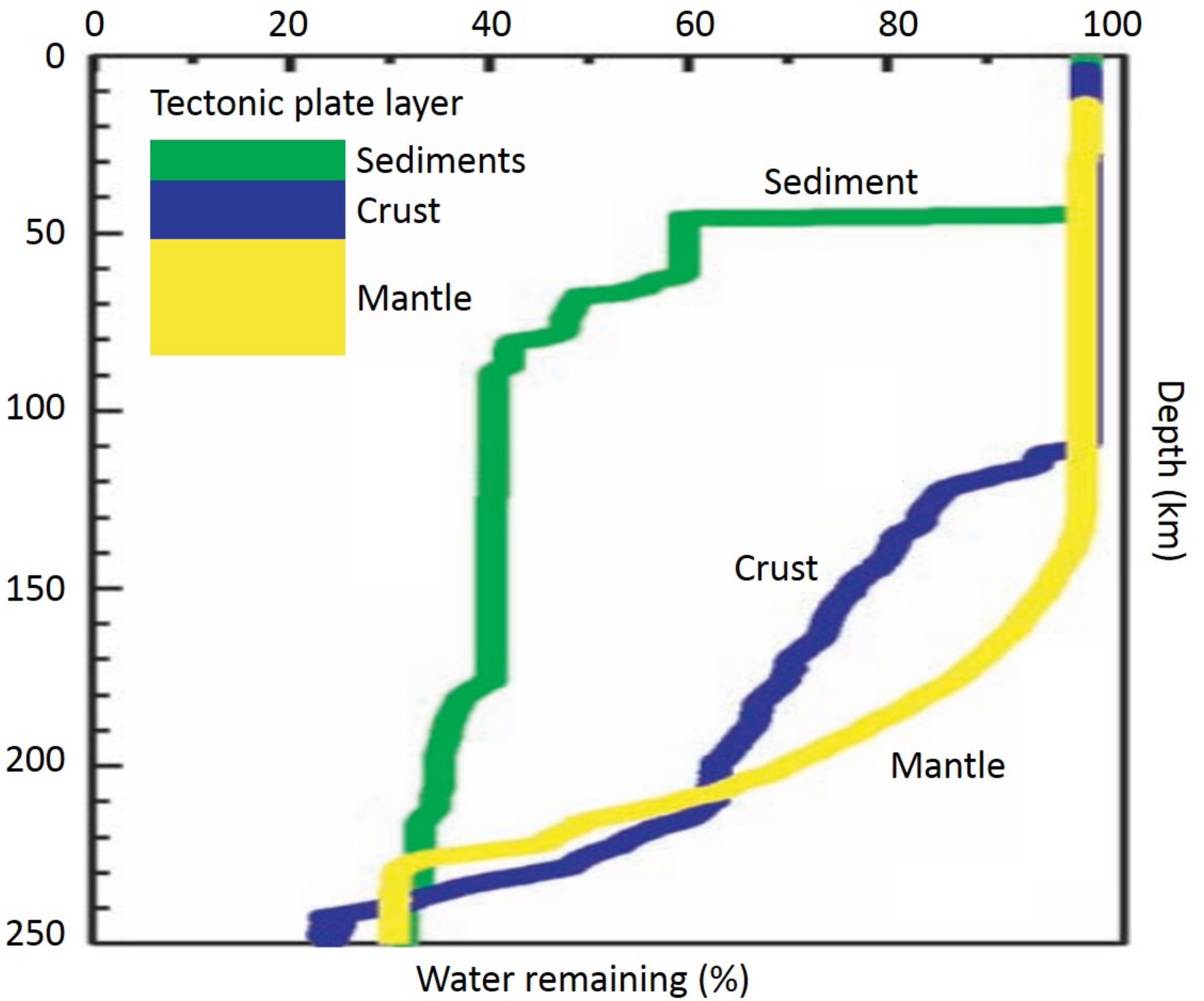


Figure 3: Earthquake Depths

Figure 4: Dewatering



(modified from Rüpke et al (2004)

Figure 5: Peridotite Melting

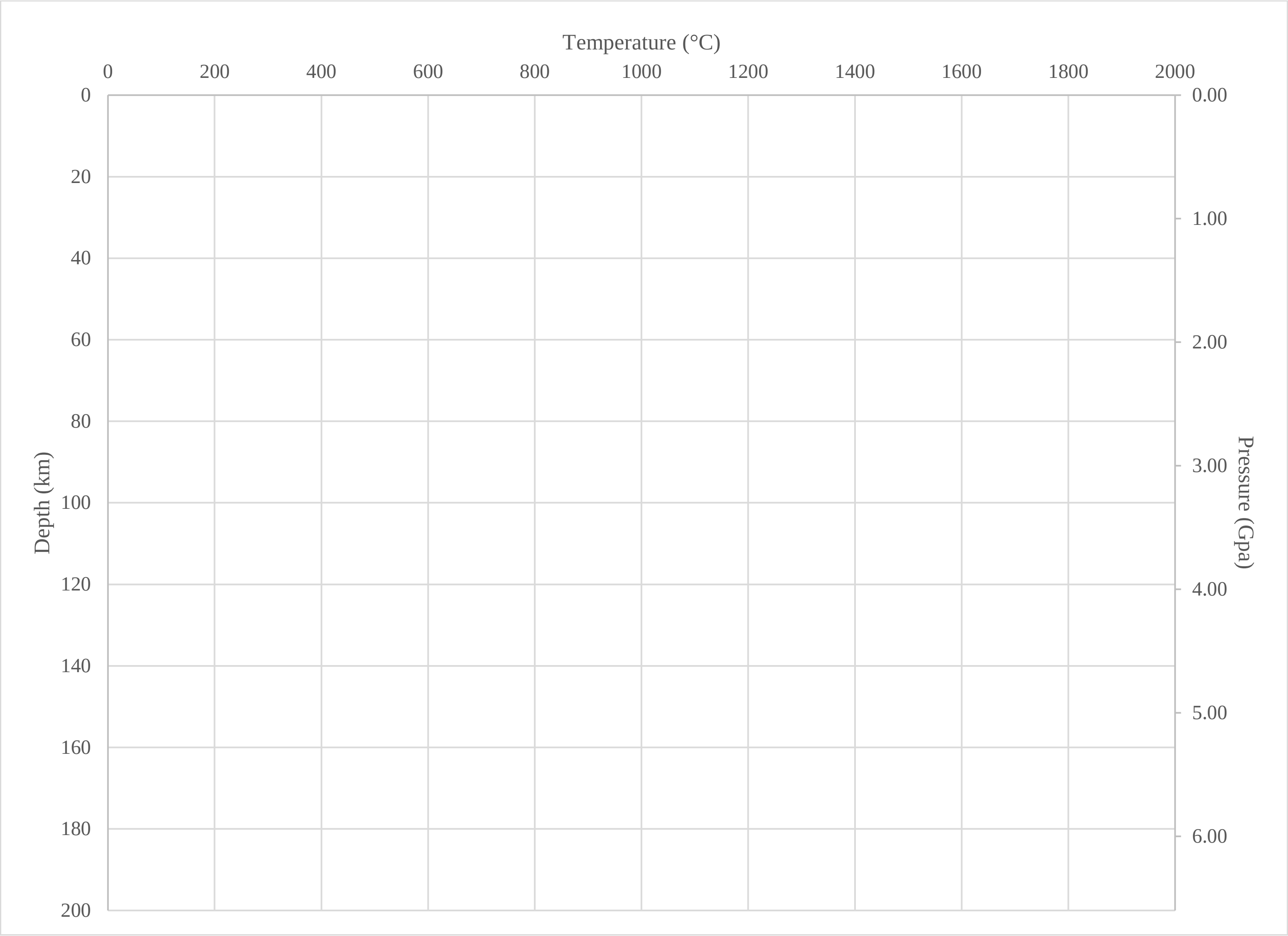
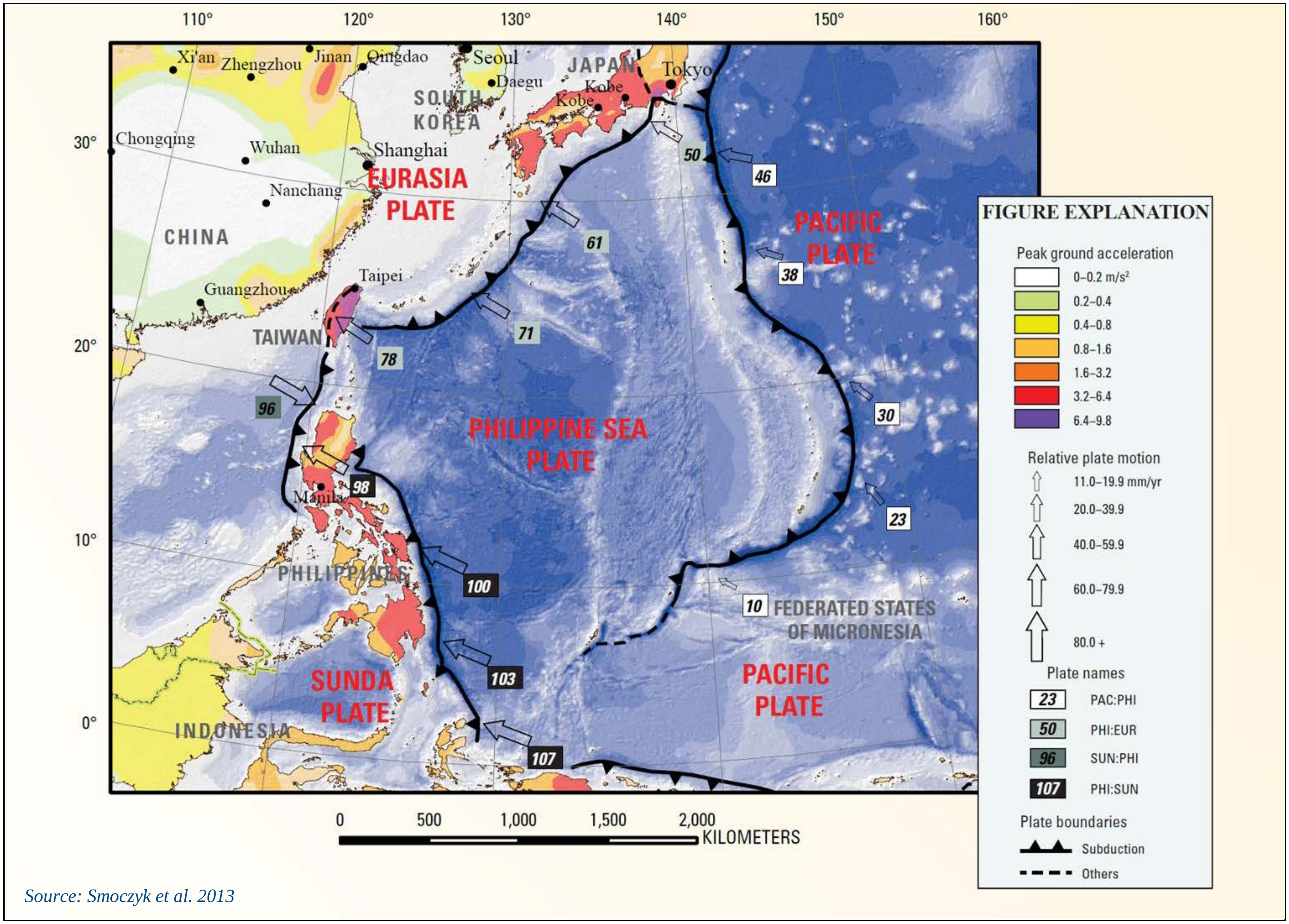


Figure 6: Seismic Hazards and Relative Plate Motion



Source: Smoczyk et al. 2013

Marianas Trench Marine National Monument: Tectonic Evolution Student Worksheet

Name____ Date_____________________________________

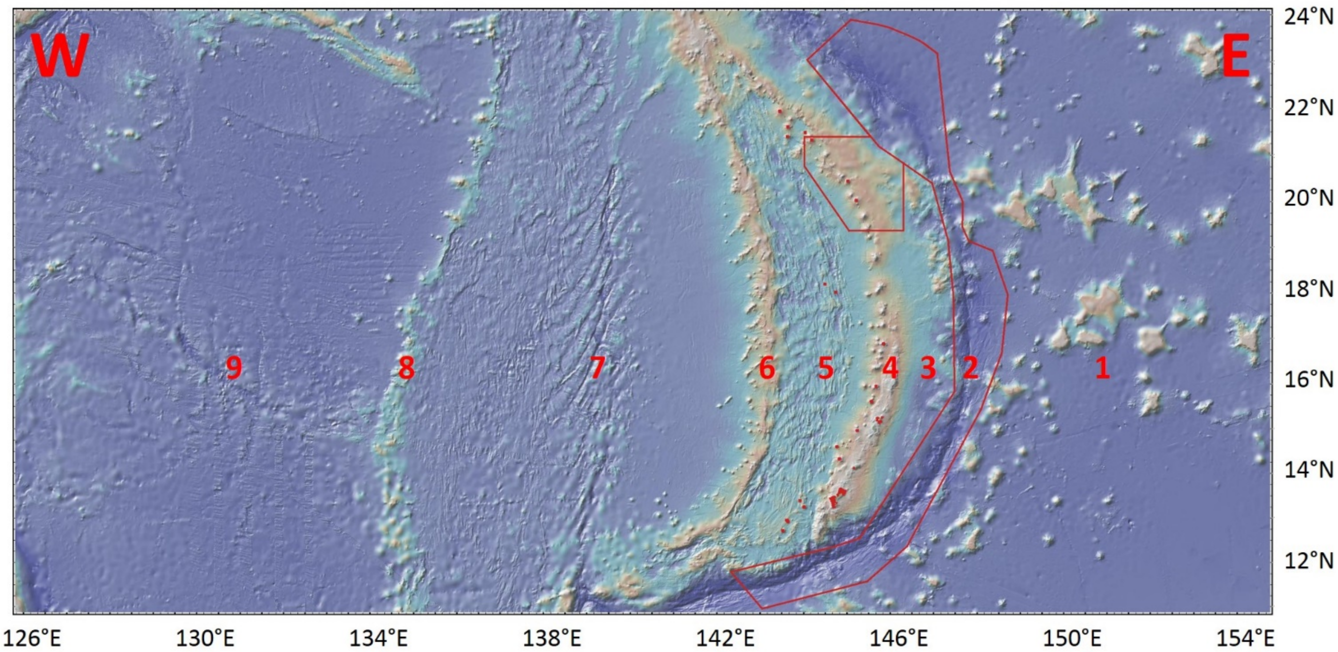
Part 1: What do you know?

What I **know** about the Marianas Trench
What I want to **learn** about the Marianas Trench

Part 2: How did THAT get there?

Figure 1 is a map of seafloor **bathymetry**, or the depth of landforms below sea level. To understand this image it is helpful to know that dark colors = deep depths, and light colors = shallow depths. The lines indicate the boundaries of the Marianas Trench Marine National Monument.

1. On the figure, from East to West number the different seafloor zones you see.
2. Describe the characteristics of each zone in Question 1. Hints: Is the seafloor shallow or deep? What features are on the seafloor? Mountains? Valleys? What trends do you see in the features on the seafloor? What texture (e.g. smooth, bumpy, fractured, etc.) does the seafloor have?



1. ***Pacific plate:*** *a deep abyssal plain dotted irregularly with seamounts (remnant volcanoes).*
2. ***Mariana Trench:*** *Deepest part of the seafloor where the Pacific Plate is subducting beneath the Philippine Sea Plate. Has a noticeable arc appearance.*
3. ***Mariana Forearc:*** *Leading edge of the overriding Philippine Sea Plate. The region follows the same arc as the trench and has clusters of mud volcanoes and seamounts on the edge close to the Trench. This region is shallower in the north and deeper in the south.*
4. ***Mariana Arc Volcanoes:*** *Volcanic region that follows the arc of the Trench and characterized by regularly spaced stratovolcanoes. The region is mostly shallow and has smooth seafloor surrounding each of the volcanoes.*
5. ***Mariana back-arc basin:*** *Follows the arcuate shape of the Trench. Wider in the south than in the north. Lots of striations (faults) on the seafloor form many ridges and valleys that give this region its crinkled appearance.*
6. ***West Mariana Ridge:*** *These are the remnants of an older set of arc volcanoes that split when the second episode of rifting began along the Mariana arc ~10 Ma.*

7. ***Parece Vela basin:*** *A wide flat basin bisected by a faulted/folded region in the center that is the remnants of a former spreading center. This basin was created by rifting and crustal spreading between ~29-15 Ma. During this time the Parece Vela basin from the south and Skikoku basin from the north merged to form one giant basin.*
8. ***Kyushu-Palau Ridge:*** *These are the remnants of an older set of arc volcanoes that split with the first episode of rifting that created the Parece Vela Basin.*
9. ***West Philippine Basin:*** *large mostly flat basin with a few scattered seamounts and a noticeable trough bisecting the region from SE-NW. A shallow ridge in the northern part of the basin mirrors the trend of the central trough.*

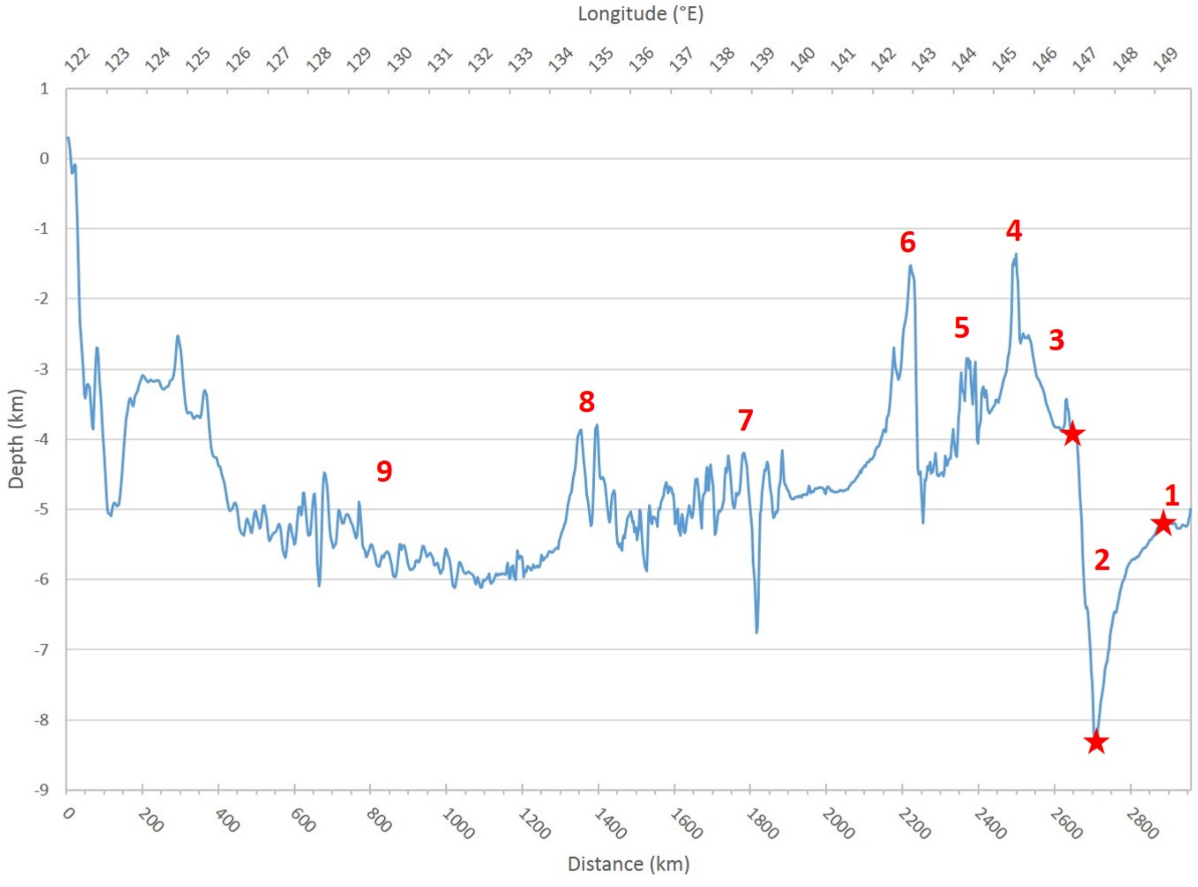
Figure 2 is a **bathymetric profile** across the Marianas Trench region at ~17°N. This profile is a plot of seafloor depth (below the surface of the ocean) vs. longitude/distance.

3. On ***Figure 1*** draw a line to indicate where this bathymetric profiles occurs on the map.

   Self-explanatory – the line should be drawn across the figure at 17°N

4. Next, using the same zone numbers you determined in Question 1, label each zone on the bathymetric profile and label the Marianas Trench.

   The goal of this exercise is to help student translate between different types of data that represent the same physical area.



5. Calculate the percent slope of the E and W sides of the Marians Trench and show your work in the space below (Remember, slope is rise over run, or in this case, the change in depth over the change in distance. Multiply your answer by 100 to get percent slope.).

   The goal of this exercise and the following questions is to have students use graphical data to determine the physical characteristics of the Marianas Trench. In addition, this exercise should help them understand that graphical displays of data often exaggerate data to make it easier to understand. Locations of the top and bottom of the Trench for calculation purposes are indicate by the red stars on the figure above.

   East side slope:

   Rise: |-8.4 km –(-5.2 km)| = 3.2km

   Run: |2700 km -2875 km| = 175 km

   *Slope = rise/run = 3.2 km/175 km = 0.018 * 100 = 1.8% slope*

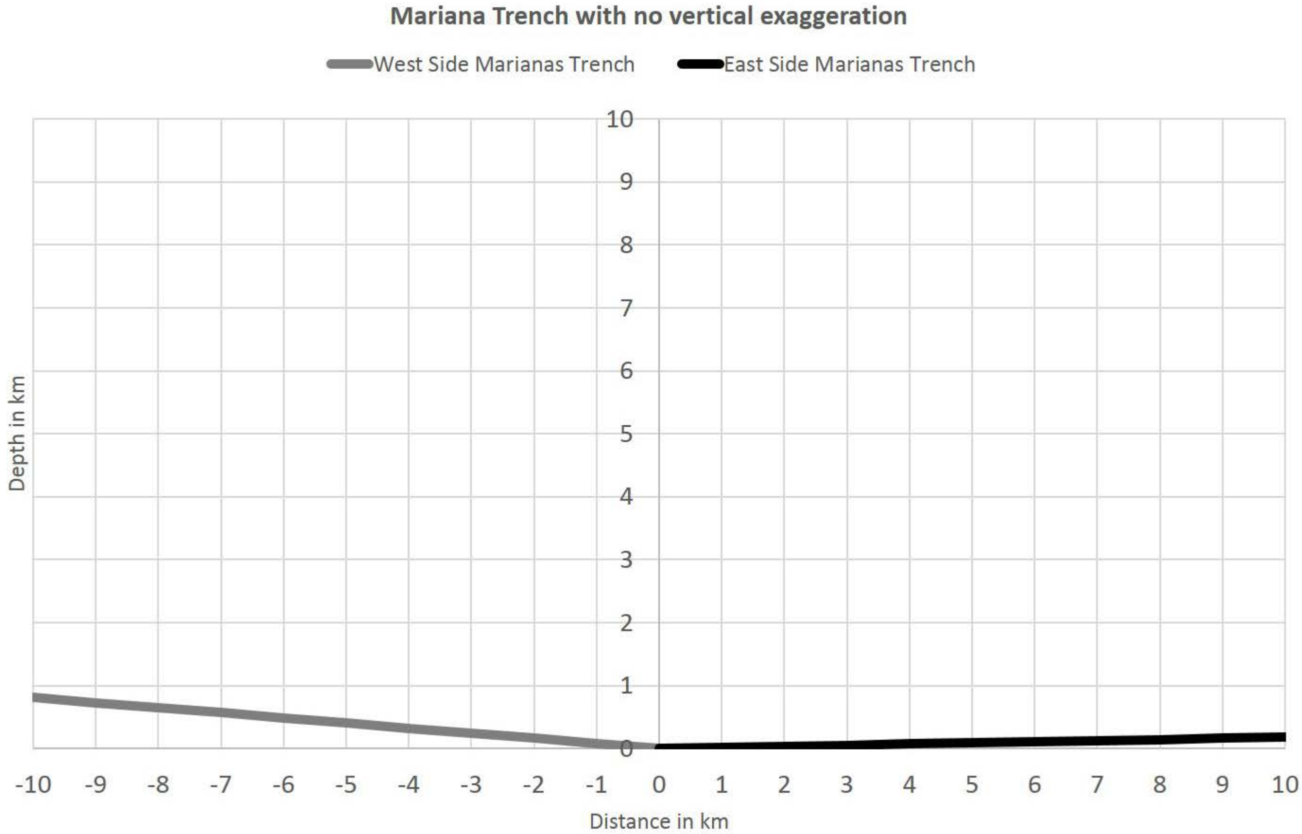
   West side slope:

   Rise: |-8.4 km –(-3.9 km)| = 4.5km

   Run: |2645 km -2700 km| = 55 km

   *Slope = rise/run = 4.5 km/55 km = 0.081 * 100 = 8.1% slope*

6. Graph the slope of each side of the trench without any **vertical exaggeration** in the graph below. *(Note: A graph with no vertical exaggeration will have the same scale for the X and Y axes.).*



7. Why might you use **vertical exaggeration** when displaying graphical data?

   When displaying data where trends in the vertical are much smaller than trends in the horizontal (e.g. height of mountains (10s of km) vs length of a mountain range (1000s of km)) vertical exaggeration can make the vertical trends easier to see. By exaggerating the vertical (Y) scale you can better highlight small changes that might be important. However, vertical exaggeration also distorts shape of the trend, which can lead to misunderstandings about the actual shape of data. This is part of the reason many people think of the Marianas Trench as a narrow canyon with steep sided walls, when in actuality the Trench as very gently sloping sides.

8. Which side of the Trench has a steeper slope? Imagine what it would be like if you were walking along the ocean floor into the Marianas Trench. What clues, other than slope, might indicate you were getting deeper into the Trench?

   The west side of the Trench has a steeper slope (8.1% vs 1.8%), though both side have very gentle slopes. If you were walking into the Trench it would be difficult to tell that you were doing so just by the slope of the ocean floor. Other clues to increasing water depth include increasing water pressures, changes in biological communities, and changes in the type of sediments on the ocean floor (carbonate compensation depth).

Part 3: Deep Quakes

Earthquake data have been a very important source of information for scientists studying the formation of the Marianas Trench.

1. How do earthquakes occur?

   From previous work students should have a basic understanding of how earthquakes occur. They should be able to describe that earthquakes occur when two plates or sections of rock move past each other. The friction between the plates/rock causes them to "stick" together and strain builds up where the plates stick together. Ultimately these sticking points fail catastrophically and causing the plates to move and readjust to a new position. This movement results in seismic waves that travel through the Earth and may result in serious damage at the surface of the Earth.

The top section of ***Figure 3*** shows a small subsection of the Marianas Trench region displaying earthquake data collected by the United States Geological Survey and the National Earthquake Information Center. Each dot represents the location of an earthquake of magnitude 5.5 or greater and the color indicates the depth where the fault begins to rupture, or the **hypocenter** of the earthquake. Answer the following question regarding the patterns of earthquakes in the region.

2. How does the number of earthquakes vary with depth?

   There are more shallow earthquakes than deep earthquakes. Note: this is because at deeper depths the plates are more ductile and so tend to deform rather than break, which is less likely to cause an earthquake.

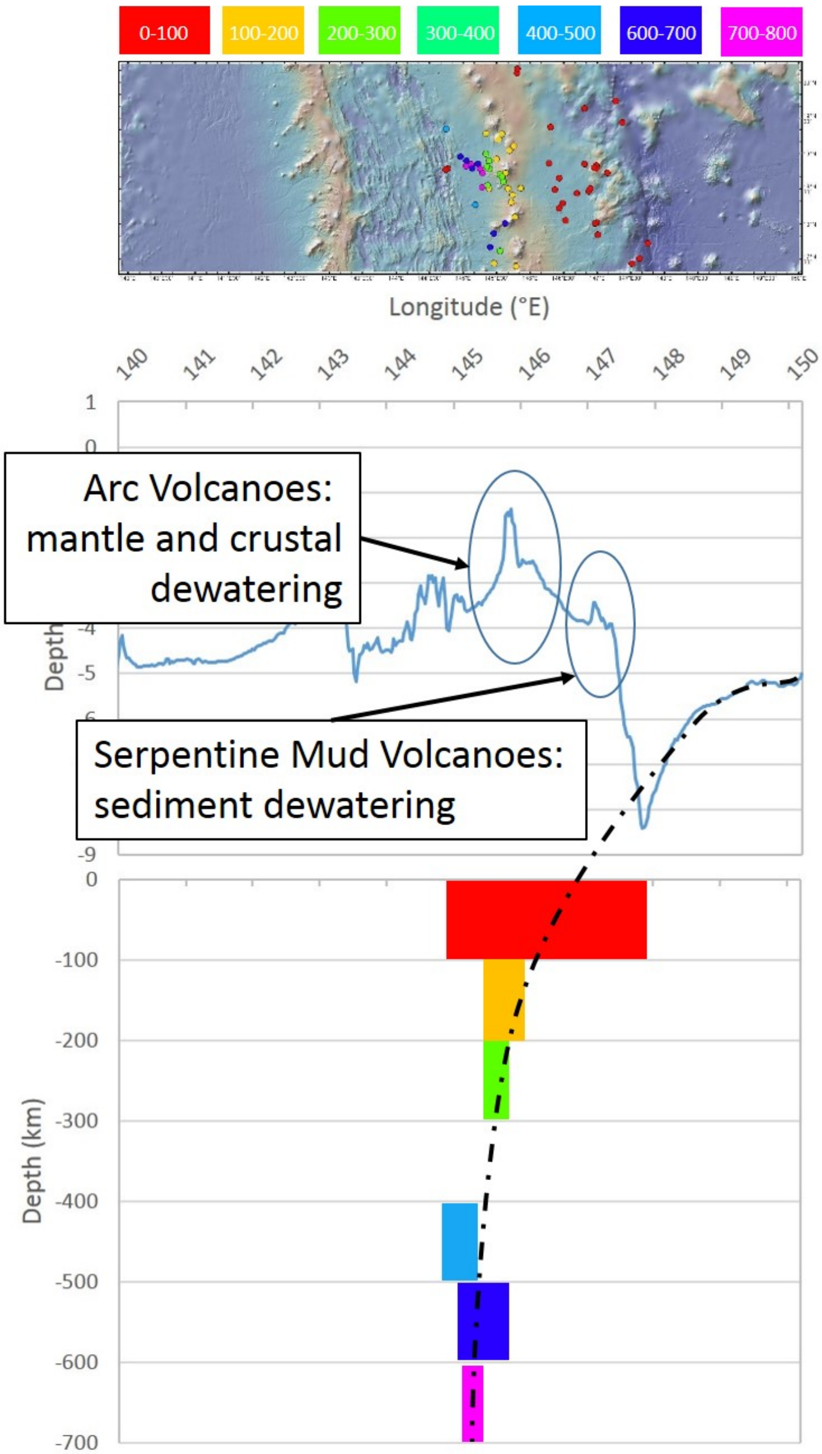
3. How do the locations of earthquakes change with depth?

   Generally the earthquakes move westward with depth, though at some depths the earthquakes appear to occur at approximately the same longitudes.

The center section of ***Figure 3*** is the bathymetric profile across the Marianas Trench region at ~17°N Latitude. Use the earthquake information from the top section and what you know about the bathymetry from the middle section to shade in the range longitudes where earthquakes occur at each depth in the bottom section of the figure. Once you are done answer the following questions:

1. Based on the earthquake data you just plotted and what you know of earthquakes, what must be happening at and below the Marianas Trench to cause these earthquakes? How is this related to the location of the earthquakes?

   At and below the Marianas Trench rocks are sliding past each other and their rough surfaces catch on each other building up strain in the process. When too much strain accumulates, the friction points on the surface will break or deform, catastrophically releasing built up energy and causing an Earthquakes. The deep earthquakes indicate that the sliding surfaces must extend to at least ~700 km deep. The sliding surfaces are the Pacific Plate subducting under the Philippine Sea Plate.


0-100
100-200
200-300
300-400
400-500
600-700
700-800
Longitude (°E)
140
141
142
143
144
145
146
147
148
149
150
Arc Volcanoes: mantle and crustal dewatering
Serpentine Mud Volcanoes: sediment dewatering
Depth
Depth (km)
1
0
-4
-5
-9
0
-100
-200
-300
-400
-500
-600
-700

Part 4: How do you like your melt?

Subduction zones occur in places where tectonic plates are moving toward each other. As the plates converge the plate with the highest density “subducts”, or gets pushed beneath the less dense plate. The earthquakes you mapped in the previous section highlight the approximate location where surface of the dense subducting Pacific Plate meets the base of the less dense over-riding Philippine Sea Plate.

As tectonic plates are forced down into a subduction zone, they are exposed to greater and greater pressures. While the majority of the tectonic plate is made of peridotite, the upper layers are composed of loose sediments and fractured basalts, which can hold large quantities of water, especially on a continuously submerged oceanic plate. Because the layers of the tectonics plate are made up of different materials (much like the layers of cake) they respond differently to increasing pressure. ***Figure 4*** shows the modelled depth at which water is squeezed out of different layers of a subducting plate. This process is known as **dewatering**. Use this graph to answer the following questions:

1. At what depth do sediments initially **dewater** (lose most of their water), and how much water do they lose?

   At 40-60 km and they lose about 40% of their water

2. Where will that water go when it is released from the sediments (hint, the density of peridotite is ~3.4 g/cm^3 and the density of water is ~ 1.0 g/cm^3)?

   The water will rise toward the surface of the Earth through cracks in the overlying rocks because it is less dense than the surrounding rocks.

3. On ***Figure 3*** circle and label the surface feature that might be related to this loss of water from sediments.

   Using Figure 3 students should be able to see that the features on the surface above the subducting Pacific plate between 40-60 km are mountains adjacent to the Trench. These are likely serpentine mud volcanoes.

4. At what depth range do the crust and mantle **dewater** and where will that water go?

   Between 120-240 km the crust and mantle dewater. The water will rise toward the surface of the Earth through cracks in the overlying rocks because it is less dense than the surrounding rocks.

5. On ***Figure 3***, circle and label the feature that might be related to the water lost from the crust and the mantle.

   Using Figure 3 students should be able to see that the features on the surface above the subducting Pacific plate between 120-240 km are the Marianas Arc volcanoes.

Now, let’s look more closely at what happen to the water when it leave the subducting Pacific Plate and rises up through the Philippine Sea Plate toward the surface. The table below shows average temperatures at different pressures/depths in an oceanic plate (for example, the Philippine Sea Plate). A profile of these temperatures is known as a **geotherm**. Also in this table are the melting temperatures of a dense rock called **peridotite**, which is the dominant rock type in an oceanic plate. Peridotite in the presence of water melts differently than when it is dry, so there is one set of temperatures for each condition. These profiles are known as a **solidus**. NOTE: If the average temperature of the rock in the oceanic plate (the geotherm) is less than the solidus temperature, peridotite will remain a solid, but if the geotherm gets above the solidus temperature, peridotite will melt and form magma.

Pressure (Gpa)	Depth below the seafloor (km)	**Geotherm** Temperature (°C)	Dry Peridotite **Solidus** Temperature (°C)	Wet Peridotite **Solidus** Temperature (°C)
0	0	27	1125	1125
0.66	20	367	1200	1050
1.32	40	687	1275	1000
1.98	60	937	1350	990
2.64	80	1127	1425	1020
3.3	100	1257	1500	1050
3.96	120	1327	1575	1160
4.62	140	1367	1650	1250
5.28	160	1377	1725	1320
5.94	180	1387	1800	1360
6.6	200	1397	1875	1400

6. Use the data in the table and graph the geotherm temperatures vs depth on the plot provided. Be sure to label the profile and answer the related questions below.
7. What happens to the temperature of the rock as you get deeper into the plate?

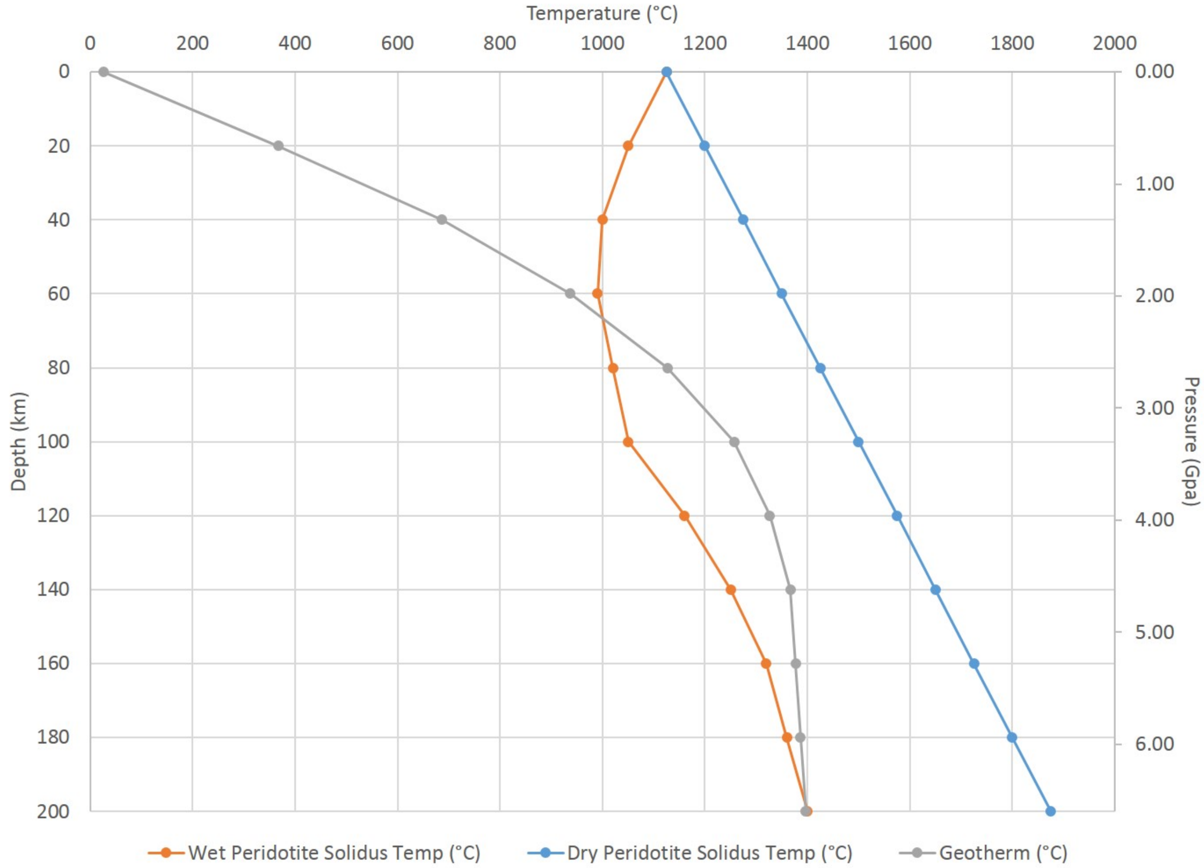
   The rock temperature gets hotter for a while and then at a depth of ~100 km the temperature gradually stops increasing.

8. On the same graph but in different colors, plot the profiles of the dry and wet peridotite soliduses vs depth.
9. How does the melting temperature (solidus) of dry peridotite change with depth?

   The melting temperature of peridotite increases linearly with depth/pressure.

10. How does the melting temperatures of wet peridotite change with depth and how is this different from the melting temperatures of dry peridotite?

    Wet peridotite melting temperature initially decreases with depth and then begins to increase again at a depth of ~60 km. However, in all cases except at the surface of the seafloor, wet peridotite melts at a lower temperature than dry peridotite.



Use what you know about geotherms and wet and dry peridotite soliduses to answer the following questions about water that is released from the subducting Pacific Plate:

11. Based on what you have just plotted, what would the temperature of the over-riding Philippine Sea Plate be at the depth where the sediments from the Pacific Plate initially dewater (Question 1 above)?

    The rock would be between 687°C and 937°C.

12. At these temperatures and depths, is peridotite (wet or dry) going to be solid or liquid?

    At these temperatures both wet and dry peridotite will be solid. Between 40 km and 60 km, the geotherm (or the average temperature of the plate) is still colder then the melting temperatures (solidus line) of either wet or dry peridotite, meaning the plate is still solid.

13. Based on what you learned in the plotting exercise above speculate about the composition of the surface features you identified as being related to sediment dewatering (Question 3 above). Hint: What happens when you mix water and ground-up rock?

    Since peridotite is still be solid between 40-60 km (depth of sediment dewatering), surface features above this region are not built by magmatic eruption. Rather, rising water pulls rock fragments and serpentine minerals from cracks in the overriding Philippine Sea Plate as it moves upward toward the seafloor. When the water exits the seafloor surface, the rock fragments *and serpentine minerals are deposited as large mud piles which have been termed Serpentine Mud Volcanoes.*

14. What would the temperature of the over-riding Philippine Sea Plate be at the depths where the crust and mantle from the Pacific Plate dewater (Question 4 above)?

    The rock would be between 1327°C and ~1400°C (not given exact temp at 240 km, but at 200 km rock is ~1400°C).

15. At these temperatures and depths, is peridotite (wet or dry) going to be solid or liquid?

    At these temperatures dry peridotite will still be a solid (dry peridotite solidus is to the right of the geotherm), but wet peridotite will be a liquid (wet peridotite solidus is to the left of the geotherm).

16. Based on what you learned in plotting exercise above speculate about the composition of the surface features you identified as being related to crust and mantle dewatering (Question 5 above). What would you call these features?

    These surface features are volcanoes fed by the basaltic magma that results from the melting of peridotite in the presence of water. They are known as the Mariana Arc volcanoes.

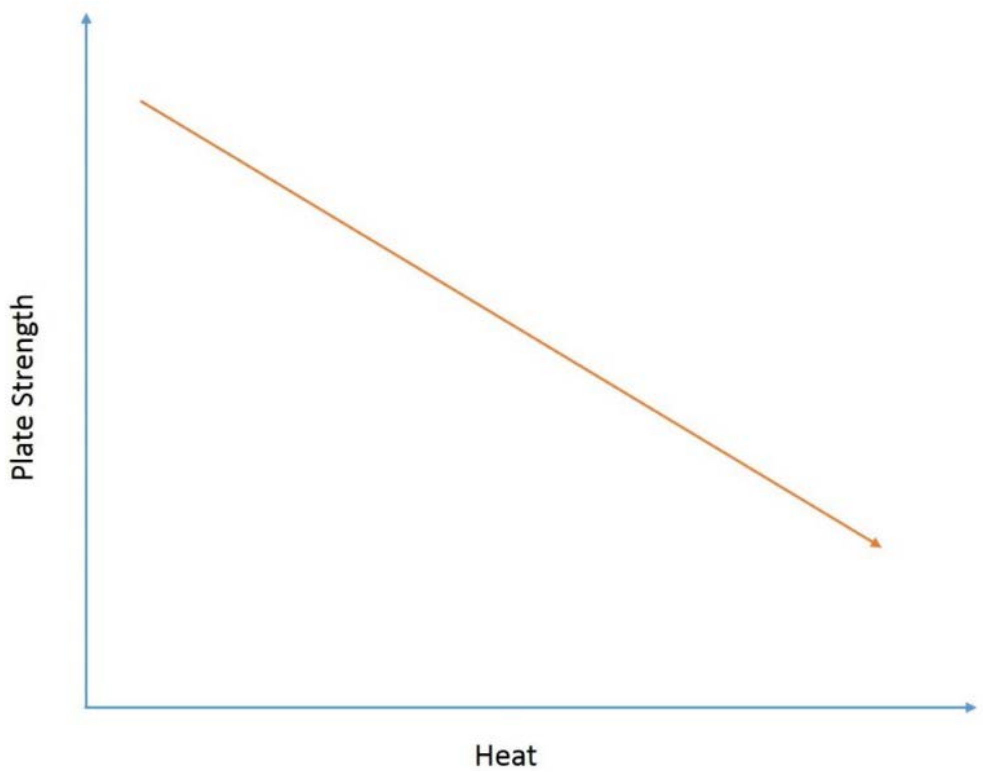
Part 5: Slow and steady destroys the plate

With a partner, brainstorm the importance of the volcanoes that occur near the Marianas Trench. Why might these features be included as part of the Marianas Trench Marine National Monument?

> *Reasonable answers might include: Creation of new land/habitat. Where the volcanoes are exposed, plants and animals have colonized the surface. Underwater, volcanoes that come close to the surface create habitat for coral reefs and other marine organisms. In addition to their physical presence, volcanoes bring recycled water and minerals to the surface. The serpentine mud volcanoes along the edge of the Trench do not involve magmatic eruptions and instead bring cold water loaded with minerals to the surface, concentrating them in one location. Rarely are many of these mineral deposits are found in such concentrations anywhere else at the surface of the Earth.*

In addition to creating new land by bringing hot magma to the surface, volcanoes can change the physical properties of the tectonic plates around them. We will use model "plates" to help us understand how volcanoes might change the way a tectonic plate responds to different forces. Use the supplies you are given to develop an understanding of how the temperature of the plate changes the strength of the plate and the way in which the plate breaks as it is pulled apart.

1. Graph the relationship between tectonic plate strength and heat below.



2. Describe the relationship between the average heat of a tectonic plate and how easily plates will break (**rifts**).

   There is an inverse relationship between plate strength and heat. As the average temperature of the plate gets hotter the plate will break more easily.

3. As the average heat in the plate increases, how does style of **rifting** change?

   When the plate is cold, the plate breaks cleanly (brittle). As the plate warms, the plate stretches more (ductile) and the break is not as clean. It is not uncommon in the warm plate to have the plate segment into multiple pieces as it breaks.

Figure 6 is an image created by the United States Geological Survey that shows the rates and directions of movement of the Pacific and Philippine Sea Plates (the Marianas Trench is where these two plates come together). The arrows indicate the direction the plate is moving and the numbers indicate how fast the plates are moving in mm/yr. Based on this figure answer the following questions:

4. Generally, which direction is the Pacific Plate moving? Where is the Pacific Plate moving the fastest? Where is it moving the slowest? What is the average rate at which the Pacific plate is moving?

   Generally the plate is moving westward. In the north the plate is moving fastest, in the south the slowest, and on average the whole plate is moving at 29.4 mm/yr.

5. Generally, which direction is the Philippine Sea Plate moving? Where is the Philippine Sea Plate moving the fastest? Where is it moving the slowest? What is the average rate at which the Philippine Sea Plate is moving?

   Generally the plate is moving westward. The Philippine Sea Plate is moving fastest in the south, slowest in the north, and on average the whole plate is moving at 83.5 mm/yr.

6. Scientists have determined that the Marianas Trench (where the Pacific and Philippine Sea Plate meet) has been in the same location for the last 13 Ma or more. How can this be true while at the same time the Philippine Sea Plate is moving westward? What must be happening to the Philippine Sea Plate in order for this information to be true?

   In order for the Marianas Trench to stay in the same place and for the Philippine Sea Plate to move westward at the same time, the plate must be stretching and breaking (rifting). This rifting allows the plate to accommodate the extensional stress that the plate experiences, and results in the formation of backarc basins such as the Parece Vela Basin and the Marianas Backarc Basin.

7. Use your bathymetric map and the relative plate motion diagram to identify by number and name which zones on the seafloor (identified in ***Part 2: How did THAT get there?***) allow the Philippine Sea Plate to move and stay stationary at the same time, either now or in the past.

   Answers will depend on student zone numbers, but they should be able to identify both the Marianas Backarc Basin and the Parece Vela Basin.

8. Thinking back to your plate breaking experiments, what do you think controls *where* this process happens on the seafloor?

   The Philippine Sea Plate is most likely to ***rift*** *along the line of the active volcanoes that result from the subduction of the Pacific Plate at the Marianas Trench. Water loss from the subducting Pacific plate causes melting and as the magma works its way toward the surface of the seafloor it raises the temperature of the plate around it. This heat weakens the plate and makes it more likely to* ***rift*** *along the line of volcanoes when the plate comes under tension.*

Part 6: Summary

Use the information from the previous parts of this lesson to describe what you learned about the formation of the Marianas Trench and surrounding regions.

What I **learned** about the Marianas Trench

Finally, use all the data you have learned to create a poster with a cross-section model of all the processes that are happening across the Marianas Trench region. Be sure to include the following in your model:

- The Pacific Plate
- The Philippine Sea Plate
- The direction the plates are moving
- Each of your labelled zones
- The location of the Marianas Trench
- Where dewatering is occurring
- Where magma is formed
- Where rifting is occurring

Marianas Trench Marine National Monument: Tectonic Evolution Student Worksheet

Name______________________________________ Date________________________________

Part 1: What do you know?

What I **know** about the Marianas Trench
What I want to **learn** about the Marianas Trench

Part 2: How did THAT get there?

Figure 1 is a map of seafloor **bathymetry**, or the depth of landforms below sea level. To understand this image it is helpful to know that dark colors = deep depths, and light colors = shallow depths. The lines indicate the boundaries of the Marianas Trench Marine National Monument.

1. On the figure, from East to West number the different seafloor zones you see.
2. Describe the characteristics of each zone in Question 1. Hints: Is the seafloor shallow or deep? What features are on the seafloor? Mountains? Valleys? What trends do you see in the features on the seafloor? What texture (e.g. smooth, bumpy, fractured, etc.) does the seafloor have?

Figure 2 is a **bathymetric profile** across the Marianas Trench region at ~17°N. This profile is a plot of seafloor depth (below the surface of the ocean) vs. longitude/distance.

3. On ***Figure 1*** draw a line to indicate where this bathymetric profile occurs on the map.
4. Next, using the same zone numbers you determined in Question 1, label each zone on the bathymetric profile and label the Marianas Trench.
5. Calculate the percent slope of the E and W sides of the Marians Trench and show your work in the space below (Remember, slope is rise over run, or in this case, the change in depth over the change in distance. Multiply your answer by 100 to get percent slope.).

6. Graph the slope of each side of the Trench without any **vertical exaggeration** in the graph below. *(Note: A graph with no vertical exaggeration will have the same scale for the X and Y axes).*

7. Why might you use **vertical exaggeration** when displaying graphical data?

8. Which side of the Trench has a steeper slope? Imagine what it would be like if you were walking along the ocean floor into the Marianas Trench. What clues, other than slope, might indicate you were getting deeper into the Trench?

Part 3: Deep Quake

Earthquake data have been a very important source of information for scientists studying the formation of the Marianas Trench.

1. How do earthquakes occur?

The top section of ***Figure 3*** shows a small subsection of the Marianas Trench region displaying earthquake data collected by the United States Geological Survey and the National Earthquake Information Center. Each dot represents the location of an earthquake of magnitude 5.5 or greater and the color indicates the depth where the fault begins to rupture, or the **hypocenter** of the earthquake. Answer the following question regarding the patterns of earthquakes in the region.

2. How does the number of earthquakes vary with depth?

3. How do the locations of earthquakes change with depth?

The center section of ***Figure 3*** is the bathymetric profile across the Marianas Trench region at ~17°N Latitude. Use the earthquake information from the top section and what you know about the bathymetry from the middle section to shade in the range longitudes where earthquakes occur at each depth in the bottom section of the figure. Once you are done answer the following questions:

4. Based on the earthquake data you just plotted and what you know of earthquakes, what must be happening at and below the Marianas Trench to cause these earthquakes? How is this related to the location of the earthquakes?

Part 4: How do you like your melt?

Subduction zones occur in places where tectonic plates are moving toward each other. As the plates converge the plate with the highest density "subducts", or gets pushed beneath the less dense plate. The earthquakes you mapped in the previous section highlight the approximate location where surface of the dense subducting Pacific Plate meets the base of the less dense over-riding Philippine Sea Plate.

As tectonic plates are forced down into a subduction zone, they are exposed to greater and greater pressures. While the majority of the tectonic plate is made of peridotite, the upper layers are composed of loose sediments and fractured basalts, which can hold large quantities of water, especially on a continuously submerged oceanic plate. Because the layers of the tectonics plate are made up of different materials (much like the layers of cake) they respond differently to increasing pressure. ***Figure 4*** shows the modelled depth at which water is squeezed out of different layers of a subducting plate. This process is known as **dewatering**. Use this graph to answer the following questions:

1. At what depth do sediments initially **dewater** (lose most of their water), and how much water do they lose?

2. Where will that water go when it is released from the sediments (hint, the density of peridotite is ~3.4 g/cm^3 and the density of water is ~ 1.0 g/cm^3)?

3. On ***Figure 3*** circle and label the surface feature that might be related to this loss of water from sediments.

4. At what depth range do the crust and mantle **dewater** and where will that water go?

5. On ***Figure 3***, circle and label the feature that might be related to the water lost from the crust and the mantle.

Now, let's look more closely at what happen to the water when it leave the subducting Pacific Plate and rises up through the Philippine Sea Plate toward the surface. The table below shows average temperatures at different pressures/depths in an oceanic plate (for example, the Philippine Sea Plate). A profile of these temperatures is known as a **geotherm**. Also in this table are the melting temperatures of a dense rock called **peridotite**, which is the dominant rock type in an oceanic plate. Peridotite in the presence of water melts differently than when it is dry, so there is one set of temperatures for each condition. These profiles are known as a **solidus**. NOTE: If the average temperature of the rock in the oceanic plate (the geotherm) is less than the solidus temperature, peridotite will remain a solid, but if the geotherm gets above the solidus temperature, peridotite will melt and form magma.

Pressure (Gpa)	Depth below the seafloor (km)	**Geotherm** Temperature (°C)	Dry Peridotite **Solidus** Temperature (°C)	Wet Peridotite **Solidus** Temperature (°C)
0	0	27	1125	1125
0.66	20	367	1200	1050
1.32	40	687	1275	1000
1.98	60	937	1350	990
2.64	80	1127	1425	1020
3.3	100	1257	1500	1050
3.96	120	1327	1575	1160
4.62	140	1367	1650	1250
5.28	160	1377	1725	1320
5.94	180	1387	1800	1360
6.6	200	1397	1875	1400

6. Use the data in the table and graph the geotherm temperatures vs depth on the plot provided. Be sure to label the profile and answer the related questions below.

7. What happens to the temperature of the rock as you get deeper into the plate?

8. On the same graph but in different colors, plot the profiles of the dry and wet peridotite soliduses vs depth.

9. How does the melting temperature (solidus) of dry peridotite change with depth?

10. How does the melting temperatures of wet peridotite change with depth and how is this different from the melting temperatures of dry peridotite?

Use what you know about geotherms and wet and dry peridotite soliduses to answer the following questions about water that is released from the subducting Pacific Plate:

11. Based on what you have just plotted, what would the temperature of the over-riding Philippine Sea Plate be at the depth where the sediments from the Pacific Plate initially dewater (Question 1 above)?

12. At these temperatures and depths, is peridotite (wet or dry) going to be solid or liquid?

13. Based on what you learned in the plotting exercise above speculate about the composition of the surface features you identified as being related to sediment dewatering (Question 3 above). Hint: What happens when you mix water and ground-up rock?

14. What would the temperature of the over-riding Philippine Sea Plate be at the depths where the crust and mantle from the Pacific Plate dewater (Question 4 above)?

15. At these temperatures and depths, is peridotite (wet or dry) going to be solid or liquid?

16. Based on what you learned in plotting exercise above speculate about the composition of the surface features you identified as being related to crust and mantle dewatering (Question 5 above). What would you call these features?

Part 5: Slow and steady destroys the plate

With a partner, brainstorm the importance of the volcanoes that occur near the Marianas Trench. Why might these features be included as part of the Marianas Trench Marine National Monument?

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8. Thinking back to your plate breaking experiments, what do you think controls *where* this process happens on the seafloor?

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