AN ABSTRACT OF THE THESIS OF

Jennifer A. Natoli for the degree of Master of Science in Geology presented on February 19, 2004.
Title: Shake, Rattle, and Roll: Awaking the Visiting Public's Curiosity of Geology via Interpretation at Redwood National and State Parks.

Abstract approved: [signature]
Robert J. Lillie

By researching aspects of the geology of Redwood National and State Parks (RNSP) and serving for two summers as a seasonal interpretive ranger, I have developed a training manual designed for fellow rangers. The descriptive nature of the manual, combined with its vivid illustrations, is designed to enable rangers of all backgrounds to present the park's geology to visitors in accurate, interactive, inspiring, and thought-provoking programs. To develop successful programs, the geological processes most appropriate for interpretation to RNSP visitors were identified.

The geology of Northern California's RNSP is dynamic. The Cascadia Subduction Zone (CSZ), where the Gorda Plate dives beneath North America, impacts the stability of the region and raises concern for earthquakes and ensuing tsunamis. The ongoing subduction, including uplift of materials from the sea floor, is responsible for the dramatic landscape of RNSP, forming the Coast Range and its rugged coastline. The landscape in turn controls ecological variables. Without the Coast Range, the fog necessary to support the towering redwood forest would not exist. The fracturing of rock layers in the park enhances erosion and landsliding. Such relationships between geology and ecology encourage rangers to present programs with interdisciplinary themes.

Geologic processes and their societal importance need to be emphasized for the benefit of RNSP's 400,000 annual visitors. The majority of interpretive park rangers have degrees in life sciences or humanities, and few have much formal training in geology. The manual provides the basic concepts and tools to encourage rangers of all backgrounds to interpret the geology of RNSP to visitors. Plate tectonics, for example,

gives interpreters the background necessary to understand a variety of geological processes germane to RNSP, such as earthquakes and related tsunamis. Chapters are designed around themes directly relevant for RNSP, including interpretation, plate tectonics, rock types, geologic structures, earthquakes, tsunamis, and geologic history. Non-technical text accompanies photographs and other illustrations to convey geologic processes at many scales, ranging from individual water particles to worldwide earthquake distribution. Analogies to familiar daily life events are used to present scientific concepts, and suggestions for methods to demonstrate the processes to the public are included. The appendices are designed to help rangers prepare for interpretive programs and relate to specific audiences. They include summaries of the geologic processes relevant to questions commonly asked by visitors, geologic limericks, interpretive program outlines, as well as results of visitor surveys. This version, submitted as a thesis to Oregon State University, will be reviewed by RNSP staff and others, and then revised to become a concise geology training manual for rangers at RNSP.

Shake, Rattle, and Roll:
Awaking the Visiting Public's Curiosity of Geology via Interpretation at Redwood National and State Parks

by
Jennifer A. Natoli

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented February 19, 2004
Commencement June 2004

Master of Science thesis of Jennifer A. Natoli
presented on February 19, 2004.

APPROVED:

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorized release of my thesis to any reader upon request.

Jennifer A. Natoli, Author

ACKNOWLEDGEMENTS

Without the support of the following people and organizations, I simply could not have been as successful a graduate student as I have become. The enduring academic, emotional, and intellectual connections these people have shared with me have helped me find my focus and direct my energies. I owe much more than thanks and I've gained much more than colleagues.

Cornell College

Paul and Ellen Garvin, Ben Greenstein, Rich Martin, and Pete Thompson

Oregon State University

The Alliance of Graduate Employee Locals, the American Federation of Teachers, Becky Ashton, Sherm Bloomer, Jason Chaytor, the Coalition of Graduate Employees, Steve Cook, the Department of Geosciences, Anita Grunder, Julia Jones, Randy Keller, Bob Lillie, Andrew Meigs, Melinda Peterson, Ann Trehu, Cindy Twohy, Joanne VanGeest, Stacy Wagner, and Dawn Wright

Redwood National and State Parks

Cathy Cook, Lyn Carranza, Judy Geniac (GIP), Doug Gordon (CSP), Coleen Hara, Lynne Mager, Lynda Mealue, Steve Moore, Vicki Ozaki, Nancy Phillips, Slade Sapora, and Debbie Weist

Special thanks for the contributions of:

David Bazard, the California State Parks (CSP), the Geoscientists-in-the-Parks (GIP) Program, Greg Harper, the National Park Service (NSP), the National Oceanic and Atmospheric Administration (NOAA), Mark Renner, and the United States Geological Survey (USGS)

And of course...

The delightfully talented lads of AMADAN (Stout Irish Music!), Louis Arighi, Cameron Bergen, Brent Boehlert, Jennifer Carrell, Nathan and Sarah Casebeer, Nicole_Czarnomski, Cris Darr, Emily Daws, Lynette Delp, Marc Duarte, Zeitel Gray, Carrie Helmold, Karl Katzke, Anne Natoli, Sam Natoli, Tessa Parshall, Mike Rowe, Jason Schleisman, Matt Tibbits, and Kim Truitt

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DEDICATION

My close friends have been my support through graduate school, and I dedicate this manual to those of you who have listened to me for hours and love me still.

In spirit, this manual is for all of you who bridge gaps in your life, who defy categories and merge the energies of creative thought and academic intellect. To all of you who endeavor to enlighten people, who are dedicated to sharing your knowledge and awareness to help others experience our natural world, I promise you: the rewards are really worth your perseverance.

Muted miles drift by on the wind
tearful weeds wave as my soul passes
unaware of anything but the past
my mind laughs as it conjures
images from fleeting moments impress
emotions for a lifetime
deep chasms of lusty sadness
carve their way through layers of carefully crafted defenses
leaving only shards of who I was before
to tumble downstream
once peppered with intense armor, now-polished grains emerge
raw at the mouth
ready to dance their way into
my vast ocean of wild secrets.

(Spring, 2002 ~ my first experience of the rocky North Coast)

Shake, Rattle, and Roll:
Awaking the Visiting Public's Curiosity of Geology via Interpretation at Redwood National and State Parks

Preface

Look around you. To the east you see the characteristic towering evergreen tops of the redwoods swaying gently in the sea breeze. To the west you see the ocean, an endlessly dynamic expanse of blue-gray rushing to meet the rocky Northern California shore. As an interpreter, your mission is to connect visitors with the tangible and intangible wonders of Redwood National and State Parks (RNSP). Your challenge is to interest visitors in all the unique aspects of RNSP so that they might want to understand more about the nature of this incredible coastal stretch of ancient forest (fig. P-1).

When you hear the phrase "National Park," what images cross your mind? Do you picture Half Dome, Mt. Rushmore, or Old Faithful? Do you think of red-orange layers of rock forming impossible archways and canyons? National Parks are preserved for their inspiring landscapes as well as the unique ecosystems that developed on the landscapes. Even their names reveal that many national parks are cherished because of those physical landscapes; "Yellowstone," "Rocky Mountain," "Arches," "Grand Canyon," "Crater Lake," "Mount Rainier," "Olympic," "Great Smoky Mountains," "North Cascades." Landscapes result from geologic processes, so understanding geology is integral to enriching visitors' experience of our national parks. The name "Redwood" alludes to the biologic elements for which RNSP was preserved, but our unique ecosystem is in fact a product of the physical landscape (fig. P-2).

Despite the importance of understanding how landscapes are formed, interpretive rangers typically are not trained in Earth science (geology). Most rangers have backgrounds in life sciences, such as biology or botany, and many have backgrounds in the humanities, like history or sociology (fig. P-3). Such backgrounds are similar to the general level of public awareness: most people have a better understanding of human studies than science, and, within the realm of science, people tend to be more familiar with life sciences than Earth sciences. Many people fail to see the dynamic connection

Figure P-1: Split Rock at sunset. We can all appreciate a beautiful landscape, but imagine how our appreciation can be enhanced by truly understanding how the landscape formed. The gorgeous rocky coastline of Northern California embodies the balance between uplift and erosion, active geologic processes shaping Redwood National and State Parks. (Photo by J. Natoli)

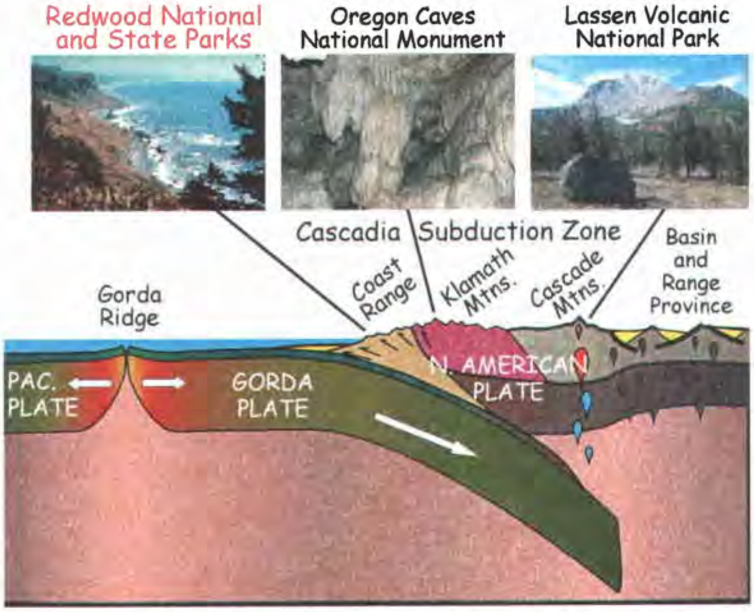


Figure P-2: The landscapes of three park areas - Redwood, Oregon Caves, and Lassen - owe their differences to the geologic processes sculpting each. All three areas lie within the Cascadia Subduction Zone, a region where coastal uplift (Redwood) and volcanic activity (Lassen) both result from process of the Gorda Plate diving beneath North America (fig. 1-9). Oregon Caves is a special case where bits of land were smashed onto the edge of North America during the conveyor-belt style of terrane accretion (fig. 1-14). (Modified from Lillie, 2004, Photos courtesy of NPS and R. Lillie) between geology and all the other natural resources of Redwood National and State Parks. At RNSP, rangers have the opportunity to help people connect life and Earth sciences by demonstrating how geological processes shape the land and create the environment in which the tallest trees in the world grow (fig. P-4, see "How naturalists use interpretation").

Simply by donning your "ranger hat" and leading a forest walk or presenting a campfire program, you are demonstrating your love for RNSP. We all appreciate the experience of hiking to special places such as Enderts Beach or Split Rock on our own time to watch the sunset or the tide go out, and we can draw on our feelings to inspire visitors (fig. P-1).

Introduction

The story of Northern California's inspiring landscape is ongoing and involves processes that mold the entire Earth. In fact, the Earth itself tells us its story: "...in every outthrust headland, in every curving beach, in every grain of sand there is the story of the Earth..." (Carson, 1955). We, as interpreters, can translate the language of the Earth to visitors. But first, we need to learn the language. That is, we need to understand how certain Earth processes result in the incredible landscape that is Redwood National and State Parks, so that we can communicate with visitors.

Rachel Carson, an eloquent nature writer, fell in love with the dynamic beauty of nature. In her 1955 book "The Edge of the Sea," she captures a moment on the coast we can all appreciate:

> *"Now I hear the sea sounds about me; the night high tide is rising, swirling with a confused rush of waters against the rocks below.... Once this rocky coast beneath me was a plain of sand; then the sea rose and found a new shoreline. And again in some shadowy future the surf will have ground these rocks to sand and will have returned the coast to its earlier state. And so in my mind's eye, these coastal forms merge and blend in a shifting, kaleidoscopic pattern in which there is no finality, no ultimate and fixed reality - Earth becoming fluid as the sea itself."*

This manual shows interpreters how they can reveal to visitors the linkage of RNSP's biology and ecology to the geologic forces of uplift and erosion that shape the park's ever-changing landscape - "...Earth becoming fluid as the sea itself."

Redwood National and State Parks

Every National Park has statements that capture the park's significance to our natural and cultural heritage. Such official statements provide interpreters with elements of the park's "story" that have been identified as important elements of visitors' experiences in the park. At RNSP, two statements relate directly to geology.

> *"Redwood National and State parks are located near the junction of three active tectonic plates of the earth's crust. Steep, highly erodible landscapes and frequent earthquakes characterize the region and are all related to the geologic forces generated at plate boundaries. These forces influence not*

only the natural characteristics of the parks, but human use and habitation as well."

"More than one-third of the land within the parks has been heavily impacted by timber harvest and are the subject of an internationally recognized restoration program designed to restore integrity and recover lost values. Erosion related to logging roads is being reduced, natural topography is being restored to hillslopes crossed by roads, and topsoil is being returned to the surface to speed revegetation and retain genetic integrity of the vegetation." (National Park Service, 2000)

The first statement deals with fundamental Earth processes and their impact on humans in the region, while the second relates surface processes to our human impact on the region. To translate the story of RNSP effectively, interpreters should have an understanding of the fundamental principles of both geology and interpretation.

Discovery Through Interpretation

The art of using tangible and intangible elements of our human experience to relate information to others is the essence of ***interpretation***. The naturalist recognized as the "grandfather" of interpretation is Freeman Tilden, who first proposed some essential elements of effective interpretation. Our interpretive training introduces us to Freeman Tilden's "Six Principles of Interpretation."

Tilden's Principles

1. Any interpretation that does not somehow relate what is being displayed or described to something within the personality or experience of the visitor will be sterile.
2. Information, as such, is not interpretation. **Interpretation is revelation based upon information**. But they are entirely different things. However, all interpretation includes information.
3. Interpretation is an art, which combines many arts, whether the materials presented are scientific, historical, or architectural. Any art is in some degree teachable.
4. The chief aim of Interpretation is not instruction, but **provocation**.

5. Interpretation should aim to present a whole rather than a part, and must address itself to the whole man rather than any phase.
6. Interpretation addressed to children (up to the age of twelve) should not be a dilution of the presentation to adults, but should follow a fundamentally different approach. To be at its best it will require a separate program.
(Tilden, 1977)

How Naturalists use Interpretation

Tilden attaches meaning to information to allow the public to connect with nature (fig. P-4). We are challenged to achieve a balance between accurate information and interesting concepts, between the technical and the non-technical, between "science" and "real life." An effective technique developed by Ranger Allyson Mathis (Grand Canyon National Park) is called "PAIRing people with parks" (Mathis, 1999). The acronym PAIR represents the following methods for building the interpretive chain to connect park visitors with the resource: Presentation techniques, Audience characteristics, Interpretive methods, and Resource information.

At RNSP, our presentation techniques range from five-minute Visitor Center "interpretive moments," to guided forest and coastal walks, to Junior Ranger and Young Naturalist programs, to evening campfire programs. Interpreters must recognize the different advantages of each presentation technique and use them effectively. We can best "tailor" our interpretation once we characterize the audience for our presentation.

Most interpreters automatically filter information for their audience. We all prepare for interpretive programs by researching our topics and amassing information, but then we selectively include only the most germane, important, and interesting elements so that we both inform and engage our visitors (Ham, 1992). If you were giving a talk about a redwood tree, for example, you might introduce and explain the term "cambium." But you initially would not use words such as "phloem" or "xylem," just as you would not describe the various sugar-manufacturing chemical reaction processes of cellular respiration while talking about photosynthesis. In a talk about banana slugs, you might interest your audience with details of the slugs' numbing slime and ability to

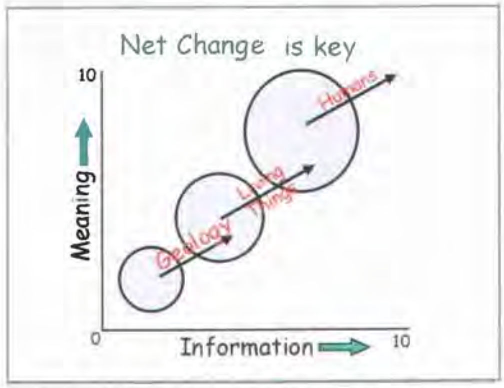


Figure P-3: In general, the public has more extensive background knowledge about human history and life sciences than Earth Sciences. For effective interpretation, we must move our audience from a background level to a higher level of understanding. Interpreters must therefore begin making Earth Science connections assuming a more basic level of understanding to reach a broader audience. (Modified from Mathis, 1999)

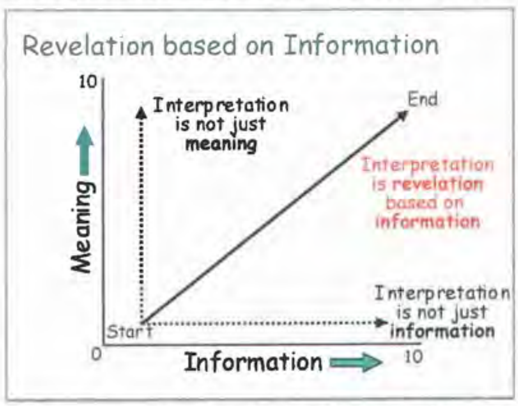


Figure P-4: Effective interpretation is enhanced by attaching meaning to information. As the saying goes, people will remember 10 % of what they hear, 30 % of what they read, 50 % of what they see, and 90 % of what they do! (Modified from Mathis, 1999)

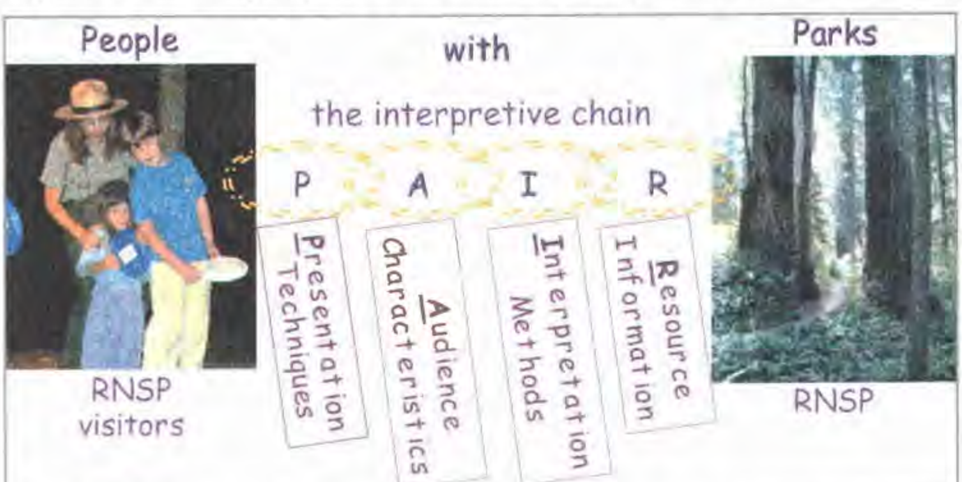


Figure P-5: PAIRing park visitors with RNSP. Effective interpretation creates a link between visitors and the resource. Through meaningful experiences, visitors can connect the information to the park and become stewards of RNSP. (Modified from Mathis, 1999; photos by J. Natoli) decompose, but probably not the details of their evolution and anatomy. Similarly, in a talk on earthquakes, whereas you might introduce terms like "subduction zone" to describe the geologic setting, you probably would stay away from detailing the various parameters of compressional wave arrival times relative to the composition of the interior of Earth. Our park is full of interpretable diadems - both living and non-living - that are interwoven to create the awe-inspiring natural "fabric" of RNSP. Geology, just like botany and biology, is a discipline that can be interpreted effectively by employing a basic knowledge of geologic processes and your own interpretive abilities (fig. P-3, P-4).

The methods we employ to interpret aspects of RNSP (such as geology) are the "art" of RNSP rangers. Interpretive rangers use all the familiar elements of national parks to connect our visitors with RNSP: our programs are given in uniform, we use demonstrations, we have "campy" campfire warm up games and songs, and we use props like hand lenses and stickers. It is important to invoke all the senses of visitors to make a powerful connection between the information we relay and the natural resource the visitors experience.

Interpretive themes at RNSP

RNSP has an extensive seasonal interpretive ranger training program. In the "Interpreter's Handbook" binders that each ranger receives at the onset of training, there is a list of five "interpretive themes" identified from the "significant statements" developed for RNSP. One of the themes makes direct reference to geology.

> *"Steep, highly erodible landscapes, heavy rainfall, powerful rivers, and frequent earthquakes are all related to local geologic forces generated near the junction of the three tectonic plates of the earth's crust that underlie the region."*
> (National Park Service, 2000)

The geologic processes active in RNSP relate directly to the Cascadia Subduction Zone, an active boundary between two of the three plates near RNSP. The movements of the plates result in periodic earthquakes and tsunamis, coastal uplift and erosion, and the addition of land onto the edge of the North American continent. The landscapes created by all of these on-going processes can be seen directly by visitors to RNSP, as long as they know where to look. Pointing out the features of the land and interpreting how they formed are engaging opportunities for RNSP rangers.

Geology, as an individual theme, may seem impersonal. We, as interpreters, need to make connections between Earth's natural processes and the daily lives of RNSP visitors. We need to convey how geological forces are *actively* shaping RNSP. Many visitors are able to identify with events that happen in their own lifetimes, such as earthquakes and tsunamis, or landslides and erosion. Integrating the geological, environmental, and cultural evidence of earthquake (tectonic) and erosional (surface) processes helps convey the meaning of the RNSP landscape to visitors (fig. P-2). A "big picture" Earth view that relates to daily human experiences allows visitors to appreciate how the present-day forces forming our coastline might shape their own lives (Johnson and others, 2002).

Personal Experiences

As an interpreter, I recognized the importance of learning the principles and techniques set before me with the express purpose of adapting them into my own style of interpretation. Modifying Tilden's principles to apply them to modern audiences is often beneficial, as is acknowledging that the "PAIRing" process is highly individualized. The components of the "PAIRing" process are important, but successful interpretation also depends significantly on the personality of the interpreter. As an academic, evaluating the effectiveness of my approach in interpreting geology to RNSP visitors was important. I have learned a great deal about interpretation and have gained an appreciation for the difficulties inherent in any teaching process.

The most daunting quandary is quantifying the successfulness or effectiveness of interpretation. If interpretation is indeed "revelation based on information" (Tilden, 1977), how can we know when a visitor is provoked to have a "revelation" experience? National parks rarely conduct "satisfaction" surveys – any visitor feedback comes through comment cards or other visitor-initiated communication. Separating individual responses from general trends is challenging. Following my campfire programs, dozens of visitors often gathered around "Ranger Jen" to ask questions, but how can we know whether the visitors would do the same were the program un-provoking? Ultimately, appreciating the consistency with which visitors are provoked about the subject matter presented in an interpretive program is a valid approximation of the effectiveness of the program.

Deciding the elements of geology that can be conveyed to visitors in an interesting program is another complex issue: how much accuracy should be sacrificed for the sake of provocation? How effective or appropriate is an analogy when the correlation is misleading? For example, I use the analogy of a beachball and a tennis ball floating in a pool to describe the difference between how the continental crust and the oceanic crust interact within the mantle. Not only does the ball analogy exaggerate the difference in thickness between the two types of crust, but it emphasizes buoyancy over several other processes that influence subduction. Nonetheless, when I used this familiar analogy to explain why one plate descends beneath another, people "got it." As an interpreter, my objective was to spark an interest in the subject matter by attaching meaning to information. The beachball/tennis ball analogy afforded me the basic understanding I needed to help explain the geologic processes involved in the Cascadia Subduction Zone. Because the beachball/tennis ball analogy is not presented as being an exact corollary to plate tectonics, it also affords the interpreter the opportunity to offer more detailed (and accurate) explanations about buoyancy and subduction. Despite any degree of accuracy sacrifice, if an analogy can connect the visitors with abstract concepts without grossly misrepresenting reality, that analogy can be an effective interpretive tool.

When visitors express their ability to relate to interpretive analogies, their responses suggest ways our programs might continue to evolve. After participating in my Junior Ranger program, a young man designed the "Gorda Plate State Park," preserved for its "rocks and fossils," for his second Junior Ranger program. The daughter of an employee of Jedediah Smith Redwoods State Park proudly announced that she had used the Oreo ® cookie demonstration from my program in her junior high school class as a presentation for a nature project on geology. Numerous adults approached me following my campfire programs to commend my teaching abilities and ask for copies of my geology lyrics. Positive responses are encouraging, but determining whether visitors found my geology program interesting because the geology is compelling or because my presentation was compelling is complicated. Regardless, the visitors were interested enough to share their thoughts with rangers other than myself, which speaks to the level to which geology can engage the public.

In recognizing that personality will dictate each interpreter's style of presentation, I have included descriptions of my demonstrations for other rangers to modify to their individual preferences. I have also described my own style of presentation and recorded my campfire and Junior Ranger programs for reference. Despite the influence of the ranger's personality, the amazing landscape of RNSP does not need much exuberance to ignite visitors' interest.

Success in anything is a balancing act. Effective interpretation is no different: accurate information must be balanced by meaningful experience. Any translation of the natural world is inherently an approximation of reality and must then compromise the "truth" on some level. For those of us concerned with increasing public awareness of, interest in, and connection to our natural world, it is more important to reach out beyond pure facts so as to hand visitors meaningful experiences.

"Do not try to satisfy your vanity by teaching a great many things. Awaken people's curiosity. It is enough to open minds; do not try to overload them. Put there just a spark. If there is some good inflammable stuff, it will catch fire."

~Anatole France

The Questions

The following list of questions includes those that have been asked by visitors without provocation from the ranger. The questions were asked multiple times during RNSP's summer season, either during visitor center or roving contacts. The geologic overview in the following chapters gives you background to understand Earth processes and knowledgeably answer the questions. Explicit responses can be found in Appendix A.

Five Geology-Related Questions Commonly Asked by Visitors:

1. **Why is the coast so rocky/steep here?**
   Related Questions: Do earthquakes happen around here?
   Wasn't there a tsunami here years ago...?
2. **How do sea stacks form?**
3. **Why are there so many green rocks?**
4. **Why are the soils orange near the Smith River?**
5. **Why is there a spit on the Klamath River?**

Common questions that can be related to geology when asked by visitors, or used as thought-provoking questions by interpreters:

6. **Is this fog typical?**
7. **Why are the trees so tall?**
8. **Why do such unique plants grow here?**
9. **What are tide pools?**
10. **Why can you find agates on the beach here?**

Chapter 1: Tectonics

Redwood National and State Parks are situated on one of the most geologically active coasts in the world. Interpretive opportunities can be enhanced by understanding the basic geologic processes involved.

The Earth is sculpted by dynamic forces on many levels. At the broadest scale, ***plate tectonics*** dictates the motion of Earth's surface. The term *tectonics* is derived from the Greek word for "builder" or "architect," suggesting that plate movements indeed sculpt Earth. Grand scale features we admire on the surface, such as mountains (the Coast Range, Klamaths, and Cascades) and valleys (California's Great Valley and Oregon's Willamette Valley), result from the movements of the large plates. Earth's surface is like a cracked eggshell (fig. 1-1). Each fragment, or ***plate***, is a separate piece of the hard outer shell, called the ***lithosphere*** ("lithos" meaning "rock," thus, "lithosphere" translates literally as "sphere of rock"). The lithosphere includes both the ***crust*** and the upper, more rigid portion of the ***mantle***, the intermediate layer of Earth's interior.

Earth's outer surface is composed of at least 15 plates. The plates ride on a softer mantle layer called the ***asthenosphere*** ("sphere lacking strength"). The boundaries between these plates, or "cracks," are where most of the "action" is, and each type of plate boundary has its own associated set of characteristic surface features (fig. 1-1).

Plate Boundaries

There are three types of plate boundaries, all defined by the relative motion of the plates (fig. 1-2): ***divergent***, where plates pull apart creating new crust (also called "spreading centers"); ***convergent***, where one plate is forced beneath another and destroys crust; and ***transform***, where plates grind laterally past each other, neither creating nor destroying, but deforming, the crust. ***Hotspots*** normally do not occur at plate boundaries, but, like plate boundaries, they involve tectonic processes producing exciting features on Earth's surface. As a plate moves over a hotspot (a plume of hot

Figure 1-1: The Earth's surface is like a cracked eggshell! It is broken into several pieces, known as "plates." The "cracks" between plates are where most of "action" happens: both earthquakes and volcanic activity generally follow the cracks. Notice that mountains are common at edges where two plates converge. (Modified from Marshak, 2001)

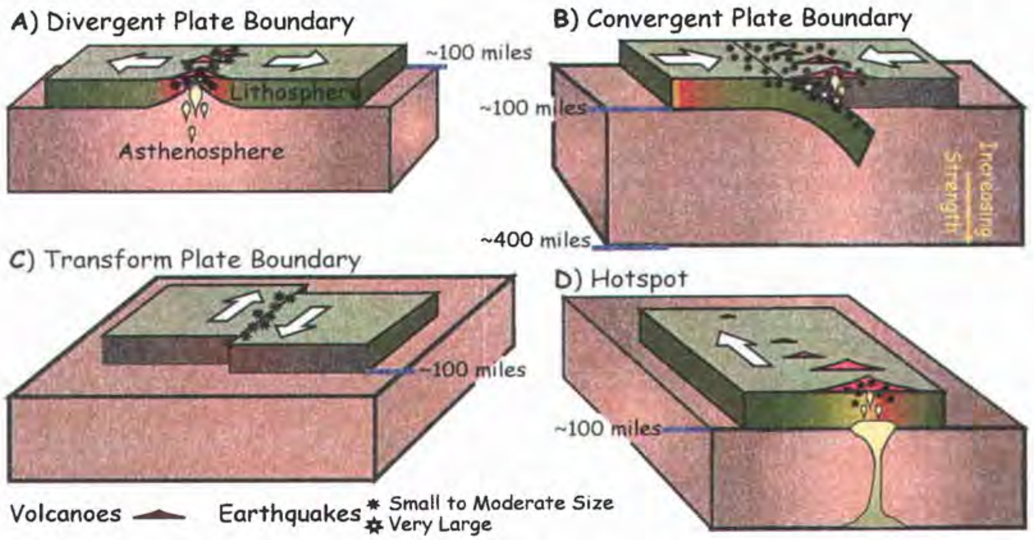


Figure 1-2: Slip slidin' away! Each type of plate boundary has characteristic motions and surface features. Divergence (**A**, fig. 1-11) occurs where two plates are pushed apart as hot material rises via mantle convection. Convergence (**B**, figs. 1-9, 1-10) occurs when two plates crash into each other. Subduction (**B**, figs. 1-7, 1-9) is a special type of convergence where one plate dives beneath the other. Transformation (**C**, fig. 1-15) occurs when two plates slide past each other without much mantle involvement. Hotspots (**D**) are not technically plate boundaries, but they produce important surface features.

mantle), volcanic mountain chains (such as the Hawai'ian Islands) form on the plate's surface. Each type of plate boundary and hotspot has characteristic tectonic activity (earthquakes and volcanism), which produces distinct surface features (mountains, valleys, and coastlines). Although Redwood National and State Parks are far from hotspot activity, there are features associated with every type of plate boundary within 150 miles (240 kilometers, fig. 1-3 A)! ***Subduction***, a specific type of plate convergence, is the most significant tectonic process shaping the landscape of the park. Subduction zones produce mountainous landscapes as well as the largest earthquakes in the world!

Wait, what are we looking at here?

Geologic processes are much easier to understand when diagrams accompany descriptions. Maps are a common way to illustrate Earth science concepts because they show us how certain features are distributed on Earth's surface. For example, let's assume that you're standing behind the desk at the Visitor Center. A couple approaches you, asking "so, where are the best places to go to see those big trees?" You smile, grab the official RNSP map and guide, lay it out in front of you, get your pink highlighter ready, and begin, "well, we are here...." As an interpreter, you use maps every day. But, maps can be used for more than just roads or hiking, and there are different types of maps designed to represent different spaces.

Road maps are the most familiar type of map, and they view space from a "bird's eye" view, as though the person looking down at the map were looking straight down on the landscape. This kind of view of Earth's surface is called ***map view*** (fig. 1-3 A). We can think of this as though there were an apple on the counter and we were looking directly down at its top surface from above. However, to understand better geologic processes sculpting the landscape, it is necessary to understand what is going on <u>below</u> Earth's surface.

Illustrations of below-the-surface processes require a different perspective, so they often portray the Earth's interior as though someone had made a vertical slice from the surface down into the Earth. We call diagrams of such "slices" ***cross-sections***. Were we to get a knife and slice the apple on the table in half and then bend down so that our eyes were level with its core to look directly at its interior, we would have a cross-sectional view of the apple.

Sometimes portraying the surface in relation to the interior is helpful in understanding geologic processes. Illustrations that show both surface and interior views of the Earth often take the form of ***block diagrams*** (fig. 1-3 B). Block diagrams attempt to portray a sort of three-dimensional "cube" of the Earth on a flat (two-dimensional) sheet of paper. We can visualize the kinds of views block diagrams represent by imagining picking up the sliced apple so that we can look at it from some angle that would allow us to see both its top surface and its interior slice.

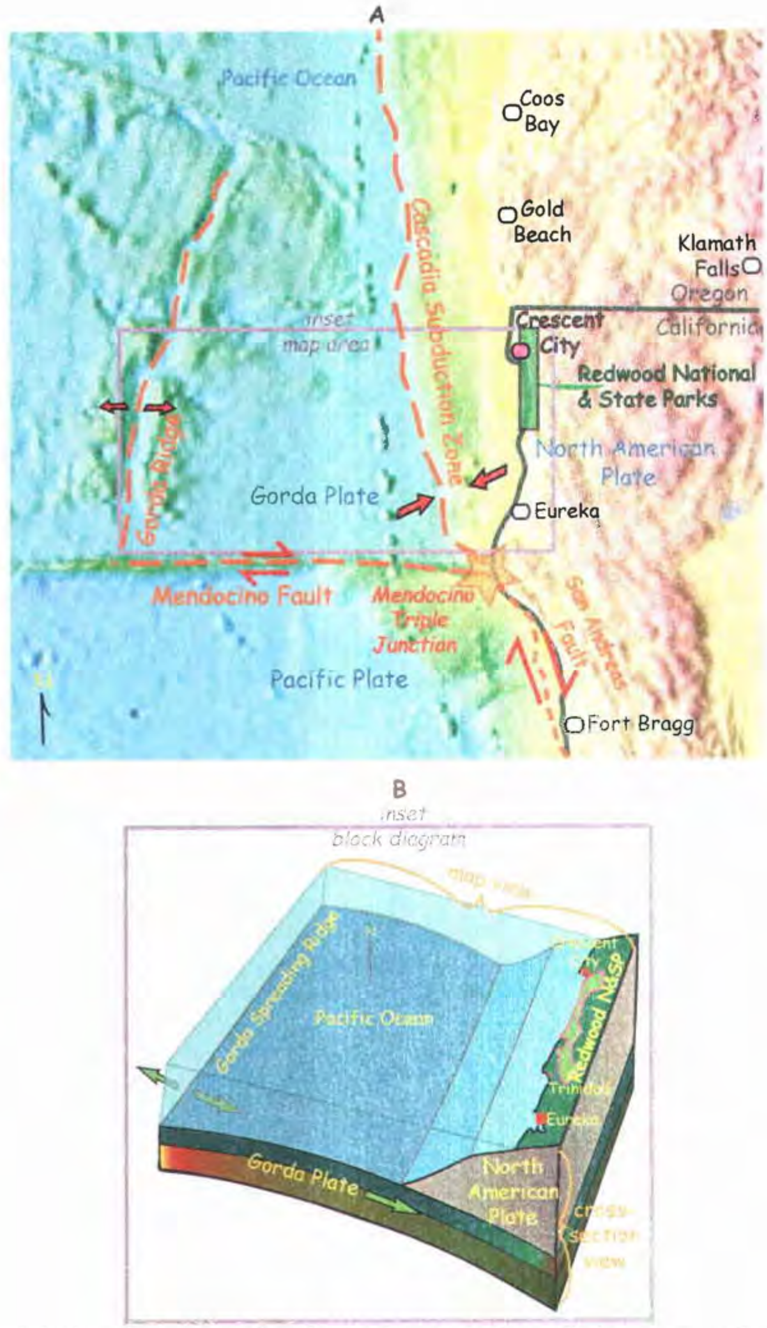


Figure 1-3: (**A**) There's some geology 'round here! In fact, all three types of plate boundary - convergent (Cascadia Subduction Zone), divergent (Gorda Ridge), and transform (San Andreas and Mendocino Faults) - are within 150 miles of RNSP, as shown on this map view. (**B**) Inset of rectangular area delineated on (**A**) portrayed in "block diagram" form, showing cross-section (side cut) view in relation to map (surface) view of RNSP. ("**A**" Modified digital elevation model from United States Geological Survey)

Contrary to popular conceptions, tectonic plates do not slide around on molten rock (***magma***). Rather, plate motions result from subtle differences in the strength of Earth materials. These differences are a consequence of two factors: 1) the composition of Earth's intermediate layer (the mantle), and 2) the increase in both temperature and pressure with depth in the Earth, so that the mantle has zones of different strength.

Inside Earth

If we travel back in time 4.6 billion years, we might imagine a spinning glob of molten material, gradually cooling from the outside inward. As it cooled, it segregated itself into layers of different chemical and physical properties. While the Earth was still molten, the inward pull of gravity preferentially separated materials. The "heavy stuff," dense materials such as iron and nickel, fell toward the center (core), whereas the lighter materials, compounds containing the elements silicon and oxygen, remained near the surface (mantle and crust). The different physical states depend on the temperature and pressure conditions of the various materials. To explore Earth's interior further, let's slice it in half (fig. 1-4).

Journey to the Center of the Earth: How do we know what's down there?

It is interesting to note that we recognize characteristics about the interior of the Earth through analysis of the very motions the Earth's interior produces. The classical triple-layer (crust, mantle, and core) Earth model is primarily based on chemical composition differences within the Earth, and scientific advancements have allowed us to understand the physical nature of those materials. Earthquakes generate several types of vibrations (seismic waves). By determining the speed at which the waves travel through different parts of the Earth, we get an image of Earth's interior as being solid, semi-solid, or liquid at different depths. Since the mid 1900s, observation of the travel of seismic waves has defined five divisions within the Earth based on the physical state of the materials in each of the three chemical layers.

Temperature

The diameter of the Earth is nearly 8,000 miles (13,000 kilometers). As we travel deeper into Earth from the surface, temperature and pressure both increase. The increase in temperature and pressure influences the ***physical state*** of Earth's chemical layers. We can use analogies to think of both of these factors. If we think of Earth as a baked potato, we can understand how temperature changes from the surface toward the core. As the potato cools, the center of the potato is insulated and remains hotter than the skin; it thus gets hotter as you cut deeper into the potato. In like fashion, at depths of 1,800 to 3,200 miles (2,900 to 5,100 kilometers), the temperature of the outer core is hot enough to melt iron, making the outer core liquid. So why then is the *inner* core thought to be solid? How is that possible? We need to think about pressure.

Pressure

Standing near sea level on the surface of the Earth, we are experiencing a pressure of one atmosphere. If you have ever been SCUBA diving, you understand that pressure increases by about one atmosphere for every 30 feet (10 meters) of water. Rock is approximately three times as dense as water, so pressure increases about one atmosphere per 10 feet (3 meters) of depth within the Earth. The inner core is 3,200 miles (5,100 kilometers), or 17,000,000 feet deep. At one atmosphere per 10 feet (assuming constant density), the pressure on you would be 1,700,000 atmospheres! If you went to the very center of the Earth (4,000 miles, or 6,400 kilometers, deep), there would be over two million atmospheres of pressure squeezing in on you from all sides! So, even though the extremely high temperatures of Earth's core melts iron at low-to-moderate pressures, the inner core is solid because of the extreme pressure; in other words, the molecules collapse into crystalline structures.

Strength and Movement

Most of the plate movement that we're interested in occurs closer to Earth's surface. So let's focus on the upper mantle, including the asthenosphere and overriding plates of lithosphere. The crust we walk on and the outermost portion of the mantle are generally cool enough to be in hard, solid states; those two layers constitute the plates of lithosphere. Deeper than about 100 miles (150 kilometers) into the mantle, temperature is high enough that the asthenosphere is not a completely hard solid (think of how butter softens when left out on the counter at room temperature). Below the asthenosphere the lower mantle is even hotter, but it is under so much pressure that it is a hard solid. If we conceptualize this "sandwiching" of the asthenosphere, we can compare the asthenosphere to the creamy filling of a moon pie. The hard upper cake would represent the lithosphere (crust and upper mantle), while the creamy filling would be the asthenosphere, and the hard lower cake the solid lower mantle (fig. 1-5).

***Jargon* alert!**

Most science fields have their own sets of terminology ("lingo") that matter mostly to the scientists in those fields. The danger of using "big words" in your interpretive talks and programs is that when people hear unfamiliar words that they don't understand, they "turn off" and stop listening because they can't relate - they have no connection with the words you're using. Once you've lost your audience, it's difficult to regain their interest and attention. (This is especially true if your audience has younger children because once you lose the kids, the parents must redirect their attention to their disinterested children.) But, even if you don't use scientific "jargon," you should understand the processes to which the jargon refers so you are able to read scientific literature and address the more-involved questions from visitors.

Most visitors are likely to have heard the terms "crust," "mantle," and "core" in reference to different layers of the Earth. But sometimes these familiar layers need to be differentiated in order to understand concepts such as plate tectonics. You might be tempted to say that the "lithosphere," or a "plate," is simply the "crust." A lithospheric plate is composed of both the crust and the outer, rigid portion of the mantle. Or you might be inclined to say that the "asthenosphere" is simply the "mantle." The asthenosphere is the softer section of the mantle between the rigid lithosphere and the rigid lower mantle.

For interpretive purposes, it may be practical to stay with the familiar terms "crust" and "mantle," but you, the interpreter, should understand that the lithosphere includes both the crust and part of the upper mantle.

So why do the plates actually slide around instead of simply "floating" in a stationary position on the asthenosphere? You will recall that temperature increases with depth in the Earth, and you may also know that, just as hot air rises, hot, solid material sometimes tends to expand and rise. Material heated within the lower part of the asthenosphere expands and slowly rises. Once it reaches the lithosphere boundary, it has cooled sufficiently enough to contract and be pushed aside by more rising material. This process creates moving ***convection cells*** within the asthenosphere, similar to the movement of water in a boiling pot (only much, much slower!). Movement of the soft,

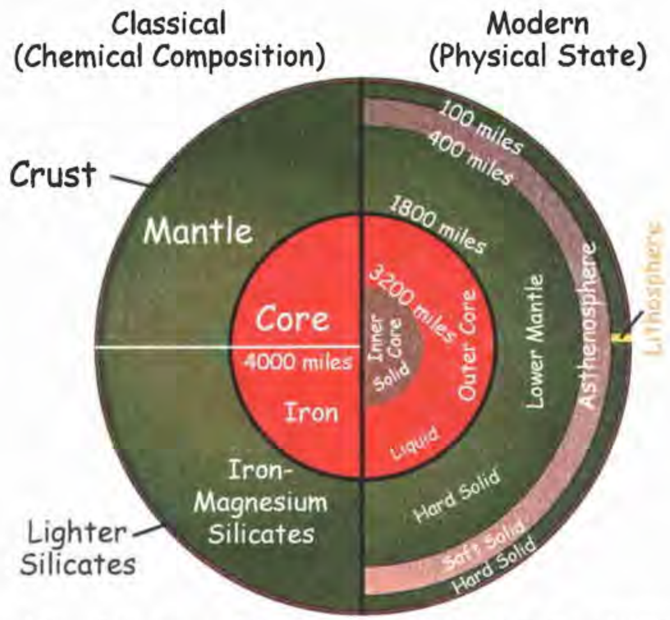


Figure 1-4: General cut-away of Earth. On the left side is the classic division of Earth's interior into core, mantle, and crust. The materials grade according to chemical composition from heavy, iron-rich material in the center to lighter silicates on the outside. On the right side is the modern division of Earth's interior, based on the physical state of the materials as determined by the way earthquake seismic waves travel through the Earth. (Modified from Lillie, 2004)

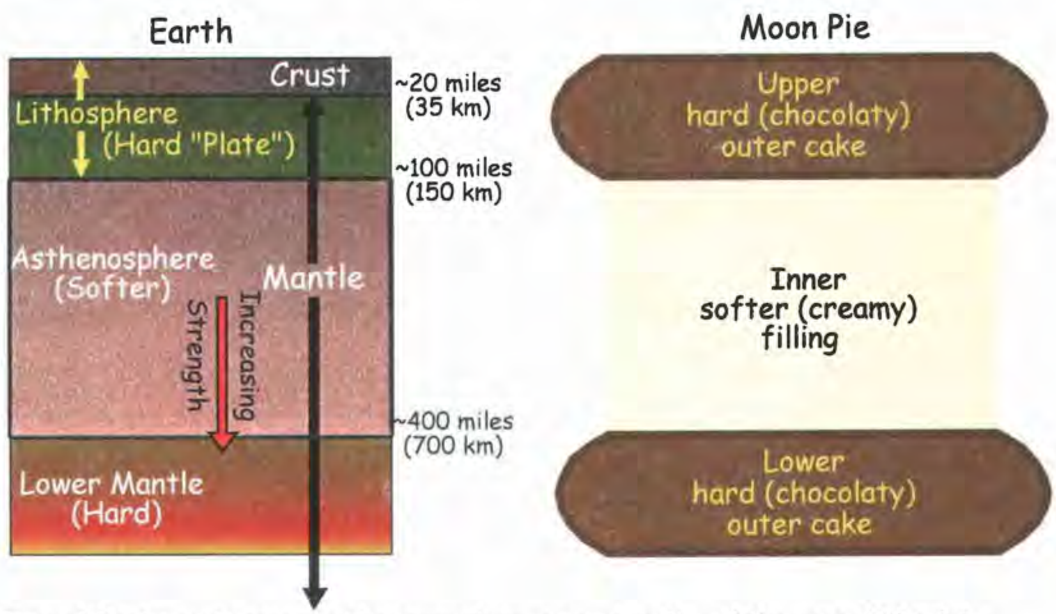


Figure 1-5: A cosmic cross-section comparison: a cross section of the upper 600 miles (1000 km) of the Earth, showing the crust and upper part of the mantle. As we go deeper into the Earth, temperature and pressure increase in such a way that the mantle exists in two different physical states. The uppermost mantle and crust are both cold and rigid and comprise the plates of lithosphere. Hotter mantle below the lithosphere forms the softer asthenosphere. Pressure increases with depth, however, so the asthenosphere gradually is more compressed and becomes stronger, forming the more solid lower mantle. Lithospheric plates can be compared to the hard, chocolaty outer cake of a Moon Pie, riding on the soft, creamy filling (asthenosphere). The lower cake (lower mantle) does not move.

flowing asthenosphere in such tectonic convection cells helps drive the overlying plates, creating the exciting tectonic features along plate boundaries.

Using Oreo® cookies to demonstrate Northwest tectonics.

Everyone can relate to food, which is the main reason that so many geologists and rangers use food analogies to explain processes that may seem too technical or complicated for most visitors. There are several ways to demonstrate the motions of plates using Oreo® cookies, but to thwart your audience from eating your props before you finish, let's concentrate on RNSP's most pertinent plate motion: subduction. Just 30 miles (50 kilometers) west of Crescent City, the oceanic (Gorda) plate is diving beneath the continental (North American) plate along the Cascadia Subduction Zone. Have your audience carefully twist off one of the hard outer cookie layers (using Double Stuff® Oreos® makes this part easier, fig. 1-6 A). Explain that the two cookie halves represent the Gorda Plate and the North American Plate. Ask your audience what is on the bottom of the ocean. Provoke answers such as "sand," "mud," and "shells," but generic terms like "muck" will do. Have them imagine that all the sand, mud, and shells is the creamy filling. Then ask them what type of plate the cookie under that filling must represent (oceanic) and what its name must be (Gorda). The other cookie is the North American Plate, which should be positioned on top of the filling of the Gorda (fig. 1-6 B,C).

Have the visitors scrape "North America" over the filling so that the filling begins to rumple and bunch just over the edge of North America (fig. 1-6 D). Ask if anyone had trouble getting the cookies to slide past each other without having them stick and release a few times (someone will always say yes). Ask people what happens when the plates have stuck together for a while and then suddenly release (just like the cookies did, but with much more impact): we get an **EARTHQUAKE**! Explain that as Gorda subducts, sediments from the sea floor are scraped off and smooshed onto the edge of the continent as the process of subduction and earthquakes continues.

Ask visitors what the smooshed-up creamy filling now represents (the Coast Range mountains, fig. 1-6 D,E). Then remind them what kinds of things are in the creamy filling (sand, mud, and shells) and have them think about what we might find in the rocks of the Coast Range (sandstone, shale/mudstone, fossils). This demonstration is ideal in places, such as Mill Creek campgrounds where some of the trails lead past outcrops of fossiliferous sandstone.

Thick and Buoyant Crust

For the simple reason that we have direct contact only with the surface of the Earth, it is this portion of the Earth - the crust (upper lithosphere) - with which we are primarily concerned. We have already established that the intermediate layer of the mantle (asthenosphere) is less solid than the overlying lithospheric plates. The crust is less dense than the underlying mantle, meaning that blocks of crust essentially "float" on

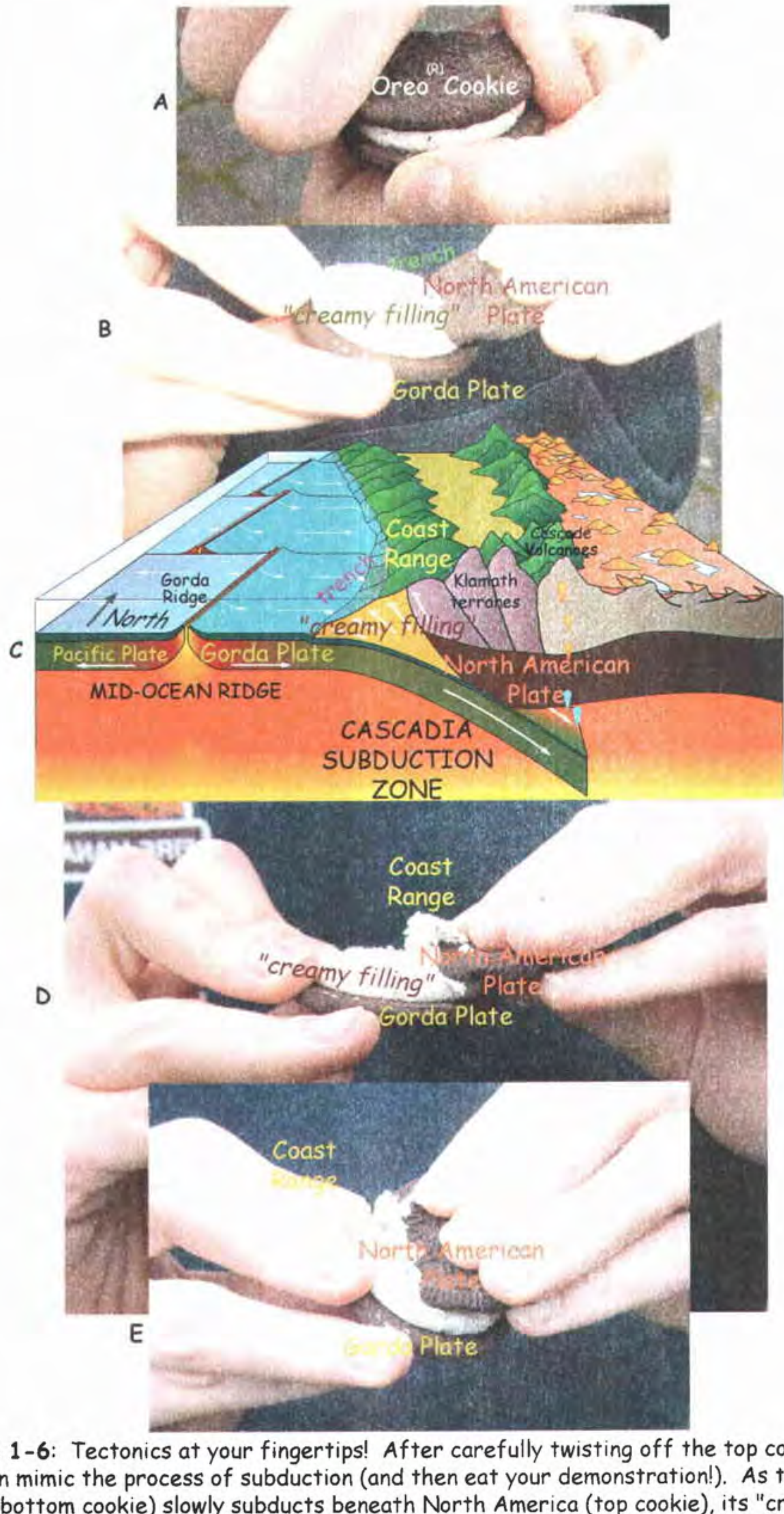


Figure 1-6: Tectonics at your fingertips! After carefully twisting off the top cookie (**A**), you can mimic the process of subduction (and then eat your demonstration!). As the Gorda Plate (bottom cookie) slowly subducts beneath North America (top cookie), its "creamy filling" (ocean floor sediments) are scraped off and shoved onto the edge of North America (**B**, **C**). These uplifted layers form the Coast Range (**D**, **E**). ("**B**" modified from Lillie, 2004, Photos by J. Natoli)

the upper mantle part of the plates. Plates are capped by two different types of crust: thin oceanic crust and thick continental crust.

Oceanic crust, for the most part, is younger and has undergone much less "smooshing" than continental crust. It is also a lot thinner: the crust beneath the oceans is only about 4 miles (7 kilometers) thick, compared to continental crust, which is about 20 miles (35 kilometers) or so thick. We can visualize how the difference in thickness between oceanic and continental crust affects tectonics by thinking of a tennis ball and a beach ball floating in a pool (fig. 1-7). If you have ever attempted to push a beach ball under the water you have probably found it rather difficult. This is because the beach ball is thick and therefore ***buoyant***. Submerging a tennis ball, which is thin, is much easier. Now, substitute continental crust for the beach ball, oceanic crust for the tennis ball, and the Earth's mantle for the pool of water, and you have a conceptual model for how the two types of crust float on the mantle. We can understand why, where plates converge in Northern California, the one with thin oceanic crust descends (subducts) beneath the one that has thick continental crust. Most Earth processes are connected, so understanding relationships like plate thickness and buoyancy help us to understand better how plates interact along their edges.

Focusing in on the Pacific Northwest

In order to see the relationships between geology and other elements of the RNSP ecological system, it is important to understand how the present redwood landscape came to be. Equally important is conveying this information to visitors in a cohesive "story." The more familiar (and dynamic) your context, the more attentive your audience, so relate the geological observations and processes to things they likely have experienced. Visitors to RNSP are undoubtedly familiar with stories of the frequent earthquakes that shake the region, thus they will likely be interested in learning about the causes. Redwood is in a unique plate tectonic setting. The North American, Pacific, and Gorda plates intersect just south of the park at the **Mendocino Triple Junction**, and just off our shore is the ***Cascadia Subduction Zone*** (fig. 1-3 A, Dengler and Moley, 1999). The near-coast processes, including plate subduction and transform (strike-

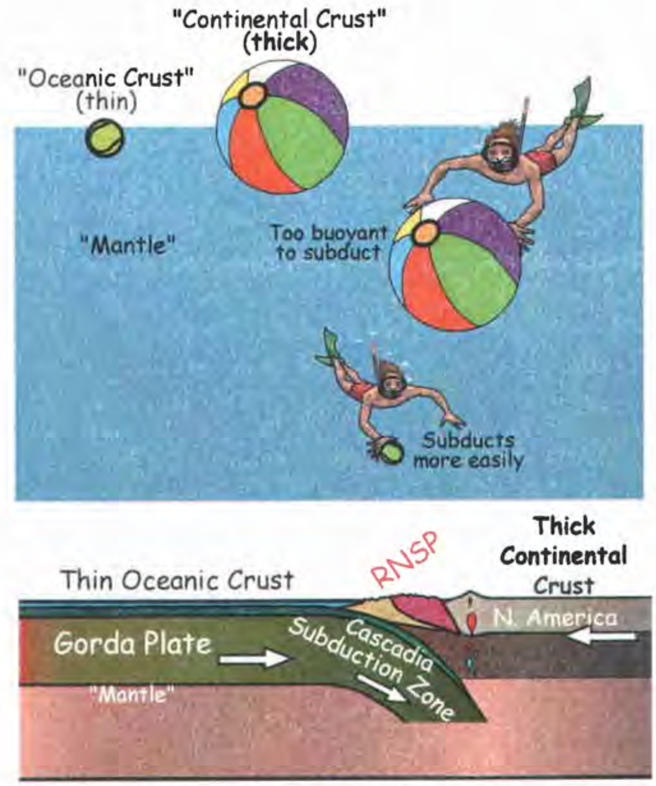


Figure 1-7: On the edge - why the land is high but the sea floor is low. The thick, buoyant beach ball floats high in the pool, whereas the thinner, less-buoyant tennis ball rests lower. Similarly, the thinner oceanic crust is less buoyant and "floats" lower in the mantle than the thick continental crust. Where the plates converge, the one with thinner oceanic crust "sinks" (subducts) beneath the one capped by thicker continental crust.

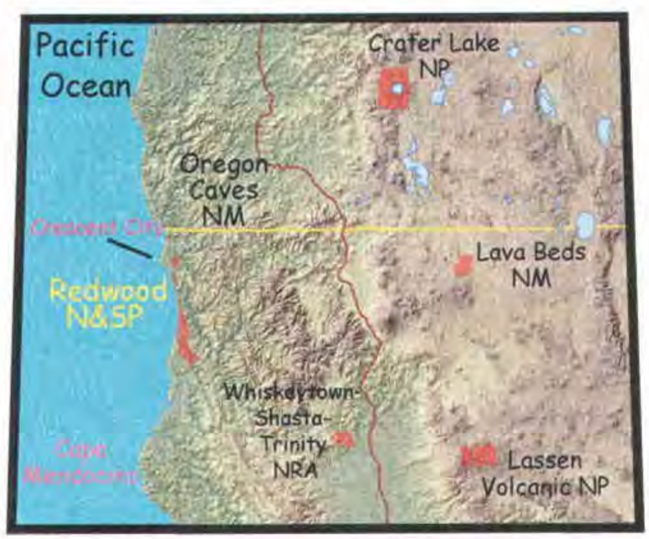


Figure 1-8: National Parks of the Northwest shown on a digital elevation model of Northern California. Note the "elbow" of California, where the Mendocino Triple Junction forms Cape Mendocino and the "Lost Coast" section of the coast. The entire west coast resembles a "crumpled rug" as mountains are shoved up from subduction-related processes (fig. 1-9).

slip) motion, are the park's primary dynamic forces. Subduction has the dominant impact on the stability and resulting landscape of RNSP (figs. 1-8, 1-9). To understand the basic geologic setting of the North Coast, let's look at the geometry and relative motions of the plates involved (figs. 1-9, 1-10).

Fingernail Tectonics: Tectonic tools right at your fingertips!

Here's an activity designed so that visitors of all ages can appreciate Earth's movements. When talking about large earthquakes or the geologic past, it's a good idea to pause for a moment and ask your audience to put their hands out in front of them and look at their fingernails. From there, you can steer the demonstration something like this: "Ok, now I want you to look at your fingernails. Look really closely - and watch them grow...[pause for ensuing laughter]. Think we'll be here a while? Well, the plates move at about the rate your fingernails grow! So, place the fingers of one of your hands against the palm of the other. Let's pretend we can stop your fingernails from growing for 50 years. Imagine the pressure you'd feel as you resist the growth of your fingernails. Then, 50 years from now, you decide you can't hold off that natural growth any longer and you suddenly allow your fingernails to shoot out from your fingertips. They would need to grow <u>four feet</u> to make up for the one inch per year growth you were blocking them from doing. That's how much plates suddenly lunge after being stuck together for decades, producing large earthquakes."

Gorda Ridge

Recall that convection currents create certain forces in Earth's mantle. Where convection cells rise and diverge, the opposing pull rips the overlying plate apart, splitting it in two and creating a ***divergent plate boundary***, or spreading center (fig. 1-11). It is here that new plate material is formed, then pushed aside and carried along in a "conveyor belt" fashion. The plates are youngest right at divergent boundaries and get older away from the boundary (fig. 1-12). This process is occurring off our coast about 150 miles (240 kilometers) west of Crescent City at the Gorda Ridge (fig. 1-3 A). The ***Gorda Ridge*** separates the Pacific Plate from the Gorda Plate, which is a fragment of the larger Juan de Fuca Plate situated to the north (fig. 1-1).

Where the Pacific and Gorda plates are being forced apart, hot mantle (asthenosphere) rises to fill in the gap. The pressure lessens as the mantle shallows, inducing melting and forming molten rock called magma. The hot magma rises and quietly erupts as pillows of lava on the sea floor at the ridge, adding new rock to the edges of both plates. Like a conveyor belt, the newly formed crust forces the plates apart,

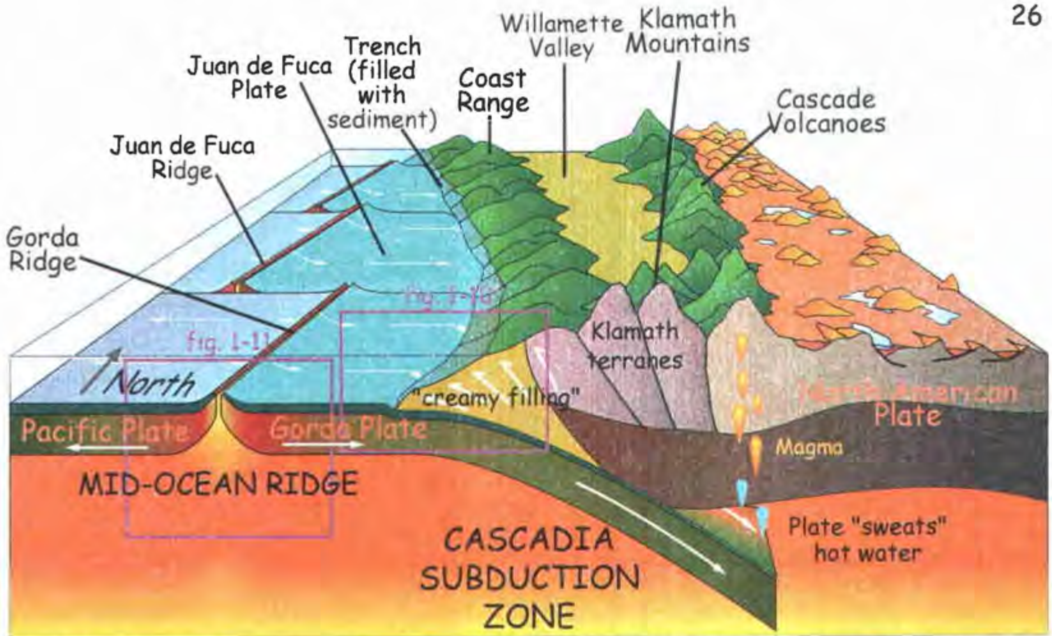


Figure 1-9: You are now entering...the SUBDUCTION ZONE! The Cascadia Subduction Zone is an active convergent plate boundary wherein the Gorda Plate scrapes beneath the North American Plate. When the plates move suddenly, we get earthquakes, and as the Gorda Plate gets "cooked" in the mantle, hot water rises, eventually resulting in magma that erupts via the Cascade Volcanoes. The process of subduction creates two parallel mountain ranges, the Coast Range and the Cascades. In between lie the Great Valley in California, and the Willamette Valley in Oregon. Directly east of RNSP, however, we have the Klamath Mountains, bits of land (terranes) that were rafted in and attached ("sutured") onto the edge of North America (fig. 1-13). (Modified from Lillie, 2004)

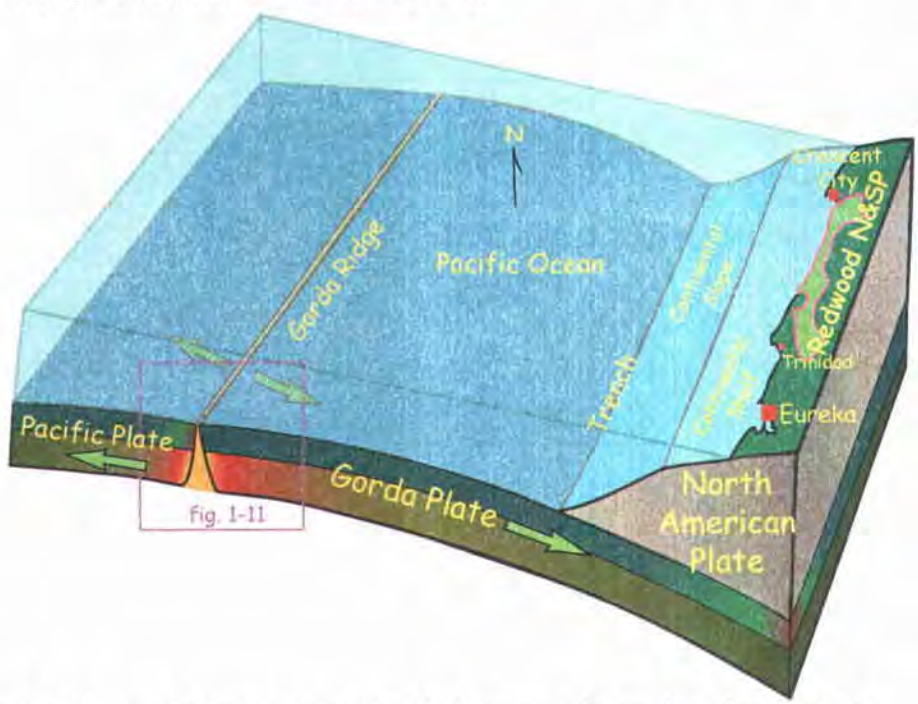


Figure 1-10: Local tectonics in action! Block diagram showing how close the plate boundaries are to Redwood National and State Parks. Geologic processes sometimes seem abstract to the public, so understanding that these processes happen within a few miles of RNSP can help make geology more meaningful.

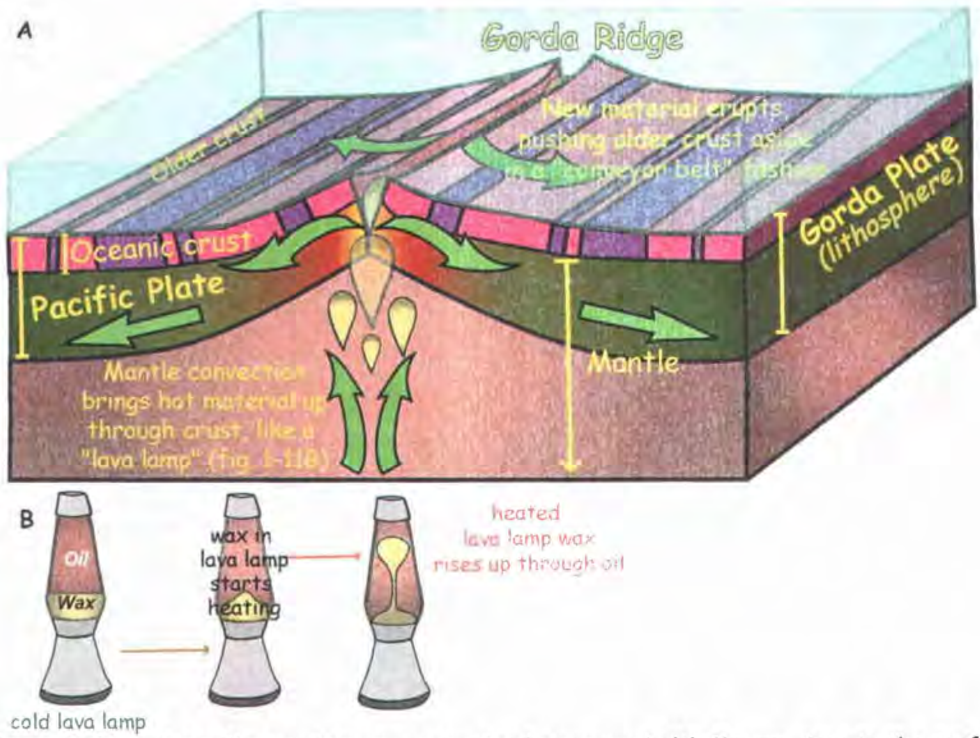


Figure 1-11: Spreading center: an ocean-sized conveyor belt! Magma rises to the surface via mantle convection (**A**) in a way similar to blobs of "lava" in lava lamps (**B**). As new material emerges and forms new oceanic crust, older crust is pushed aside from the ridge just like it was on a conveyor belt, forming mirror image patterns on either side of the divergent boundary (fig. 1-12). (**B**) Instant mojo: hot magma rises from the mantle like blobs of wax "lava" moves through lava lamp oil as the lamp heats up the wax. ("**B**" modified from Lillie, 2004)

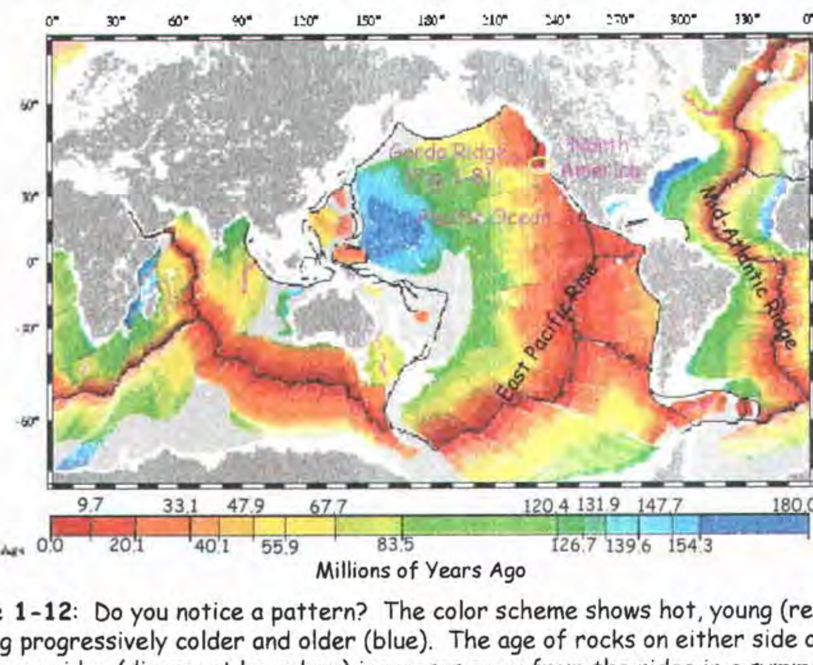


Figure 1-12: Do you notice a pattern? The color scheme shows hot, young (red) rocks getting progressively colder and older (blue). The age of rocks on either side of a mid-ocean ridge (divergent boundary) increases away from the ridge in a symmetrical pattern. Such a "mirror image" pattern suggests a process whereby molten rock solidifies near the surface and then is pushed aside by newer magma (fig. 1-11). Notice the color (age) of the ocean floor nearest the Gorda Ridge. Would you say the sea floor near RNSP is old or young? (Modified from Muller, Roest, Royer, Gahagan, and Sclater, 2000)

forcing the Gorda plate to move toward North America (figs. 1-9, 1-10). The full rate at which new crust is produced at the southern end of the Gorda Ridge is just under 2 inches (4 centimeters) per year (Wilson, 1989). That's about as fast as your fingernails grow! To figure out how fast the Gorda Plate is being forced toward North America, we need to cut 1.5 inches per year in half (because half of the new crust goes East and half goes West), so the Gorda Plate is growing at about an inch (2.5 centimeters) a year. At its widest, the Gorda plate is about 150 miles (240 kilometers) from ridge to trench. In about 5 million years, a segment of new crust is transported about 100 miles (160 kilometers) from the Gorda Ridge (where it is created) to the Cascadia Subduction Zone (where it descends back into the Earth and is recycled). In fact, the oldest rocks found on the Gorda Plate are about 5 million years old, pretty young for a plate (Beaudoin and others, 1996).

Cascadia Subduction Zone

The landscape of the Pacific Northwest from Cape Mendocino (California), 650 miles north to Vancouver Island (British Columbia), and extending 100 miles east to the Cascade Mountains, can be largely attributed to the Cascadia Subduction Zone. The process of subduction creates the parallel mountains comprising both the Coast Ranges and the Cascades, with prominent valleys in between.

About 5 million years after it forms at the Gorda Ridge, oceanic crust of the Gorda Plate enters the Cascadia Subduction Zone (Beaudoin and others, 1996). Like the tennis ball in our earlier analogy, the young, thin crust of the Gorda Plate descends beneath the thick, buoyant crust of North America (beach ball) (fig. 1-7). The Gorda Plate is converging with the North American Plates at a rate of about 1 - 1.5 inches (2.5 - 3 centimeters) per year (Oppenheimer and others, 1993). The two plates meet about 33 miles (52 kilometers) west of Crescent City. We can visualize the process of subduction by simply pantomiming the Gorda Plate descending beneath North America with our hands. As one hand slowly scrapes over the other, both tend to "crumple" and bend (fig. 1-13).

A structural ***trench*** forms where the two plates crash into each other and the Gorda Plate flexes downward under the pressure of convergence (figs. 1-9, 1-10, 1-13). The Cascadia trench is shallow relative to other subduction trenches around the world because the wet climate of the Pacific Northwest erodes mountains at a high rate, supplying much sediment to the system. The sediment is then deposited off shore and naturally fills in the trench (Willett and others, 1993). Trench sediments are eventually scraped off the top of the Gorda Plate and uplifted into the Coast Range Mountains. (So, were you to go SCUBA diving, you would not actually see a depression on the sea floor because the trench is completely filled with sediment.)

Coast Range

The Coast Range is dominantly tilted layers of sea floor sedimentary rocks (mostly sandstone and shale) that have been crumpled onto the edge of North America (figs. 1-9, 1-10). As in our Oreo® Cookie demonstration, some of the "stuff" at the bottom of the Pacific Ocean that comprises the top of the Gorda Plate gets scraped off and smashed up onto North America. (Geologists call this wedge of material "smooshed" onto the edge of the continent an "***accretionary wedge***," or "***mélange***.") Accretion crumples rocks around the subduction zone, creating the surface textures (structures such as folds and reverse faults, discussed in Chapter 3) and causing earthquakes along the coast. The process of accretion has been occurring in the Pacific Northwest for the past 150 million years, but the oldest rocks comprising the northern California Coast Range formed about 100 million years ago, after the Klamath Mountains formed (see "Klamath Mountains").

The Franciscan assemblage is the name given to most of the rocks we can see exposed along the coast of RNSP (see "Enderts Beach"). The rocks comprising the Franciscan assemblage were accreted to North America about 50 million years ago (Blake and others, 1985). They were subducted to a depth of about 11 miles (18 kilometers) along the subduction zone before being added to the continent (Beaudoin and others, 1996). The heat and pressure 11 miles down inside Earth essentially "pressure cooks" (metamorphoses) the rocks, after which rocks were uplifted and exposed along the present-day coast by about 14 million years ago (Harper, 1980).

Klamath Mountains

We can think of the Klamath Mountains as an anomaly to an otherwise straightforward subduction zone system. The geography of a "normal" subduction zone system consists of two parallel mountain chains separated by a low area, or basin. The chain farthest from the subduction zone is volcanic (Cascade Mountains), and the chain nearest the subduction zone is accreted material (Coast Range). We can see this geography all the way from the Olympic Mountains (separated from Mount Rainier by Puget Sound in Washington), to the Oregon Coast Range (separated from the Cascades by the Willamette Valley), and then the California Coast Range (separated from Mount Lassen and Mount Shasta by the Great Valley). The southern basin that is equivalent to Puget Sound and the Willamette Valley is the Great Valley in California. But the Klamath Mountains in southern Oregon and northern California seem to block the otherwise smooth continuation of the basin.

The simplest way to explain the formation of the Klamaths is to think of the Cascadia Subduction Zone as functioning as a "conveyor belt," smooshing the sea floor and other "exotic" bits of land onto the West Coast (fig. 1-9). As ancient parts of the oceanic plate subducted during the past 150 million years, volcanic island chains and other bits of thick crust were carried eastward and crashed into the area that is now southern Oregon, forming the Klamath Mountains (fig. 1-14).

The first (oldest) material to be accreted onto North America in the Klamath region is about 160 million years old, and it is called the Smith River terrane (see Josephine Ophiolite section). Everything else was added later and to the west of the Smith River terrane, so the rocks of the Klamath Mountains generally are in bands that parallel the north-south trend of the Coast Range and get progressively younger toward the west. In fact, the two youngest terranes are the King Range (see Mendocino Triple Junction section) and the Coastal terrane (see "Enderts Beach"). The Coast Range terrane started *accreting* onto North America about 90 million years ago, and the

Figure 1-13: A "handy" demonstration of subduction! As one hand scrapes over the other, your fingers and skin will crumple in a manner similar to the way rocks are "smooshed" near the Cascadia Subduction Zone. (Photo by J. Natoli)

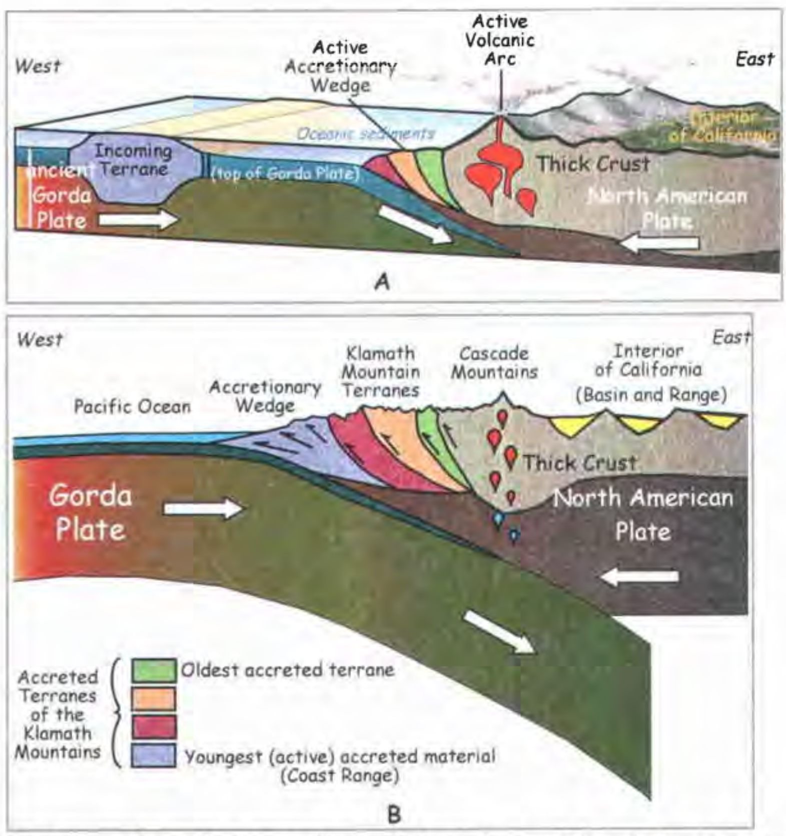


Figure 1-14: Incoming! As the Gorda Plate subducts beneath North America, materials being carried along with the plate crash into the edge of North America. The materials include everything from sea floor sediments to whole "exotic" volcanic islands! This process of "smooshing" large blocks of material onto the edge of the continent is called terrane accretion. (**A**) Block diagram showing an individual terrane of the Klamath Mountains moving toward the edge of North America before being "smooshed" against older terranes.
(**B**) Cross section showing RNSP at present, thousands of years later. A series of accreted terranes have become the Klamath Mountains. Note that the Klamaths fill the space that would have been a continuation of the Willamette Valley to the north connecting with the Great Valley to the south (fig. 1-9). Did you know that much of the land west of the Rocky Mountains was added to North America via terrane accretion over the last 200 million years? ("**A**" modified from Marshak, 2001)

Franciscan rocks (see "Enderts Beach") were accreted by about 50 million years ago. The King Range terrane is the most recent addition to the North Coast, having been accreted about 14 million years ago (Blake and others, 1985).

How's that again?

Remember! There can be a very long time difference between when rocks originally form and when they end up where you can see them today (that's why we can find rocks that are over a billion (!) years old in Australia even though they didn't originally form there). So while the youngest Klamath terrane, the Coastal terrane, originally formed (became rock) at the ancestral Gorda Ridge about 100 million years ago, it took about 10 million years for the Coastal terrane to travel along in "conveyor belt" fashion to the edge of North America - that's why it didn't start accreting onto North America until 90 million years ago. Accretion of the Coastal terrane lasted for about 40 million years. The last part of the Coastal terrane, the Franciscan rocks, were finally in place (emplaced) by 50 million years ago.

The Klamath terranes have unique minerals uncommon to the rest of the RNSP region (Harper, 1980). There are even ore deposits in the Klamath Mountains that have been eroded and transported and deposited in other parts of RNSP, including Gold Bluffs Beach (see "Gold Bluffs Beach").

Cascade Mountains

Gorda plate subduction also explains the presence of volcanoes paralleling the Coast Range. Let's think of it this way: how does temperature change as you go deeper into the Earth? (It gets hotter.) And what do you start to do when you get hot? (Sweat!) This analogy is useful to explain what happens to the Gorda Plate as it subducts deeper into the mantle beneath North America. There is a significant amount of water in the sedimentary layers and underlying igneous rock comprising Earth's crust beneath the Pacific Ocean. As the crust is forced deeper and experiences higher and higher temperatures, the water is "squeezed out" (scientists call this "slab dehydration"), rises, and interacts with rocks of the overlying plate (fig. 1-9). The chemical reaction between hot water and hot rock causes some rock to melt. The hot, molten rock (magma) then rises through cracks and melts its way upward, eventually reaching the surface and forming the Cascade volcanoes.

The top of the plate is quite wet
but deeper and hotter it gets
hot water melts rock
the magma goes up
volcanoes form when the plate sweats.

Mendocino Triple Junction (King Range)

South of Redwood National and State Parks, Cape Mendocino is famed for the rugged, beautiful "Lost Coast" and the steep, dramatic King Range. The King Range is, in fact, one of the most rapidly uplifting mountainous regions in the world. The rapid uplift (between 1 and 1.5 inches, 3 to 4 centimeters, per year) can be attributed to the interaction of <u>three</u> different tectonic plates (Heaton and Hartzell, 1987). This region, where the Pacific, North American, and Gorda Plates meet, is called the Mendocino Triple Junction. The triple junction was "born" probably between 25 and 29 million years ago, when part of an ancient plate (the Farralon Plate, of which the Gorda Plate is a remainder) was subducted beneath the North American continent (Atwater, 1970). The nature of the motion between oceanic crust and continental crust changes at this point from subduction on the north to transform motion on the south (fig. 1-15). This is where the San Andreas Fault "begins" (or ends, depending on your perspective). The San Andreas Fault is part of the transform boundary along which the Pacific Plate slides by North America in a northwesterly direction. Another transform boundary (called the Mendocino Escarpment) exists between Pacific Plate oceanic crust and Gorda Plate oceanic crust, where the Pacific Plate moves westward past the easterly-subducting Gorda Plate. Phew! Lots of activity and interaction make the Mendocino Triple Junction an incredibly earthquake-prone area, and Eureka lies on the surface not far away. Caution your visitors if they're heading south!

<u>As Seen in Redwood National and State Parks!</u>

In RNSP, unique vegetation flourishes because of the 80 to 100 inches (200-250 centimeters) average precipitation it receives per year (Pitlick, 1995; see Appendix A, answer #6). The high precipitation in RNSP classifies the climate as just shy of a temperate rainforest, helping to explain the region's dense vegetation. The thick plant cover makes observation and interpretation of RNSP's geology more challenging because the greenery largely obscures the rock, yet there are a few high visitation places in the park where rocks are exposed. Such outcrops, coupled with fantastic panoramas of the landscape along the coast, afford opportunities to interpret the geologic processes responsible for the way the rocks look.

Enderts Beach

Many tidepool programs begin at the parking lot to Enderts Beach. A steep, rocky cliff flanks the short, half-mile trail down to the ocean. On the right, the cliff extends down to the Pacific, and the cliff rises up dramatically on the left. The rocks are cracked (fractured, figs. 1-16, 2-4 A) and there is evidence of frequent rock slides (slope failures) all along the trail. The rocks are slightly greenish near the top of the trail and more grey near the beach. In fact, look closely, and you'll see swirled patterns of grey and white layers in outcrops at the beach. Let's figure out how they got to look like that way.

Layers of sand, silt, and mud particles flushed out to sea from North Coast rivers eventually become sedimentary rock at the bottom of the Pacific Ocean. Sediments from continental rocks contain the mineral *quartz* and other light-colored, silica-rich compounds. As the layers are compacted and pushed down the Cascadia Subduction Zone, hot water percolates through and dissolves silica from the sediments. This silica-rich water then follows cracks in the rocks along which the silica precipitates in the form of sinuous ***quartz veins***. The sedimentary layers of sandstone, siltstone, mudstone, and shale are then scraped from the top of the subducting Gorda Plate and smashed onto the edge of the continent, complete with quartz veins. So, we see these deformed layers at the coast after they've been "smooshed" (hence the swirled appearance and cracks, fig. 1-16) and uplifted!

If you were to gaze across Crescent Bay from the Enderts Beach lookout, you'd be looking northward across Crescent City Harbor. Barring fog, you'd see the Battery Point lighthouse. If visibility were particularly good, you might be able to see even

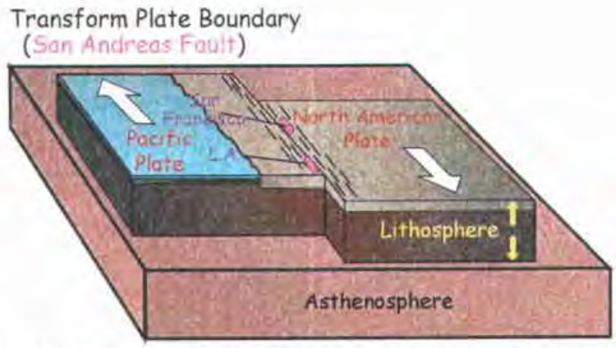


Figure 1-15: Will Los Angeles join San Francisco? The San Andreas Fault is gradually sliding L.A., which is on the Pacific Plate, toward San Francisco, which is on the North American Plate. Don't worry - L.A. would have to wait for Cape Mendocino to migrate north before it meets Crescent City!

Figure 1-16: And you thought waiting until the next rest area on Hwy 101 was a lot of pressure! Sandstone and shale layers originally deposited horizontally on the Pacific Ocean floor have been scraped from the top of the subducting Gorda Plate and uplifted onto the edge of North America. The "smooshed" layers of sedimentary rock exposed at Enderts Beach show the effects of the high pressures of subduction. (Photo courtesy of NPS)

farther north to the Point St. George lighthouse. People who come into the visitor center at RNSP's Crescent City headquarters often ask about scenic drives near Crescent City, and interpreters can recommend the Pebble Beach drive, which routes visitors north to the Point St. George lighthouse. Along the way, the drive passes Pebble Beach, where there is a well-known rock formation called the St. George Formation (named after Point St. George, where the lighthouse is). The rocks of the St. George Formation are much younger (about 150,000 years) and have not been as "smooshed" as the rocks exposed at Enderts Beach (Aalto, 1999). The St. George Formation rocks are dominantly siltstone and sandstone, similar to the grey layers of rocks seen at Enderts Beach . Obvious in these younger sedimentary rocks are intact fossil seashells, which would have been altered or destroyed had the rocks been as deformed as those at Enderts Beach. Rangers leading coastal walks at Enderts Beach might want to use this comparison to illustrate the differences in processes active around RNSP.

Josephine Ophiolite (Smith River)

Any visitor driving to RNSP along US highway 199 from Grants Pass, Oregon, will not be able to avoid noticing the green-colored, serpentine cliffs flanking the Smith River. We can help them realize that serpentine rock is prone to landsliding because it is weakened from all the pressure it experienced while being exhumed from near the mantle. Those visitors camping at Jedediah Smith Redwoods State Park get to see the Smith River gorge just east of their campsites, and there's even a popular rock jumping spot at the confluence of the Smith River and the South Fork in the Smith River National Recreational Area (US Forest Service). The Smith River has cut down through the ***Josephine Ophiolite***, whose highly fractured green serpentine cliffs easily weather and erode, which is why there are so many landslide scars on the cliffs along highway 199 (fig. 1-17 B, D; Harper and others, 2002). To explain why the rocks along the Smith River look like they do, we need to understand how an ophiolite forms.

The Gorda Plate smashes against North America as it plunges down into the Cascadia Subduction Zone. The oceanic plate resists the extreme force behind this collisional process, and sometimes even deep parts of the oceanic plate are shoved up

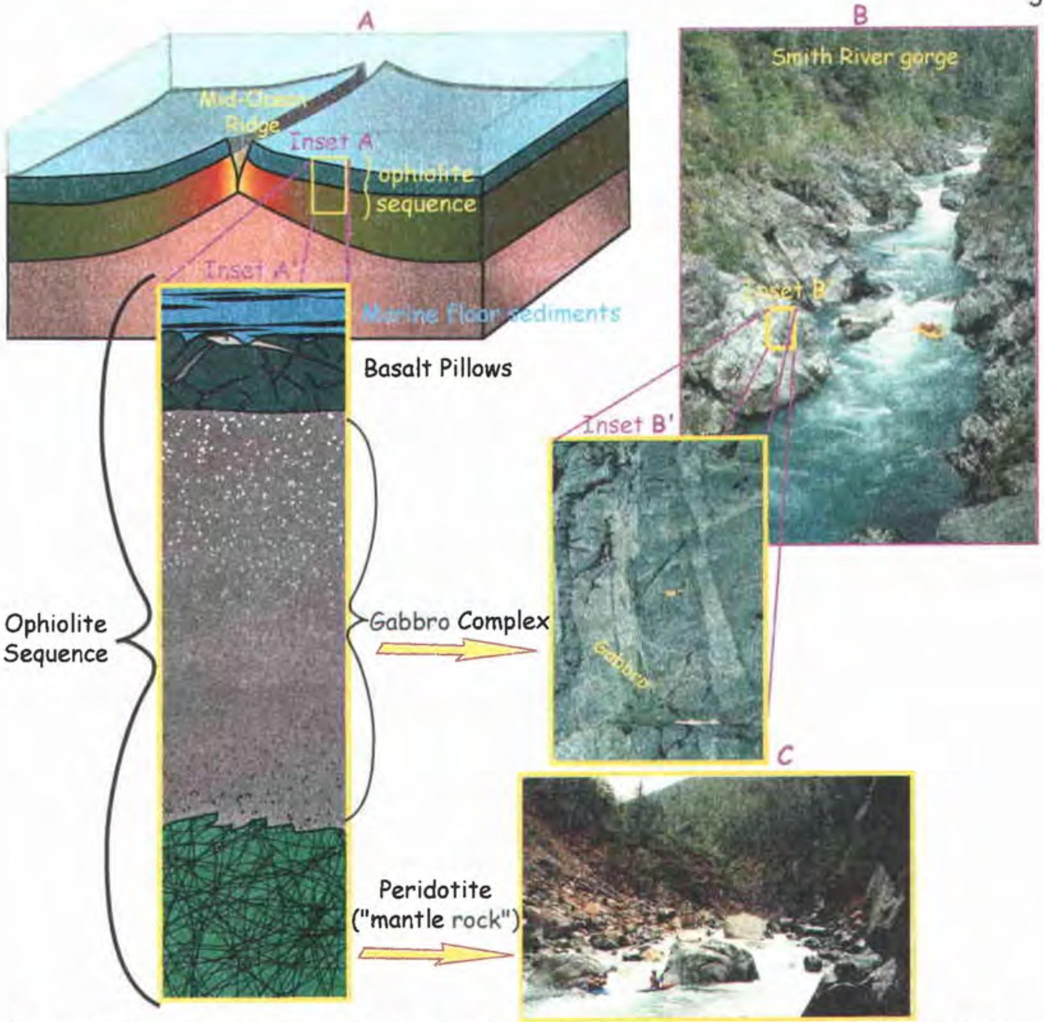
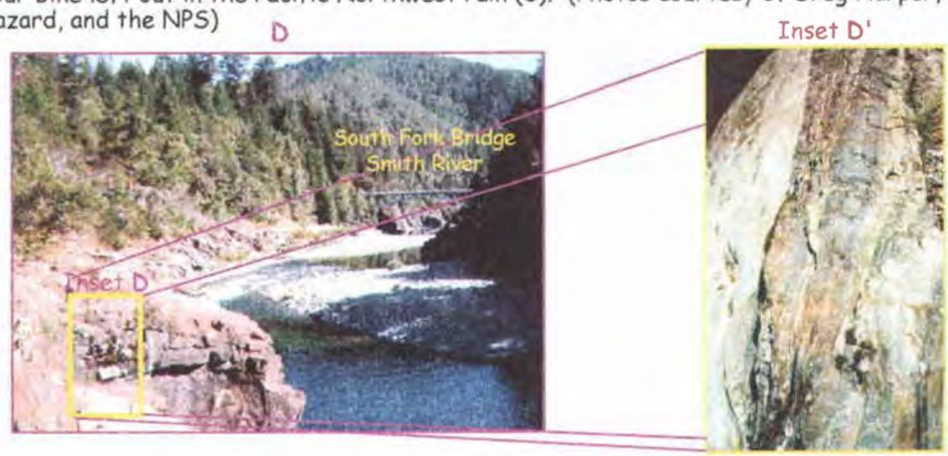


Figure 1-17: The Josephine what? The cliffs forming the Smith River gorge (**B**, **D**) are composed of notably green rocks and topped by odd burnt-orange soil. The rock was originally formed deep beneath the ocean (**A**, inset **A'**) and has been scraped off of the subducting Gorda Plate (**A**) and smooshed onto the edge of North America (fig. 1-14). This process is called "obduction," a term reminiscent of people being "abducted" by aliens! The rock is dominantly serpentinite (inset **D'**), an altered form of peridotite ("mantle rock," **C**). Mantle rocks contain a lot of iron and magnesium, forming the mineral called olivine (accounting for the green color). The iron can rust to a burnt-orange color when exposed to moisture, like your bike left out in the Pacific Northwest rain (**C**). (Photos courtesy of Greg Harper, Mark Bazard, and the NPS)



onto the edge of North America. We know that the top of the Gorda Plate is laden with layers of sand, mud, shells, and other muck deposited on the seafloor (the "stuff" of most of the rocks that form the Coast Range). Underneath all the accumulated sediments is the hard plate material formed from magma that cooled and hardened (fig. 1-17 A). The densest of the rocks that crystallize from the cooling magma form at the greatest depths. So the lower portion of the Gorda Plate is mostly made of the rock ***peridotite***, which is composed of some of the same iron-rich minerals that make up Earth's mantle. The sequence of rocks representing mantle and the overlying oceanic crust (composed of gabbro, basalt, and the sedimentary layers) is called an ***ophiolite*** (fig. 1-17 A). The intense pressure at depth within the subduction zone and the shearing forces involved in smashing the ophiolite up onto the continent both combine with hot water to alter iron-rich minerals into serpentine. In fact, *serpentine* is the state rock of California (***serpentine*** is actually the mineral comprising a rock known as ***serpentinite***, but shhh! ...we won't tell anyone they got it wrong ☺) We know that serpentine is a mineral that has the metal element iron in it, so guess what happens to serpentine in the North Coast, where we have plenty of rain and fog? That's right, even rocks can rust! The orange soil topping the Smith River cliffs forms from weathered ("rusted") serpentine that is rich in ***iron oxide*** (or, rust; fig. 1-17 C).

Smith River gorge rocks are green
over time rain dulls their sheen
like your car left outside
rusts to iron oxide
here we form soil from serpentine.

Redwood National and State Parks offers kayak tours of the Josephine Ophiolite and its impressive geologic features during the late spring and early summer (until the Smith River becomes too low sometime in August). So visitors can take a "magical kayak ride" through the very crust and mantle of the ocean (fig. 1-17 B).

Redwood Creek

The direction of convergence between the Gorda and North American plates generates structures, such as mountain chains, folds, and faults, which are aligned in a northwest-southeast direction (see Chapter 3). Folds form in the same way rugs crumple when you push them from the edges. Once the land is folded, the strength of the rocks and the region's climate dictate how much the land is etched by weathering and erosion processes. The gravel along Redwood Creek is commonly shades of green, grey, and white. The rocks composing both slopes are metamorphic, and they have been "smooshed," but not at the same time or to the same extent (see Chapter 2, "metamorphic").

The lack of bends in the channel of Redwood Creek is quite notable on maps (or to over-night hikers). River channels with lots of sediment, such as at Redwood Creek (see "Tipping the Balance"), tend to curve (meander) in order to navigate through by the easiest passage. The 280-mi^2 (725-$kilometers^2$) drainage basin of Redwood Creek is approximately 50 miles (80 kilometers) long and 6 miles (10 kilometers) wide (Cashman and others, 1995). Following a northwest trend, Redwood Creek is remarkably straight and narrow because it follows a structural weakness in the rocks (fig. 1-18). Whenever rock breaks along faults, the force of rock-against-rock shears and fractures much of the rock along what is known as the ***fault zone***. The structure controlling Redwood Creek is known as the Grogan Fault, and has been identified partially because it defines such a linear river channel and partially because the types of rock on either side of the steep channel are quite different.

On one side is the Redwood Creek schist, on the other is rock made of slightly metamorphosed sandstone and siltstone (fig. 1-19 *C*, see Chapter 2; Harden and others, 1982). Both rock types are members of the Franciscan assemblage (see Ch.2), but were formed millions of years apart (Cashman and others 1995). Both rock types also have been sheared and weakened, exacerbating the effects of weathering and erosion.

The cobbles that comprise the gravel bar of Redwood Creek have built up into a thick "slug" of sediment because of hillslope erosion catalyzed by logging during the 1960s and 1970s (fig. 1-19 *A*, see "the story;" Madej and Ozaki, 1996). The removal of Redwoods and construction of logging roads allowed rocks to crumble down from the steep slopes into the channel of Redwood Creek.

Figure 1-18: Straight as an arrow. The shape of Redwood Creek's channel is controlled by the Grogan Fault, which shears and weakens the bedrock. Water draining from the steep Coast Range then finds a well-defined path along which it flows.

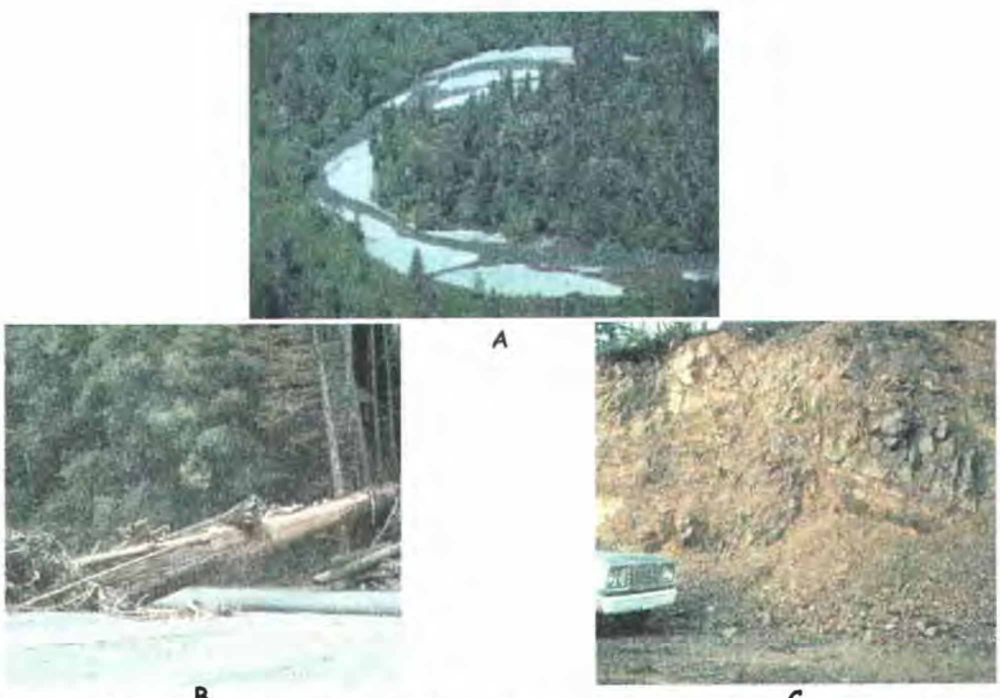


Figure 1-19: Take a hike! The gravel bar covering much of the lower reaches of Redwood Creek's channel (**A**) is dominantly cobbles of schist, moderately "smooshed" (metamorphosed) shale and sandstone (**B**). Higher up on the hillslopes of Redwood Creek are slightly "smooshed" layers of the sedimentary rocks sandstone and shale from the top of the Gorda Plate (**C**, fig. 1-9). (Photos courtesy of NPS)

Testifying to the high degree of "etching" at RNSP, the crinkles of Redwood Creek are very pronounced. Prominent ridges and valleys mean that the slope from the ridges to the creek is steep and narrow. Despite the tendency of Redwood Creek slopes to fail in landslides, the narrow channel allows dead trees to become lodged and create habitat for river life (fig. 1-19 B).

Gold Bluffs Beach

If you have driven down Davidson Road, you've probably noticed that the road changes from gravel to sandy dirt. If you've ever camped at Gold Bluffs Beach, hiked that section of the Coastal Trail, or visited Fern Canyon, you may have noticed that Gold Bluffs Cliffs look different from the rock cliffs north of Gold Bluffs, near the Klamath River mouth. So, how are the rocks different? You might first notice the color - the cliffs at Gold Bluffs are much lighter and very yellow when compared to the dark-colored rocks near the Klamath Overlook. If you look closer, you'll see that the bluffs are actually composed of thousands of cobbles and pebbles with lots of sand in between. Upon closer inspection, you will notice that most of the gravel is well rounded and forms defined patterns in the bluff exposure. The rounding and sorting of the rocks is indicative of how the rocks were formed. Were you to hike north to the Klamath River itself, you might notice that the rocks in its channel bear a similarity to the rocks in the bluffs. In fact, the sedimentary particles comprising the bluffs were brought to the coast by the Klamath River, making them ancestral Klamath River deposits. Looming over 100 feet (30 meters) above campers, the spectacular cliffs exposed at Gold Bluffs Beach show where the ancient mouth of the Klamath River was between 1 and 3 million years ago (fig. 1-20).

Once again, the RNSP landscape illustrates the dynamic nature of Earth processes over geologic time. The Klamath River drains the Klamath Mountains, so small amounts of placer gold were found at Gold Bluffs Beach in the mid-1880s, hence their name (Trexler, 1989). The rocks comprising the cliffs at Gold Bluffs Beach are part of a group of sediments known as the Prairie Creek Formation, which is between 600,000 and 2 million years old (Kelsey and Trexler, 1989). The gravel is very different from the

Figure 1-20: There's gold in them thar hills! Gold Bluffs Beach campgrounds affords front row seating for a Pacific Ocean view, with an impressive 100 foot tall backdrop of Klamath River deposits that are over 1 million years old! (Photo courtesy of Northern California Geographic Information Center)

northern cliffs near the present-day Klamath River mouth. Those cliffs are part of the metamorphic Franciscan assemblage rocks (see "Enderts Beach," Chapter 2). To the south, the Redwood Creek schist (another metamorphic rock, see "Metamorphic rocks") is buried under the sand around Kuchel Visitor Center. Truly, because they so strongly resemble deposits we can see forming at the Klamath River mouth today, the rocks exposed at Gold Bluffs Beach serve as a unique little window into what the coast of RNSP was like in the past.

<u>Chapter 2:</u> In the Palm of Your Hand: Rocks Found in RNSP

There are only a handful of rocks that are common in RNSP: *sandstone, chert, shale, slate, schist, serpentine, quartzite,* and *basalt*. Those eight rocks serve as representatives for the three basic rock types: ***igneous***, ***sedimentary***, and ***metamorphic***. Most are common in a group of rocks known as the *Franciscan Assemblage* exposed along the coast. So, unless the visitor has been to the gravel bars on the Smith River where cobbles and boulders transported from distant mountains are found, rangers will not have to worry too much about identifying many different rocks (remember to remind visitors not to remove the rocks they find from the park!).

The Rock Cycle

We differentiate between rock types because of the vastly different processes responsible for each. One way to "make a rock" is to cool liquid-hot magma enough so that it becomes solid and hardens (or crystallizes) into an ***igneous*** rock, such as *basalt* (the most common igneous rock in the Earth's upper crust). When the rock is exposed to weathering and erosional processes (such as wind, rain, or waves), it begins to weaken and break apart. The pieces, known as *clasts* or *sediments*, may be transported some distance and deposited where they compact and eventually harden into ***sedimentary*** rock, such as *sandstone* or *shale*. If a sedimentary rock is subjected to increasing pressure or temperature, minerals can re-crystallize in solid state, altering the rock's texture and structure to form a ***metamorphic*** rock, such as *slate, schist*, or *quartzite*. If the temperature becomes great enough, then the rock melts, returning ("recycling," if you will) it back to liquid magma from which another igneous rock may form. So, although different processes create each type of rock, they comprise a continuum known as "<u>the rock cycle</u>."

Season(al)s Change: Rock Recycles, too!

During the summer season, rain and fog may seem more appropriate to discuss, but snow is a useful analogy to how the three different rock types are related. As snow falls, snowflakes settle on the ground one on top of another forming layer upon layer. Sedimentary rocks form in much the same way as particles of rock settle in layers on the ground over time. A sudden warm spell would melt the snow to liquid water. If a cold front followed, then the water would re-freeze into solid ice. Igneous rocks can form in an analogous way: sedimentary rock can melt to magma and then crystallize into an igneous rock. We can also demonstrate how metamorphic rocks form from sedimentary rocks. Were we to scoop up handfuls of the snow and make snowballs, the heat from our hands and the pressure from our forceful reshaping would recrystallize the snowflakes just as the heat and pressure at depth in the Earth recrystallize (metamorphose) rock. (Adapted from Wagner, 2002)

The Smith River exposes many different rocks, including pieces of serpentine, gabbro, and peridotite, as well as the array of rocks comprising the Franciscan assemblage, in cliffs along its banks and in its bedrock. It also carries pieces of other rocks, such as granite, diorite, and rhyolite, from its headwaters in the Klamath mountains. Cobbles of all these different rock types – from both local and "exotic" sources – are found along the gravel bars in quite a diverse collection.

Elements, Minerals, and Rocks (Oh My!)

It is important to distinguish between the three components that make up Earth materials: elements, minerals, and rocks. Elements are the most basic ("elemental," if you will) "building blocks" of rocks. Most of Earth's materials are composed of just eight common elements (in order of abundance in Earth's crust): oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium. Those elements combine into the compounds that define the minerals we see in rocks. Simply put, elements make minerals; minerals make rocks.

Analogy by Ranger Allyson Mathis, Grand Canyon National Park

Nature writers like Rachel Carson were often inspired to write stories based on the landscapes they experienced. Landforms, such as mountains, can be thought of as stories. Stories are composed of passages of prose, just as landforms are composed of rocks. Prose is composed of words, just as rocks are composed of minerals. At the finest scale, words are made up of letters, just as minerals are made up of elements. (Adapted from Ashton, 2003)

The two most common elements, *oxygen* and *silicon*, combine to make various forms of the mineral *quartz*. Quartz is found in many rocks around RNSP, such as *sandstone* (most of the individual sand grains are rounded fragments of quartz), and *chert* (microscopic crystals of quartz similar to agate), both of which are common along the coast. *Iron* is an element that is common in the mineral *serpentine*, which dominates the rock *serpentinite*, found in the Josephine Ophiolite and exposed in cliffs along the Smith River (see "State Rock vs. State Mineral"). Let's find out more about the rocks we'll see at RNSP.

Igneous Rocks

For many people, the most familiar image of forming rock is that of liquid-hot magma cooling once it reaches the surface of the Earth during a volcanic eruption. The process of solidifying molten material (magma) makes ***igneous rocks***. There are not many igneous rocks in RNSP, but you might see some *basalt* around the coast, or some various other volcanic rocks, such as *rhyolite* and *andesite*, on the Smith River gravel bar. Also along the Smith River, you'll find rocks associated with the Josephine Ophiolite (see "Josephine Ophiolite (Smith River)"), including *gabbro* and *peridotite*. These few examples of igneous rocks can be classified into two types: those that form within the Earth (***intrusive***, or ***plutonic***), and those that form on Earth's surface (***extrusive***, or ***volcanic***). Visualize a chamber full of magma within the Earth. As the magma cools, solid minerals start to form (this process is called ***crystallization***). If we let the magma cool slowly inside the Earth, the crystals will have time to grow large enough to see, and that's when an ***intrusive*** (plutonic) rock forms. If, however, the magma erupts to Earth's surface, the resulting lava cools so quickly that crystals are too small for us to see and an ***extrusive*** (volcanic) rock forms.

Basalt, andesite, and rhyolite are examples of the volcanic rocks you'll most likely find around RNSP. *Basalt* is a dark-colored rock without many visible crystals (because it cooled quickly on Earth's surface). The reason we find basalt along the coast of RNSP is because it erupted during volcanic activity under the Pacific Ocean (fig. 2-1). Among other origins, basalt erupts at mid-ocean ridges (such as the Gorda Ridge, (fig. 1-11) or oceanic hotspots (such as the Hawai'ian Islands), and is then carried along as part of a plate (such as the Gorda Plate). At RNSP, along the Cascadia Subduction Zone, basalt layers move toward the edge of North America and were "smooshed" up into the Coast Range along with marine sedimentary layers (fig. 1-9).

I form rock from volcanic assault
Aligned along a submarine fault
Pillow lava cools fast
And sometimes forms glass
But usually it just forms <u>basalt</u>.

If the same molten material that forms basalt were to cool slowly inside the Earth, the crystals would be much larger. This rock is called gabbro, and it is common in ophiolite sequences. Gabbro forms below pillow basalt lavas as part of the oceanic crust (fig. 1-17). Below the gabbro, material with more iron-rich minerals cools slowly to form *peridotite*, which we often refer to as "mantle rock" (fig. 1-17, 2-2).

From liquid hot magma I grow
I stay in the Earth far below
my dark crystals shine
they form over time
I'm the intrusive rock - <u>gabbro</u>.

Forming deep in the Earth far from sight
Iron minerals add to my might
I'm called mantle rock
I form rusty blocks
Smith River gorge - <u>peridotite</u>.

Rhyolite and *andesite* are both lighter-colored volcanic rocks, and they are much more common in volcanic areas like the Cascades and at Yellowstone National Park. Rhyolite tends to be more pink than andesite, which is typically a greyish-pink color. The light color of rhyolite and andesite indicate the presence of silica-rich minerals. Silica is an element that tends to make magma viscous (sticky). High-silica magmas tend to erupt explosively. To put it in real-life terms, we can think of it this way: how much more effort is it to clear your throat when you have a gross, sticky infection than when you're simply spitting saliva?

Now, think of a chamber of magma beneath Earth's surface. Let's say the magma sits there just long enough for a few crystals to start to form, but then a volcanic eruption suddenly forces the mixture of pasty magma and small crystals to the surface. The result will be volcanic rocks that have small visible crystals in a matrix of fine-grain crystals too small for us to see. This is a common texture you can see in rhyolite and andesite rocks along the Smith River gravel bar.

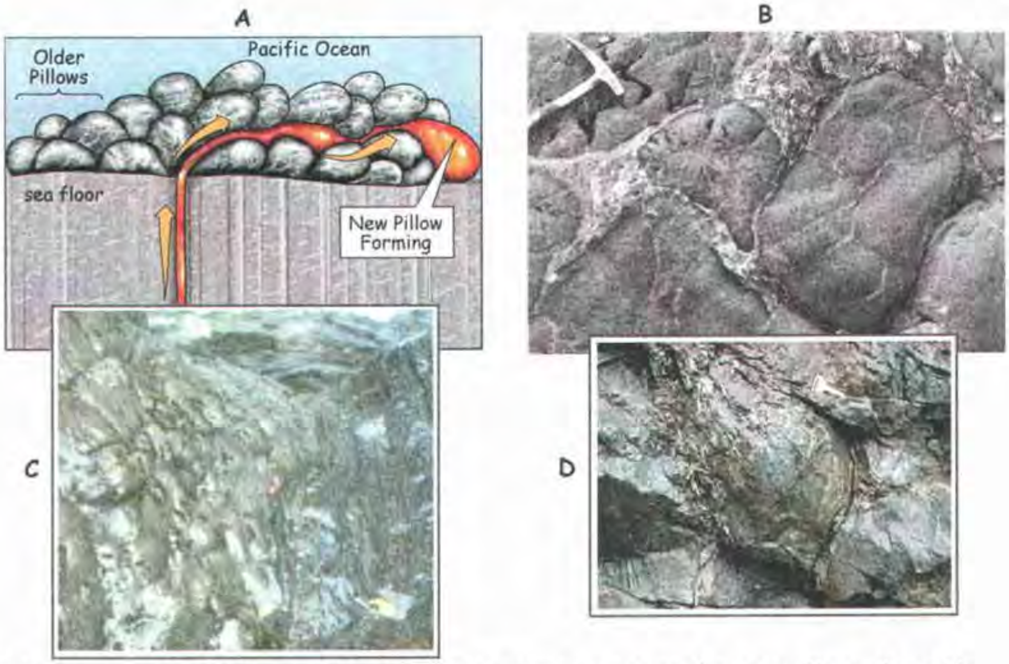


Figure 2-1: Hard pillows. When liquid hot magma erupts on the ocean floor, the cold ocean water "molds" the lava into rounded blobs called "pillows" (**A**). After millions of years, these basalt pillows are scraped from the ocean floor during subduction and exposed along the coast and Smith River gorge (**B, C, D**). ("**A**" modified from Marshak, 2001; "**B, C**" courtesy of Gregg Harper; "**D**" courtesy of Mark Renner)

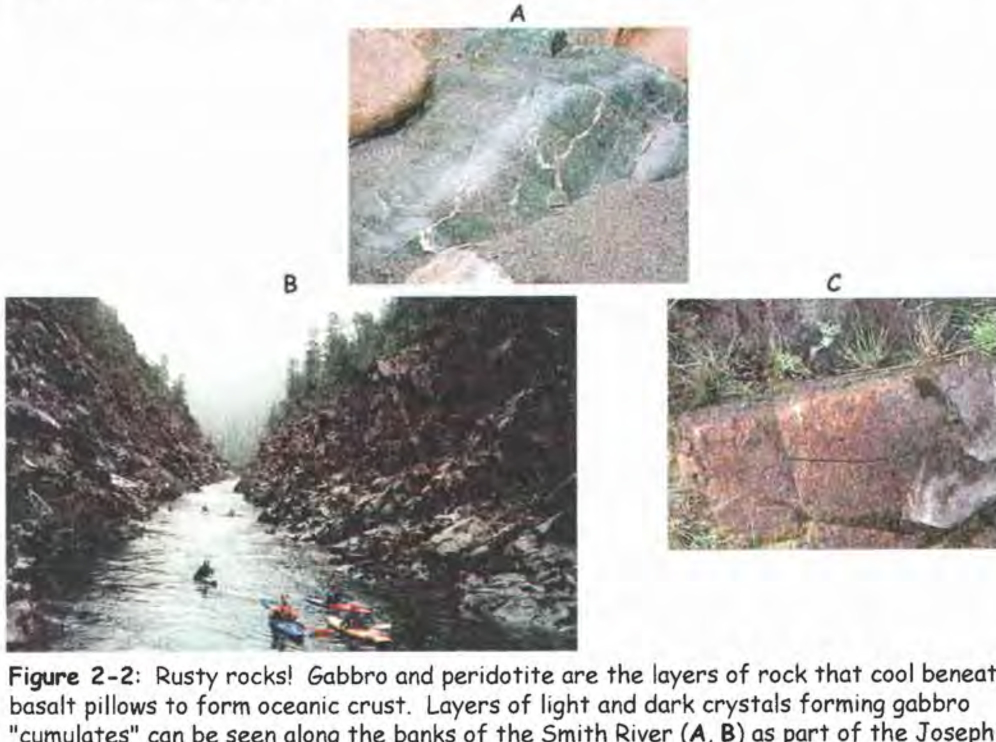


Figure 2-2: Rusty rocks! Gabbro and peridotite are the layers of rock that cool beneath basalt pillows to form oceanic crust. Layers of light and dark crystals forming gabbro "cumulates" can be seen along the banks of the Smith River (**A, B**) as part of the Josephine Ophiolite sequence (fig. 1-17). Below the cumulate gabbro, iron-rich crystals form a rock called peridotite, or "mantle rock." When exposed to water, peridotite "rusts" to a distinctive orange-red color (**B, C**). ("**A, C**" courtesy of Mark Renner; "B" courtesy of David Bazard)

Sedimentary Rocks

Walking around RNSP, you will most likely see sedimentary (and commonly metamorphosed sedimentary) rocks. Rock exposed at Earth's surface is subjected to weathering and erosion, processes which eventually break the rock into smaller bits (called ***clasts***, ***particles***, ***fragments***, or ***sediments***). As the name implies, ***clastic sedimentary rock*** can form from bits of other materials (such as other rocks, parts of dead marine organisms, or precipitated crystals) that are cemented together. Gravity, wind, and water (such as the Smith River and Redwood Creek) transport the sediments, eventually flushing the finer sand- and clay-size particles out to the deep-ocean floor.

The size of the clasts tells us about the energy needed to transport the particles; the larger the size of the clasts, the more energy that was needed to move them. More energy is needed to transport sand particles than is needed to transport tiny clay particles. Using this premise, we know that a rock made mostly of clay particles (shale) was probably formed in a quiet (low energy) setting, such as the deep ocean.

Above the subduction zone
by currents and winds we are blown
our grains settle down
under water we drown
and harden into sandstone.

Look closely and see my detail
My layers are broken and frail
In still waters I form
From clay bits well worn
I'm rock on the coast now called shale.

Sediments settle to the bottom of the Pacific Ocean and accumulate in layers, but not all of the sediments were flushed away from the North American continent. Critters that live in the ocean usually die in the ocean, and if the critters have shells, the shells settle to the ocean floor when the critters die, deposited as organic marine sediments (***organic sedimentary rock***). (Fossils are deposited in rocks in much the same manner.)

Sometimes, the shells of the critters are made of silica, so the layers of shells become silica-rich ooze. The mineral quartz is composed of silica, so such ooze becomes layers of *chert* and *agate*. As more and more layers of sediment accumulate, the pressure of the overlying material compacts the particles, creating solid rock. Chemicals that are dissolved in the surrounding water (such as calcium-carbonate and silica) can seep into the tiny pores between particles of sediment and *precipitate* crystals that *cement* the bits together into cohesive rock.

Along a river rocks sit
next to each other we fit
sand gets in our cracks
we're stuck back-to-back
together we're conglomerate.

Sedimentary rock often preserves materials and structures that are indicative of the processes active while the rock was forming, meaning that the rock records its ***depositional environment***. Preserved signatures - such as clast size and layering - allow us to "read" the story of the Earth by examining the rock's features.

Metamorphic Rocks

Metamorphic rocks form when the structure of minerals in a rock change (recrystallize), but the rock does not melt. "*Meta*" means "change" and "*morph*" means "form," so a metamorphic rock is a rock whose form changes. You can't make a metamorphic rock unless you have a pre-existing rock (called "parent rock," or ***protolith***). To metamorphose a rock, you must increase the temperature and/or pressure conditions around the rock (heat up or "smoosh" the rock), which alters the minerals that comprise the protolith. (So, when you start with a sedimentary rock, it becomes a meta-sedimentary rock after the rock is metamorphosed,.) The degree to which the protolith changes its form is dictated by several factors: the minerals comprising the parent rock, the amount of heat and pressure the rock endures, and the amount of water present during metamorphosis.

Serpentinite is a metamorphic rock found all along the Smith River (associated with the Josephine Ophiolite) and in certain spots along highway 101 (fig. 2-3).

I'm known for slope failure, not might
I can't put up much of a fight
I break down in toil
and make orange soil
I'm our state rock - serpentinite.

State Rock vs. State Mineral: A battle over serpentine

Serpentine is a mineral that forms under pressure when water interacts with rocks that are rich in the elements iron and magnesium, such as basalt, gabbro, and peridotite (fig. 2-3 A, B). *Serpentinite*, the rock formed from the mineral *serpentine*, has a distinctive "soapy" feel and "waxy" look, and you might notice many tiny wavy layers if you look at a chunk from the side (fig. 2-3 C). These are characteristic features that develop because of the environment in which the rock forms: the waxy sheen and soapy feel come from the minerals changing form (metamorphosing) in response to high temperatures and pressures at depth within the Earth. Commonly, *serpentinite* forms when mantle rock, *peridotite*, is metamorphosed. Heat and pressure change the minerals *olivine* and *pyroxene* to *serpentine* (fig. 2-3). The intense convergent plate process that drags rocks down to depths where such heat and pressure exist is happening directly beneath RNSP!

Along Redwood Creek you can find *schist*, shiny rocks composed of wavy layers of greenish-grey and white rock (fig. 2-4 B; Cashman and others 1995). The parent rock of schist is often some sort of *shale* (sedimentary rock), and the white rock is often smooshed layers of *sandstone* or *chert* (both sedimentary rocks, fig. 2-4 A) that were metamorphosed to *quartzite*. So, the schist in Redwood Creek began as layers of shale and sandstone that got metamorphosed during the process of subduction.

With pressure and heat rock can twist
Its particles caught in the midst
Smooshed sandstone and shale
Quartz and mica prevail
Transforming the rock into schist.

Were you to continue dragging rocks deeper down the subduction zone, the schist would become a *gneiss*, with layers that are more wavy and often contain bands of different-colored minerals. Visualize for a moment the slab of the Gorda Plate subducting beneath North America. The rocks comprising this slab of lithosphere are metamorphosed to higher and higher temperature and pressure as the plate descends deeper into the mantle. (Rocks that have descended to extreme depths of as much as 30 miles - 50 kilometers - are quite rare to see at the surface, but some can be found along the coast around Bandon, Oregon.) If the rock gets so hot that it melts it is no longer a metamorphic rock because the magma could only solidify to form an igneous rock.

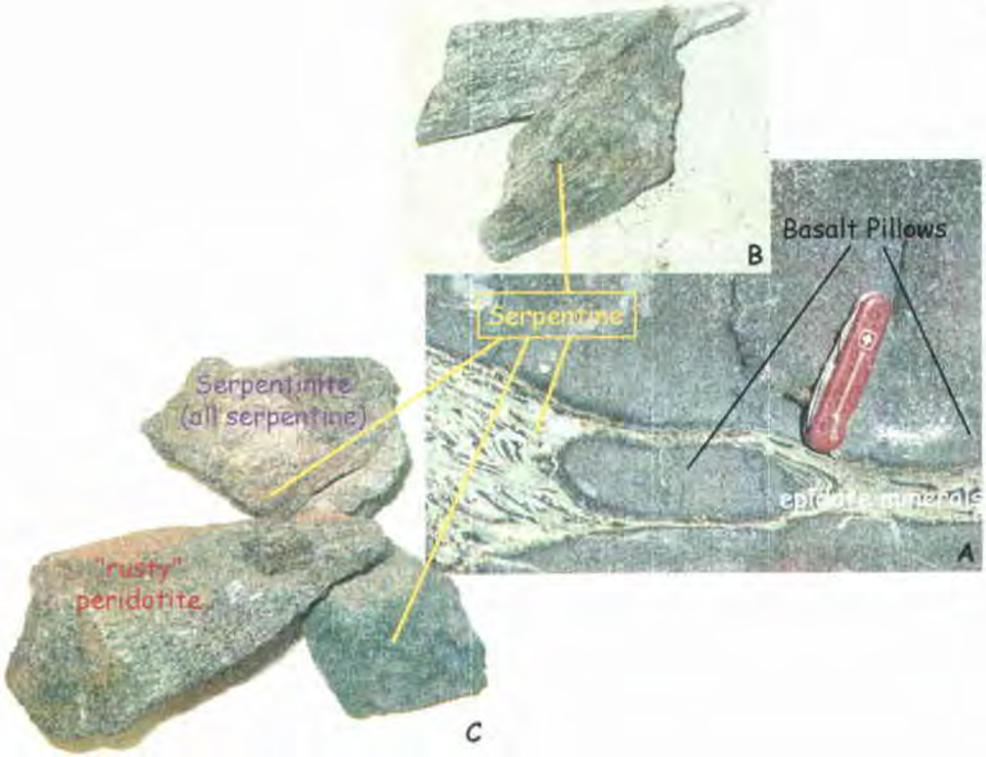


Figure 2-3: It's not easy being green! The mineral serpentine forms when iron-rich rocks are metamorphosed and interact with water (i.e., serpentine forms by"smooshing" a wet, iron-rich rock; **B**). A rock made up entirely of the mineral serpentine is called a "serpentinite," California's state rock (**C**). ("**A**" courtesy of Greg Harper)

A

B

Figure 2-4: "Smooshed" schist. Near both Redwood Creek and the coast, rocks of the Franciscan assemblage have been metamorphosed to various degrees. The slightly "smooshed" laters of siltstone on the coast (**A**) would eventually become shiny, thin layers rich in the mineral mica, like some rocks found along Redwood Creek (**B**). ("**A**" courtesy of Greg Harper)

"Leaverite": a common specimen!

Remember, the most universal rock at National Parks is "Leaverite." This rock is found within park boundaries and is therefore preserved by mandate of the U.S. Department of the Interior. *Leaverite* was named for the process by which it forms: if visitors find and examine rock within national park boundaries, then they should *leave her right* where they found 'er!

Chapter 3: Geologic Structures (or, What You See and How You Get It)

Viewed by our human scale, the crust of the Earth is not smooth, and the rumples result from deformation of the crust. We characterize deformation in terms of the structures, such as folds and faults, that form from forces that stretch or compress the crust.

The next time you're having coffee, look closely at the ceramic mug you're holding. You'll probably notice that there are lots of tiny cracks in the glazed surface of the mug. The rocks of Earth's crust have lots of cracks, too, which are called ***joints*** (fig. 3-1 A, B). Joints can be enhanced by geologic forces that breaks rock apart, such as weathering and erosion. In fact, once joints form in a rock, water can more easily seep into the crack and further weather the rock, eventually causing pieces to break off (this process is happening all along RNSP's coast, fig. 3-1 C). Should the rock on either side of a crack move significantly in a direction parallel to the crack, the crack becomes a different geologic structure called a ***fault***.

Faults

Rocks break in response to stress, and we can understand the nature of the forces creating the stress by characterizing how rock layers break along a ***fault***. Faults tend to be planar surfaces along which rock masses slide past each other. Let's visualize separating the chunks of rock on either side of a fault so that there would be enough space for a person to hike along the plane defined by the fault. The side of the fault the person's feet would hike on is known as the "***foot wall***," and the side that would then be hanging over the person's head is known as the "***hanging wall***" (fig. 3-2). We now know enough to start naming types of faults as they are associated with types of forces.

Normal Faults

To understand the forces that create each type of fault, it is best to visualize a block of rock with a diagonal fault break cracking it in half (fig. 3-2). Imagine pulling (*extending*) either side of the block apart. What happens to the hanging wall? When we pull apart the block of rock, we can envision the hanging wall dropping down relative to

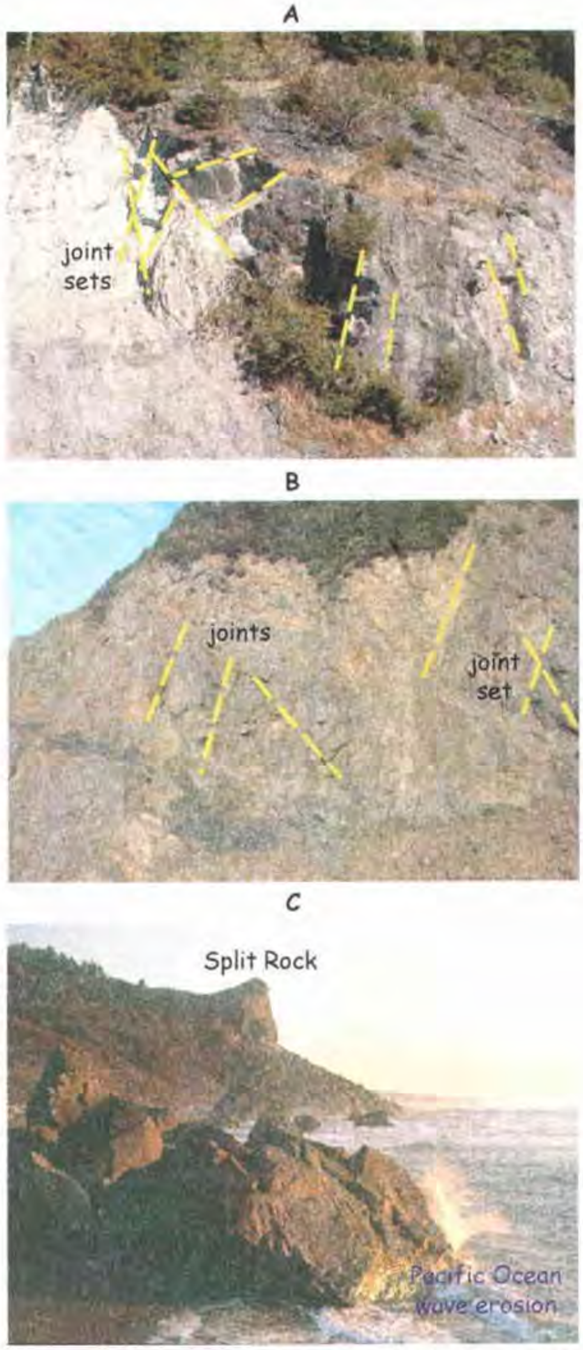


Figure 3-1: The coast really is all it's cracked up to be! The Franciscan assemblage forming most of the rock exposed on the coast has been weakened and cracked. Just south of Del Norte Coastal Redwoods State Park along Hwy 101 (**A**), the impressive fractured cliffs face West toward the Pacific, and there are similar exposures near Wilson Creek (**B**). The cracks are called "joints," and rock commonly falls apart along these fractures, in the process of erosion. Sea stacks are formed by the process of ocean waves attacking sea cliffs at the weak points (**C**). The joint is termed a "fault" if there is forced movement of rock along the crack (fig. 3-2). ("**C**" courtesy of NPS)

the foot wall, making a "***normal fault.***" ***Extensional*** (or "pull apart") forces are common at divergent plate boundaries, such as the Gorda Ridge, where normal faults are common. RNSP is situated where two plates converge, so we don't see many normal faults.

Reverse Faults

Let's again imagine the block of rock split by a diagonal fault (fig. 3-2). This time, instead of pulling the block apart, let's visualize what happens to the hanging wall when we push (*compress*) the sides of the block toward each other. Instead of dropping down, the hanging wall is shoved up relative to the foot wall. When the earth is squeezed, the compressional forces thrust the hanging wall up, forming a "***reverse fault.***" Compressional forces, common at convergent plate boundaries like subduction zones, tend to shove slices of rock past each other at a low (shallow) angle, and these shallow reverse faults are called "***thrust faults.***" RNSP is situated on the Cascadia Subduction Zone, so there are many thrust and reverse faults sculpting the landscape. The faults are not always obvious. For example, Redwood Creek flows along a canyon developed along the Grogan Fault, which is a reverse fault (see "Redwood Creek;" Cashman and others, 1994). Many of the thrust faults are covered by vegetation, but small faults and joints are prominent in exposures of coastal rocks, especially at Enderts Beach and in the road cut near Wilson Creek (fig. 3-1 A, B).

Strike-Slip Faults

Returning to the block of rock, let's imagine sliding the sides past one another horizontally, without any pulling (extensional) or squeezing (compressional) forces. Neither the hanging wall nor the foot wall moves vertically, rather, the rocks slip laterally past each other, making a ***strike-slip*** fault. Strike-slip movement is common around transform plate boundaries, like the San Andreas Fault (SAF) in central and southern California, where the Pacific Plate slides northwestward past the North American Plate (figs. 1-15, 3-3). Because RNSP is close to Cape Mendocino, where the SAF ends at the Mendocino Triple Junction, there is some strike-slip motion along faults within the park, including parts of the Grogan Fault (Cashman and others, 1994).

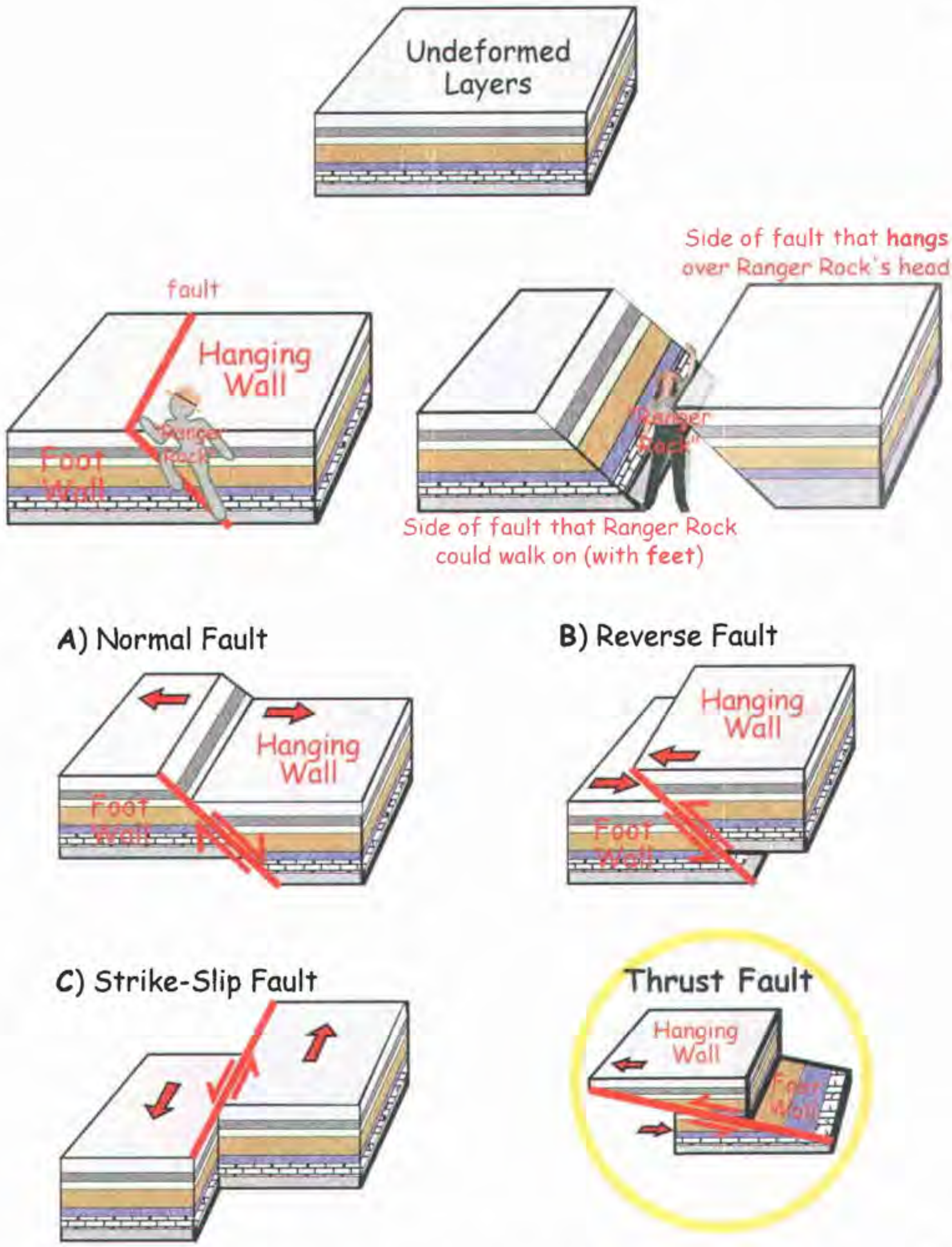


Figure 3-2: It's all your fault! When layers of rock crack along a plane of weakness, a fault is formed. If we imagine a daring Ranger with an interest in geology deciding to hike along this plane, the side of the fault upon which our Ranger Rock can put her feet is called the "foot wall" and the side that hangs above Ranger Rock's flat hat is the "hanging wall." There are three types of faults: normal, reverse, and strike-slip (transform). A normal fault (**A**) is one where the hanging wall drops down relative to the foot wall. A reverse fault (**B**) is just the opposite -- the hanging wall is shoved up relative to the foot wall. A thrust fault is a kind of reverse fault where the angle of the fault plane is very shallow (these are the most common around RNSP). A strike slip fault (**C**) occurs where the two sides slide laterally past each other. A well known example is the San Andreas Fault in California (fig. 3-3). (Modified from Lillie, 2004)

Folds

Another type of structural feature that forms as rocks deform in response to being stressed is a ***fold*** (fig. 3-4). If you have ever vacuumed a throw rug, you understand the concept of pushing the edges of the rug to make wrinkles, and rocks fold in much the same way. The resulting deformed land is then subject to erosion, a process that can create topographic relief. In fact, if you look at a digital elevation model (D.E.M.) of the United States, parts of the western U.S. looks rather crinkled, especially when compared to the mid-west and eastern portions of the states (fig. 3-5). In an aerial photograph of the North Coast, you can see that the Coast Range mountains of RNSP have a linear pattern of alignment – the mountains generally trend in a northwest-southeast chain (fig. 1-18). This "rumpled carpet" kind of structural grain results from plate convergence (subduction), compressing the region from the southwest toward the northeast (fig. 1-9). Imagine continuously pushing the edge of the rug (North American Plate) as you gradually move the vacuum (Gorda Plate) forward, and you can approximate how the Coast Range actively grows.

Two simple types of folds are anticlines and synclines, both named for their shape. ***Anticlines*** are folds where rocks are warped upward, each fold resembling the capital letter "A" from a cross-section view. ***Synclines*** are folds where the rocks are warped downward, each resembling a smile ("s" for *s*mile, "s" for *s*yncline) (fig. 3-4).

Unconformities

Rocks contain the story of the Earth's history, so if layers of rock are like pages of a book, then ***unconformities*** are places where the pages were either never written, or written but later ripped out. Let's think of rock being deposited one layer on top of another (like sedimentary rocks in the ocean, see "Sedimentary rocks") through time. The bottom rock layers represent the farthest back in time (oldest) and the top rocks are the most recent (youngest). All the rock layers in the stack would be "***conformable***," that is, complete and without time gaps, assuming constant deposition and no erosion. But nature is messy, so such complete stratigraphic records without geologic time missing are quite rare.

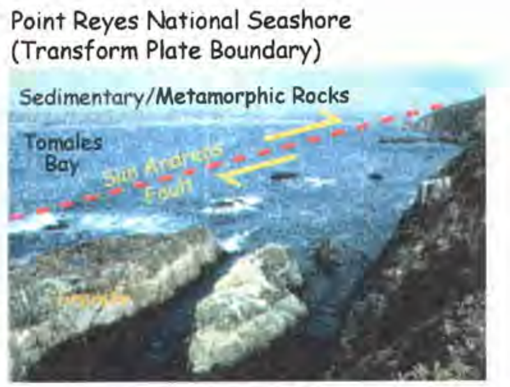


Figure 3-3: The San Andreas Fault: the most (in)famous fault in the nation. As the Pacific Plate moves north-northwest relative to North America, the west coast endures large magnitude earthquakes where millions of people reside. The benefit? The millions who live near the west coast enjoy spectacular views of the Pacific crashing into our rocky shoreline. (Modified from Lillie, 2004)

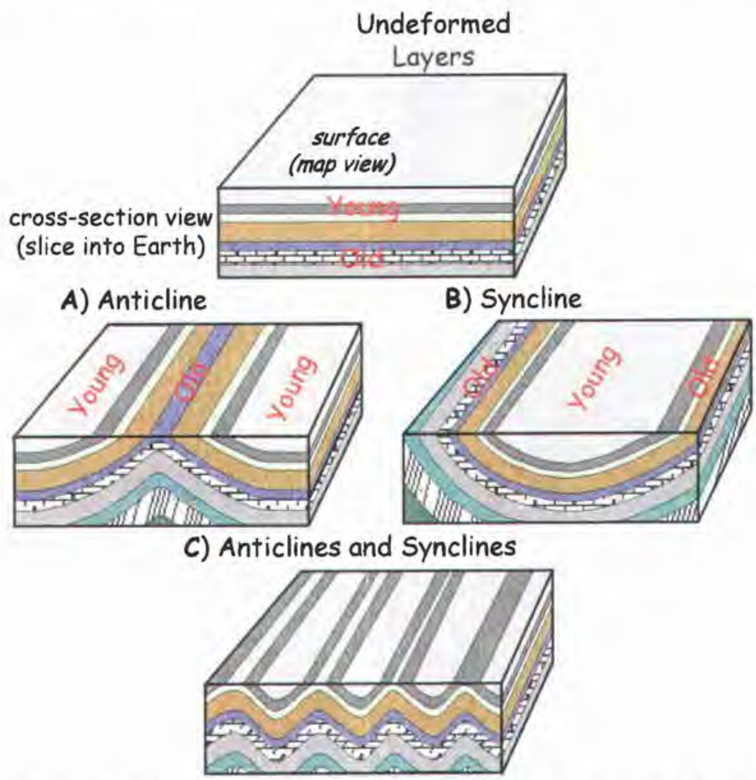


Figure 3-4: Gettin' all bunched up. Sometimes, instead of simply breaking along a plane of weakness (fault), rocks deform by bending into folded patterns. There are two main fold structures - upward folds, known as anticlines (**A**), and downward folds, or synclines (**B**). If you were to look at each of these structures from a cross-section slice into the Earth, an anticline would resemble an "A-frame" tent, and a syncline would resemble a smile ("s" for smile, "s" for syncline). Rock layers are flexed upward into an anticline and then eroded at the top, older layers are exposed in the middle. The opposite is true of a syncline, which forms a structural sink with the youngest rocks in the middle. On a regional scale, if you were to crumple rock layers continuously, you would end up with a series of anticlines and synclines (**C**) bunched up like a crumpled rug. (Modified from Lillie, 2004)

Unconformities are strange concepts because they represent something that is not there, and so some are challenging to recognize in the rock record. Recognizing gaps in time help us read the landscape more thoroughly and understand better the geological story the rock tell.

Figure 3-5: Which side is rumpled, the East Coast or the West Coast? The rugged coastline of RNSP is rocky because it is an active continental margin, where there are plate boundaries. The gentle, sloping beaches of the East Coast have been deposited from erosion of the Appalachian Mountains over the past 300 million years. (Modified from Lillie, 2004)

Chapter 4: Earthquake!!!

Stressing our rocks makes them break
During the rupture they shake
North America scrapes
O'er the thin Gorda Plate
That's when we get an earthquake!

Much of the difficulty in interpreting geology to visitors is that people may not realize that they experience geology directly. They can look around them and see the results of past geologic events (in essence, they can "read" the Earth's history in the landscape), but without an understandable translation (the interpreter), they my not attach much meaning to what they see. Of course, the vegetation growing over bedrock covers the rock, so the best exposures are often limited to roadcuts, streambanks, and along the coast. Compounding this problem is that rocks are not obviously active - they do not move very fast! Every time visitors watch the Klamath River empty into the Pacific or hike up along the gravel bar of Redwood Creek, they are witnessing sediment transport and erosion, both geologic processes (see "Sedimentary rocks," and Chapter 6), but not all geologic processes are quite so obvious. By presenting visitors with stories of the power of the energy stored in the Earth, the interpreter can more easily engage the visitor and have them contemplate the geologic processes responsible for what they're seeing. Earthquakes occur within a time frame that people normally experience and are aware of: they are geological events that are most pertinent to many visitors, especially those from California.

The Pacific Northwest is a geologically active region. Many of the earthquakes that occur in the vicinity of the North Coast and RNSP result from Gorda Plate subduction (fig. 1-9). Other earthquakes off the coast result from the divergence of the Gorda Plate from the Pacific Plate, and the interactions between all three plates near the Mendocino Triple Junction (Cape Mendocino, 106 miles - 170 kilometers - south of Crescent City, fig. 4-1; Dengler and Moley, 1999).

Earthquakes that occur as a result of the convergence of the Gorda Plate with North America can be classified into four categories (fig. 4-2). As the cold, brittle

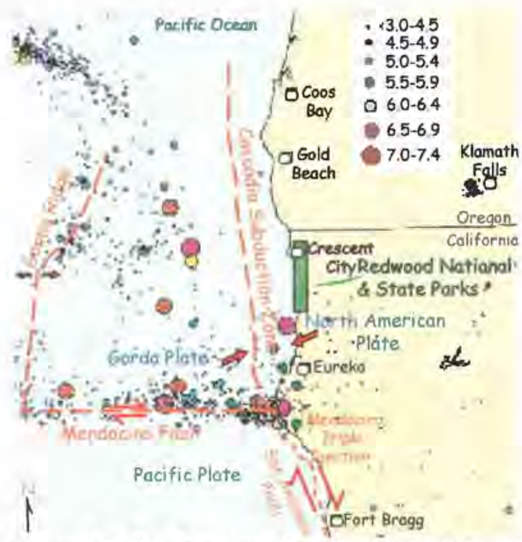


Figure 4-1: Shake, Rattle, and Roll - Crescent City is where all the action's is! This map view corresponds to the block diagrams (figs. 1-3, 1-9) and shows how close RNSP is to all the seismic activity around the plate boundaries (fig. 1-1). The size and color of the dots indicate the magnitude of earthquakes that occurred from 1975-1995. You can see that most of the large earthquakes occur near the Mendocino Triple Junction. (Modified from Dengler and Moley, 1999)

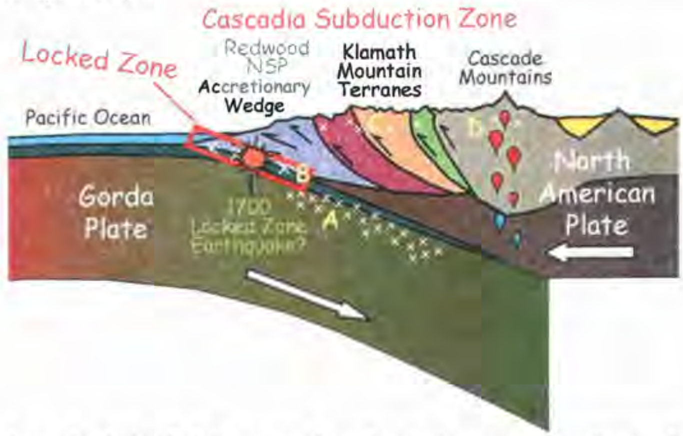


Figure 4-2: Did you feel that? There are four basic types and locations of earthquakes related to Gorda Plate subduction (x's on diagram). A) Earthquakes within the Gorda Plate. The upper portion of the Gorda Plate stays relatively cool (brittle) for some time as it subducts farther and deeper beneath North America. When it breaks, it can generate earthquakes to depths of about 30 miles (50 km) beneath the Coast Range and Klamath Mountains. These are commonly referred to as "subduction slab" earthquakes, such as the magnitude 6.8 Nisqually earthquake that occurred beneath the Seattle, Washington, area on February 28, 2001 [Preston, 2003]. B) "Mega thrust," or "locked zone," earthquakes. The earthquakes occur between the subducting Gorda Plate and the overriding North American Plate. The plates slip and suddenly grind past each other after being locked together for hundreds of years. The energy released generates extremely high magnitude earthquakes (fig 4-6), which can generate tsunamis (fig 5-2). This type of earthquake happened on March 27, 1964 off the coast of Alaska, registering a moment magnitude 9.2, and generating a tsunami that hit Crescent City, California, lessthan 5 hours later. C) Those within the North American Plate. As the edge ofthe continent is crumpled (like a rug) by the Gorda plate, inland areas experience compression and reverse faulting at shallow depths. These small-to-moderate size earthquakes are common in the Seattle and Portland areas.
D) Shallow rumbles from rising magma beneath the Cascade volcanoes. The magma "jostles" rock out of its way, generating small earthquakes. Such earthquakes can at times be used to track the rise of magma prior to volcanic eruptions.

Gorda Plate subducts beneath North America, the oceanic plate contorts and cracks, releasing energy in small-to-moderate magnitude earthquakes (fig. 4-2 A). The actual boundary between the Gorda and North American plates is a stressful zone where the two plates stick and grind past each other. Because the rate of subduction is relatively slow and the rocks are rough and resist slipping, the two plates can remain locked together for centuries. Instead of slipping easily past each other at the rate your finger nails grow (more than 1 inch, 2.5 centimeters, per year), the plates suddenly lunge (thrust) tens of feet (meters) past each other to relieve the built up pressure (fig. 4-2 B; Clarke and Carver 1992; Christensen and Beck, 1994). The release of this locked zone produces the highest magnitude and most devastating earthquakes of any that occur in the Pacific Northwest. Similar to the earthquakes that occur within the subducting Gorda Plate, there are smaller earthquakes that can occur in the overriding North American plate to accommodate compression as the Gorda Plate crashes into North America (fig. 4-2 C). Other, very small earthquakes occur in association with magma rising beneath the Cascade volcanoes, such as Lassen Peak and Mount Shasta (fig. 4-2 D).

What Causes Earthquakes?

Despite the adage "hard as a rock," rocks actually turn out to be somewhat elastic. Like a steel beam, rocks can slowly bend (fig. 4-3 B). Because most tectonic activity occurs on geologic time scales (meaning large motion occurs in small increments spread over large amounts of time), under small amounts of stress caused by plate movement, rocks can gradually deform (bend) without breaking. If the stress were no longer acting, the rocks would return to their original state without permanent deformation. But so much stress can be applied to a rock that it deforms permanently, either by warping (ductile flow, like silly putty) or cracking (brittle failure, like splintering a 2 x 4). The level of stress where the material begins to flow or crack is called the rock's ***elastic limit*** (fig. 4-3 C).

We can think about the way rocks respond to stress in a different way. Before setting off on a hike or engaging in other physical activities, many people like to stretch, or warm up. Without being warmed up, cold muscles can tear painfully. The same is true of rocks. Rocks that have been warmed up will be more likely to deform (stretch) in a ductile fashion (fig. 3-4). However, when rocks are cold, they tend to be brittle. So their response to stress beyond their elastic limit is brittle failure. Brittle failure in rocks is commonly accompanied by a sudden snap along a fault line, causing an earthquake.

It is important to recognize that "rocks move," not only when layers snap during an earthquake, but motion also occurs within the Earth while the stress leading up to the earthquake builds up. This motion within the Earth generally gradually deforms regions. The coast of RNSP is slowly uplifting in some places and slowly subsiding in others, but stress that cannot be accommodated by gradual deformation is released during an earthquake.

Where Earthquakes Happen

In order for an earthquake to occur, two things must happen: 1) Earth motion must stress material beyond its breaking point (elastic limit); and 2) the stress release that occurs must be sudden. Temperature increases with depth within the Earth, so earthquakes are generally confined to the upper portions of lithospheric plates, because even the bottom portions of the plates are so warm they tend to deform in a flowing, ductile fashion (Yeats and others, 1997). Where the cold, brittle plate does not extend to great depths (meaning that brittle deformation is limited to the near-surface), only shallow earthquakes occur (Yeats and others, 1997). ***Divergent*** and ***transform*** boundaries and hotspots typically experience only shallow earthquakes, well within the Earth's upper 20 miles (30 kilometers). ***Convergent*** boundaries (subduction zones where one cold, brittle plate is being shoved downward) can experience earthquakes at great depths. Where subduction is fast enough for the down-going plate to remain cold, very deep earthquakes (400 miles, 600 kilometers) can occur (Lillie, 1999). This process is like pushing an ice cube into a cup of hot coffee at the Continental Bakery; the ice does not melt for some time, and in fact, often cracks (brittle failure) before it melts. To appreciate this better, we need to understand how earthquakes originate and how the energy released is propagated through overlying rock.

The exact point within the Earth at which an earthquake occurs is its ***focus***, which is defined by pinpointing the earthquake's latitude, longitude, and depth (fig. 4-4). The ***epicenter*** is the point on Earth's surface directly above the focus. The distance between the epicenter and the focus is the ***focal depth***. Focal depths relate to plate boundary types. Most earthquakes occur at shallow focal depths (from the surface to about 40 miles, 60 kilometers); these shallow-focus earthquakes abound at every type of plate boundary. Most intermediate (40 to 200 miles, 60 to 300 kilometers) and virtually all deep (up to 400 miles, 600 kilometers) earthquakes occur at convergent boundaries, where cold plates subduct to great depths (Lillie, 1999).

<u>Earthquake Strength</u> (you thought visitors losing their tempers was bad!)

In addition to relating to earthquake depths, each type of plate boundary has the ability to produce earthquakes spanning a range of strengths. The strength of an earthquake is described by two attributes: magnitude and intensity. An earthquake's magnitude quantifies the <u>amount of energy released</u> by the earthquake and is measured using scales such as the Richter Scale. An earthquake's intensity is qualified by the <u>severity of shaking at a given location</u> (for example, the degree to which your windows rattle or your washing machine jumps across the floor) and is measured using the Mercalli Scale (table 4-1).

Magnitude

The public often hears about the Richter Scale during news accounts of an earthquake, and thus is most familiar with this scale of earthquake measurement. Richter Scale magnitude describes the size (amplitude) of seismic waves a standard distance from the earthquake focus, which is a function of the <u>amount of energy</u> released during the earthquake. Seismograph stations measure the amplitude (height) of the seismic waves at known distances from the earthquake. You may be familiar with the phrase "order of magnitude," which is often used when describing phenomena that span a broad range. This phrase refers to the logarithmic nature of some scales, such as the Richter Scale, wherein an increase of one unit of magnitude corresponds to a 10-fold

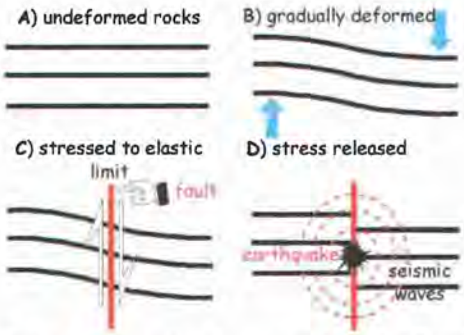


Figure 4-3: What happens when the Earth gets too stressed. Applying pressure at the rate of a few inches per year, over hundreds of years, can eventually stress rocks past their ability to deform smoothly (their "elastic limit"). Beyond that point they "fail" (break), along a fault, and the stress is released in the form of seismic waves. This is an earthquake. (After Lillie, 2004)

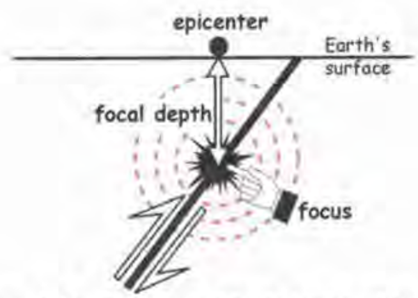


Figure 4-4: Terms used to describe what happens when the earth breaks. For example, Olympia, Washington, was the epicenter for the 2001 earthquake whose focus was 30 miles (50 km) below in the Juan de Fuca Plate (northern extension of the subducting Gorda Plate). The distance from the focus to the epicenter, or focal depth, was thus 30 miles. (After Lillie, 2004)

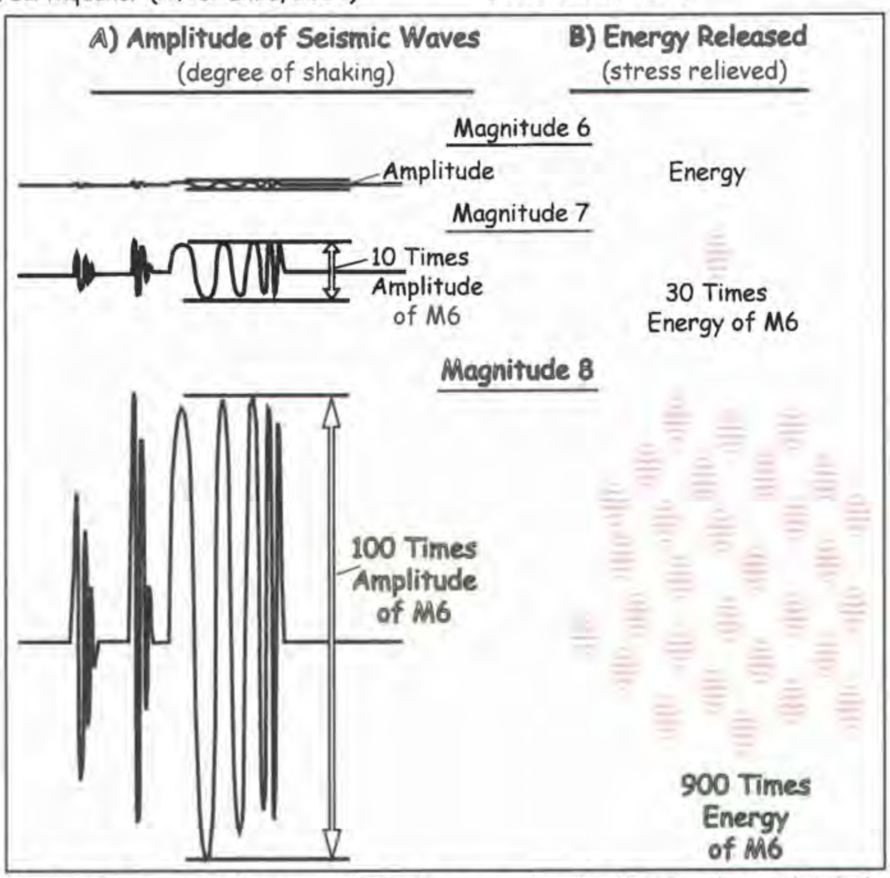


Figure 4-5: The amount of energy released in an earthquake dictates the amplitude (up and down ground motion) of the seismic waves, which is used to compute the magnitude of the earthquake. People often make the erroneous assumption that a couple of magnitude 6 earthquakes will release the same amount of stress as a magnitude 8 or 9 earthquake. In fact, we would need 900 magnitude 6 earthquakes to release the same amount of energy as just one magnitude 8 earthquake, and 27,000 magnitude 6 earthquakes to equal the energy of a single magnitude 9! And the amplitude of the seismic waves generated by a magnitude 8 earthquake is 100 times that of magnitude 6 waves. (Modified from Lillie, 2004)

increase in amplitude of the seismic waves (fig. 4-5). Beneath the coast, moderately large earthquakes of magnitude 6 are common (moment magnitude reported in Trehu, 1995). Although a jump in magnitude to 7 does not seem much larger, the amount the ground moves up and down would be 10 times as high ($10^7/10^6 = 10^1 = 10$, fig. 4-5 A). If we now compare a magnitude 6 to a magnitude 8, we see the power of this logarithmic scale: the ground shakes in waves 100 times as large in a magnitude 8 earthquake compared to those produced by a magnitude 6 ($10^8/10^6 = 10^2 = 100$).

So we've discovered that the amplitude of the waves increases logarithmically in the Richter Scale, but we need to consider how magnitude expresses the amount of energy released by the earthquake. Hundreds of years of stress can store a lot of energy that is suddenly released when the rock finally fails. But it takes a lot of energy to increase the amplitude of seismic waves. In fact, it takes about a 30-fold increase in energy to increase the amplitude of seismic waves by a factor of 10 (fig. 4-5). That means it would take approximately 30 magnitude 6 earthquakes to release the same amount of energy as a single magnitude 7 earthquake. Following this logic, it would take 900 (30 x 30) simultaneous magnitude 6 earthquakes to equal the energy released by a single magnitude 8 earthquake (fig. 4-5 B). So, when we think about the stress of plates colliding in a subduction zone, we would be wildly underestimating the power of Earth processes if we say, "oh, we just had a magnitude 6, so we won't have a larger earthquake for a while because a lot of stress was just released." **Wrong!** In fact, we would need somewhere between 900 and 27,000 magnitude 6 earthquakes to release the energy of a large (magnitude 8 to 9) Pacific Northwest earthquake, as will be discussed later.

Scales of earthquake magnitude are useful to scientists if they provide a way to measure the energy released by the earthquake using specific parameters. Scientists sometimes prefer to report earthquake magnitude based on the size of the fault that ruptures, rather than the degree of shaking of the ground (wave amplitude) measured by the Richter Scale classification. This scale, called the ***moment magnitude*** scale, reflects not only the area of Earth that ruptured, but also the amount the fault surface slipped. The energy released during an earthquake is a function of three parameters: 1) the surface area of the ruptured fault, 2) the amount of slippage along the fault, and 3) the amount of friction along the fault zone (Clarke and Carver, 1992; Yeats and others, 1997). Thus, the larger area ruptured (the bigger the fault), the larger the earthquake.

Scaling it down: Moment magnitude versus other earthquake measurements

One type of measurement of earthquake magnitude is based on the recorded amplitude (size) of seismic waves. However, in cases where the ground shakes very violently – as common in great earthquakes – measuring earthquake magnitude via the amplitude of seismic waves has been found to underestimate the amount of energy released in the earthquake. The scale becomes saturated as the shaking approaches its upper limit, so the maximum extent of shaking cannot be recorded. To estimate the amount of energy released in a large earthquake, the moment magnitude scale is more accurate (Clarke and Carver, 1992; Main, 2000).

Put into a context of plate tectonics, divergent boundaries (such as the Gorda Ridge) and hotspots are only capable of earthquakes up to a magnitude of about 7.5 (Lillie, 2001). In those settings, hot asthenosphere rises and heats the overlying plate, thereby reducing the volume of material capable of brittle failure. At transform boundaries, where the hot asthenosphere stays put at a deeper level, the overlying plate is generally cooler, allowing a larger volume of material to break (bigger faults mean bigger 'quakes). The San Andreas Fault, for example, is capable of rupturing along fault segments more than two hundred-miles long. The fault segments can slip about 15 feet (5 meters), producing earthquakes with magnitudes up to 8.5 (Yeats and others, 1997). The nature of plates at convergent boundaries allows them to suddenly lunge past each other after being locked together for centuries. Such a break could rupture fault zones up to 1,000 miles (1,600 kilometers) long, slipping about 50 feet (15 meters), thereby producing earthquakes up to magnitude 9.5. An example is the 1964 earthquake in Alaska, which produced the tsunami that devastated Crescent City.

Magnitude and area

Here's an example of how the length of the fault that breaks has an impact on the size of the resulting earthquake. Let's first examine the maximum magnitude possible for an earthquake rupturing only part of the Cascadia Subduction Zone. The Gorda Plate portion of the CSZ is 150 miles (240 kilometers) long, from Cape Mendocino (MTJ) to southern Oregon (Blanco fracture zone), and about 50 miles (80 kilometers) wide. The dimensions of the Gorda Plate yield an approximate rupture area of about 7,000 miles^2 (18,000 kilometers^2), corresponding to a magnitude 8.4 earthquake. But what if the entire 750-mile (1,200-kilometers) length of the Cascadia Subduction Zone is more likely to rupture as a cohesive unit instead of separate portions rupturing individually? We can use 40,000 miles^2 (100,000 kilometers^2) as a conservative estimate of the rupture area of the entire Cascadia Subduction Zone. Thus, the Cascadia Subduction Zone is capable of producing earthquakes greater than magnitude 9.1 (Clarke and Carver, 1992).

"Hands On" Demonstration of Moment Magnitude

To better understand this concept, put your hands together in "prayer" position and make them slide about 2 inches past each other. Listen to the sound that movement makes. The sound waves created by your hands moving are just like the waves created by an earthquake. Now, imagine putting on those gaudy "We're Number One!" foam hands you can get at sporting events. What have we increased? The **area** of your hands. If we move those larger hands the same amount, more area slips; thus the resulting earthquake magnitude is proportionally larger. Let's say that the Styrofoam hands are about 30 times as large as your own. Again, we can think of the energy released by these larger hands in terms of sound: clap your own hands together and listen to the sound by a single pair of hands clapping. Now have 30 people clap their hands together and compare the noise. By multiplying the number of people by 30, you have effectively increased the energy released from clapping by a factor of 30, hence by one order of magnitude (fig. 4-5 B). So let's extend our example to all of Cascadia - the full extent of the Juan de Fuca and North American Plate Locked Zone. If we round it to be 625 miles (1,000 kilometers) long and (6 miles) (10 kilometers) wide, the area would be 4,000 miles^2 (10,000 kilometers^2). After having remained locked for 300 years when it should move at 2 inches per year, the plate would suddenly slip 50 feet (17 meters). The combined effect of 50 feet of slip over 4,000 square miles produces a moment magnitude 9 earthquake. Because an earthquake of this magnitude requires an incredibly large area be ruptured, the effects would be incredibly far reaching and leave no sanctuary for escape.

Intensity

Although the public may have heard about earthquake magnitude as expressed by the Richter Scale, anyone who has ever experienced an earthquake remembers the shaking, or intensity, they experienced at the surface. The Mercalli Scale qualifies this intensity, which is influenced by three factors: 1) magnitude of the earthquake, 2) nearness to the earthquake's focus, and 3) local ground (soil, bedrock) conditions (table 4-1).

Table 4-1: Describing earthquake magnitude and Modified Mercalli Intensity scales. Generally, higher magnitude earthquakes mean more shaking, but the degree to which the ground shakes and buildings are damaged is often determined locally by the type of ground on which structures have been built. (From the United States Geological Survey)

Magnitude	Intensity	Description
1.0 - 3.0	I	**I**. Not felt except by a very few under especially favorable conditions.
3.0 - 3.9	II - III	**II**. Felt only by a few persons at rest, especially on upper floors of buildings. **III**. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
4.0 - 4.9	IV - V	**IV**. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing cars rocked noticeably. **V**. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned.
5.0 - 5.9	VI - VII	**VI**. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. **VII**. Damage negligible in well-designed and constructed buildings; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0 - 6.9	VII - IX	**VIII**. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. **IX**. Damage considerable in specially designed structures; well-designed frame structures skewed. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
7.0 and higher	VIII or higher	**X**. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. **XI**. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly. **XII**. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Crowd Surfing! Compressional Wave Demonstration

Loose soil magnifies the effects of shaking, whereas firm bedrock transmits the waves without significant amplification. To convey this concept better, gather several rows of people and instruct them to link their arms loosely. Tell people at one end to bump into the person they are next to and so forth to send the "wave" to the other side and back (fig. 4-6). Ask them to think about how much they moved and how fast the wave traveled through them. Next, instruct the group to tighten their arm grip so that they scrunch together closely. Have the same people begin the "earthquake" at one end and again ask them to think about how much they moved and how fast the wave traveled. It should be clear that compressional (P) waves travel fastest through tightly packed particles (such as those of solid rock), but with small amplitudes. Loose particles (such as sand or gravel) slow the wave down, but its amplitude is magnified. Have the visitors think about this in relation to the kind of ground into which buildings are constructed, and what will happen to the building as the earthquake waves pass through.

People often describe experiencing several sensations during an earthquake. Commonly, people report first "hearing" the ground rumble (something like an approaching train), and then "feeling" the ground shake (depending on the earthquake's intensity, this shaking could be violent or more subtle, like the way your windows rattle when a large semi truck speeds past your home). The reason there are different sensations is because earthquakes generate three distinct types of waves that travel through the Earth at different speeds and in different manners.

The fastest of the three types of earthquake waves are ***compressional waves***, which are really sound waves traveling through the rock of the Earth. Visualize stretching a slinky (fig. 4-7 A), holding one end, and then flicking your wrist outward from you so that the metal spirals compress and expand, compress and expand, as the wave propagates from your wrist to the other end (fig. 4-7 B). This is what happens to Earth materials (rock and overlying soils) as compressional waves pass through. Another set of waves, ***shear waves***, follow compressional waves at about half the speed, contorting the Earth in sideways motions (flicking your wrist side to side instead of outward so that the slinky snakes toward the other end in a horizontal "S" motion, or

Figure 4-6: Earthquake!!! This audience is getting a real feel for how compressional seismic waves (P-waves) move through particles because each participant gets to "be" a particle. If their arms are linked loosely, they bounce around more (like sand particles), whereas if their arms are linked tightly, the energy quickly passes through them without as much movement (like solid rock). (Photo by T. Parshall)

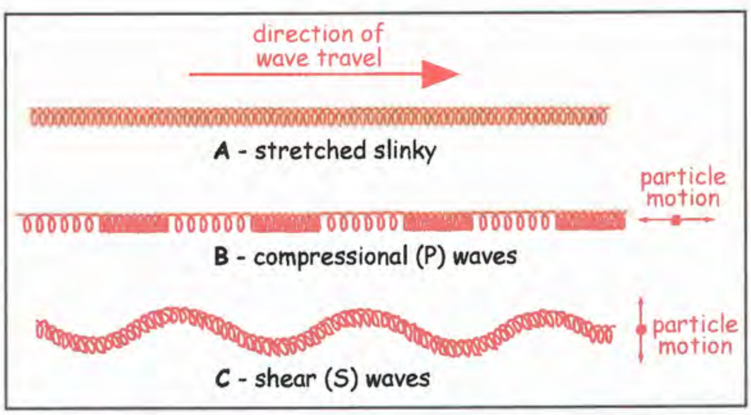


Figure 4-7: Everyone loves a slinky! Using a moderately stretched slinky (**A**) as a proxy for Earth material (rock), we can simulate seismic waves in a similar fashion to the linked arms demonstration (fig. 4-6). The fast, compressional (P) waves, propagate through the Earth by alternately squeezing and stretching the rock (**B**). Secondary shear (S) waves travel through the Earth either side-to-side or up-and-down (**C**).

flicking your wrist up and down so that the "S" is vertical, fig. 4-7 C). Arriving shortly after shear waves are ***surface waves*** that roll the land surface up and down and back and forth. These relationships explain why people sense the "sound" vibrations of the less-severe compressional waves before they feel the higher amplitude and more severe ground motions associated with the slower shear and surface waves. These later, more intense waves cause the bulk of the damage associated with earthquakes.

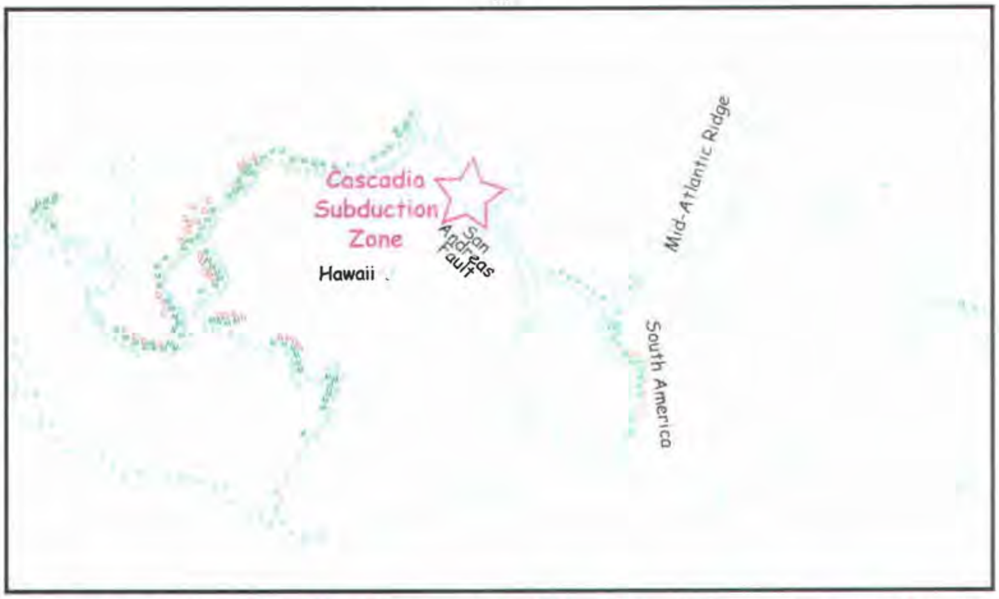
Earthquake intensity generally decreases with increasing distance away from the epicenter because seismic wave amplitudes gradually die down as the waves travel through the Earth. But local conditions, such as valley sediment or landfill, amplify seismic waves, thus locally increasing the intensity. People's observations during and after an earthquake provide valuable information on the region's response. Immediately after an earthquake, surveys are circulated to residents of the affected region to determine the extent to which specific areas experienced seismic intensity. The survey information can then be used to produce intensity contour maps locating the areas of high shaking.

Earthquakes in the Pacific Northwest (Where the Action is – or Will Be)

We have already recognized that convergent boundaries like the Cascadia Subduction Zone, where the Gorda and Juan de Fuca plates are being shoved beneath North America, are capable of producing the largest types of earthquakes ("locked zone," fig. 4-2 B). Unlike other subduction zones, however, there is no written indication of a large (magnitude 8 or higher) earthquake during the past 300 years or so of recorded history in the Pacific Northwest (for example, Rogers and Dragert, 2003, as cited in Kaye, 2003). But there is evidence that large earthquakes did indeed cause extreme coastal flooding and tsunamis at least four times over the past 2,000 years (see "How we know" and Chapter 5; Satake and Tanioka, 1999). So, where's all the action (fig. 4-8)?

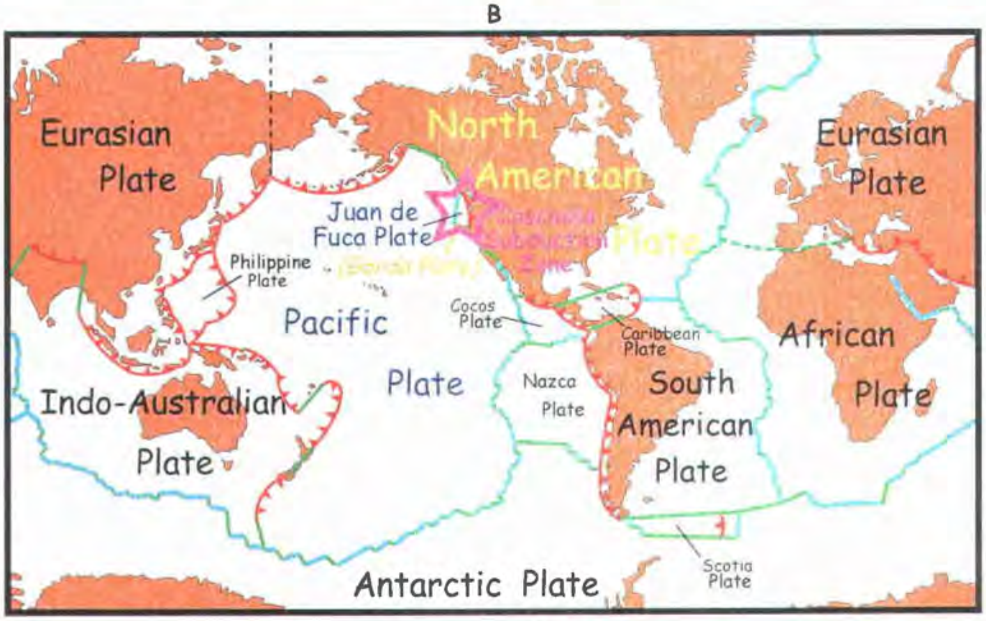
Some dramatic things happen when large locked-zone earthquakes occur. For example, the coastal and offshore areas suddenly drop down after being slowly bent upward (uplifted), thereby generating tsunami waves (fig. 4-9). These events leave

A



S = Shallow (< 40 miles) **M = Intermediate (40 - 200 miles)** D = Deep (> 200 miles)

B



Divergent Convergent "Teeth" on Overriding Plate Transform

Figure 4-8: Seeing double? You may think the dots on the top map (**A**) were plotted intentionally to outline plates (map **B**), but the dots are simply showing the locations of earthquakes around the world. Notice how well the dots (**A**) correspond to the boundaries of plates (**B**). Also notice that the dots are in fact letters - S (shallow), M (intermediate), and D (deep) - that indicate the depth at which the plotted earthquakes occured. The red "D"'s only occur at the red convergent boundaries, showing that deep earthquakes happen where one plate subducts beneath another. Will the Cascadia Subduction Zone be the only subduction zone to never have large magnitude earthquakes? (Modified from Lillie, 2004) "signatures" in the geologic record, and such imprints can be seen in the Pacific Northwest. In fact, geologic evidence shows that 13 events have occurred in the past 7,700 years (Atwater and others, 1987, Goldfinger and others, 2002). There is thus a "***recurrence interval***" of several hundred years between these large earthquakes, and this delay can be attributed to the mechanics of subduction. The Gorda Plate grinds beneath the North American plate in "fits and spurts," remaining locked for centuries before the two plates suddenly unlock and lunge past each other. Incredible stress builds in the years that the plates are stuck together, so when the rocks finally do reach their elastic limit after 200 to 800 years, the resulting earthquake shock waves are catastrophically large. This interpretation lends itself to some sobering thoughts: if the recurrence interval is every 200-800 years, and the last great Cascadia earthquake was 300 years ago, the Pacific Northwest may be due for the next one! Of course, given the 600 year recurrence interval range, we might not experience the next great earthquake for another 300 years.

The impact of a subduction locked zone earthquake (magnitude 8 or 9) on RNSP would mostly affect the coastal regions and the headquarters in Crescent City, but could produce intensities up to XII in the park (table 4-1). Because Crescent City is built on mostly unconsolidated beach sediments, it is likely to amplify the seismic intensity, which means the area would experience lots of shaking. Inland, because the park has many steep hillslopes, landslides and road failures are likely hazards.

Case Study: rattles from Alaska to California and everything in between

Another way of evaluating the earthquake hazard of RNSP is to analyze the impact of recent large earthquakes near RNSP, such as the 1992 Cape Mendocino earthquake. The effects of the Cape Mendocino earthquake can be compared to what we know about the 1964 Great Alaska earthquake and we can learn from these "case studies" to be savvy about RNSP's earthquake risk.

On April 25, 1992, a magnitude 7.2 earthquake shook the Cape Mendocino region of northern California. Along localized regions of the Lost Coast, as much as 2-5 feet (.5-1.5 meters) of uplift was reported, raising tide pools above sea level and killing many intertidal organisms (fig. 4-10; Oppenheimer and others, 1993). There was no loss of human life, but 356 injuries were reported (Oppenheimer and others, 1993). The relatively low human impact is partly due to Cape Mendocino's sparse population. The magnitude 9.2 Great Alaska earthquake claimed 125 lives (110 tsunami; 15 earthquake) due to the analogously sparse population (140,000) of the Prince William Sound region (United States Geological Survey; Main, 2000). Also contributing to relatively low incidence of fatality, Kodiak, Alaska, had developed and implemented a hazard mitigation plan, which was efficiently executed (see "What can we do;" Main, 2000). The maximum uplift observed at Montague Island, Alaska, was around 45 feet (14 meters; Johnson and others, 1996). Both of these large earthquakes involved the rupture of segments of subduction zones and impacted regions with relatively low-population density.

Let's think for a moment about the area that would be impacted if the entire Cascadia Subduction Zone ruptured at once. There are over 10 million people living in the potential hazard zone. Imagine if regions of the coast, like Crescent City, California, or Newport, Oregon, were submerged or uplifted several feet. Compared to the Prince William Sound region of Alaska, there are over 90 times more people (and proportionally more property and development) within the Pacific Northwest hazard zone. Given the reality of natural risk around RNSP, our understanding of the ongoing geologic processes is quite important and it is paramount that we convey this risk to RNSP visitors.

How We Know: Evidence for Locked Zone Earthquakes

There are several lines of evidence for great Cascadia Subduction Zone earthquakes, including submerged shores, tsunami deposits, tsunami records, and turbidity flow deposits. There is enough friction between the Gorda and North American plates to keep them from smoothly sliding continuously past each other, so the force of compression and the influx of material as the plates converge must be accommodated in some other fashion (Kaye, 2003). To absorb the stress, the Earth's surface slowly contorts, in places bending upward, uplifting the coastal region about 6 feet (2 meters) in 300 years (Lilllie, 2001; Doser and Brown, 2001). Over those 300 years, ecosystems change along the uplifting coast, as shallow bays become marshes that develop into lowland forests. When the stress becomes too great and the plates unlock suddenly, the surface (coastal region) will drop down those 6 feet! Along the coast of northern California, Oregon, and Washington, there are deposits of marsh plants and trees buried by sand, which is overlain by bay muds, then more marsh, then sand again (Atwater and others, 1987; Jacoby and others, 1995).

The sequential deposits are thought to represent a progression of deposition relating to coastal earthquakes. Where land drops during a great locked zone earthquake, a shallow bay is created into which mud is deposited. The plates become locked again, but convergence continues to uplift this bay until it shallows and becomes a marsh in which trees and other plants grow. When the next great earthquake occurs,

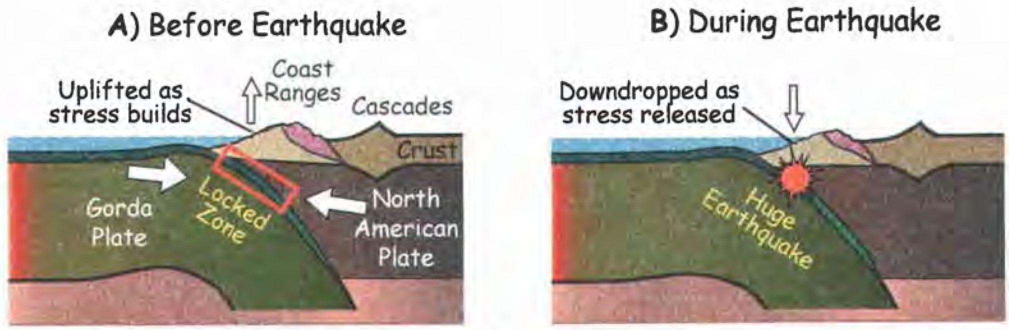


Figure 4-9: Snap! Just like a tree branch suddenly breaking, once a great earthquake releases the stress of the locked rocks (**B**), the coastal areas that had been flexed upward (**A**) will snap down.

Figure 4-10: Rocky shore areas that are usually submerged about 4 feet beneath the Pacific Ocean were uplifted up to 8 feet locally during the 1992 magnitude 7.2 Cape Mendocino earthquake. Residents of the area noticed the smell of dying sea creatures within days of the event. (Photo courtesy of NPS)

the area once again is submerged and deluged with sand deposits brought by tsunami waves. (Tsunami deposits have been studied extensively to characterize the nature of these so-called "tidal waves," and are discussed in Chapter 5.) The tsunami-wave inundation is indicated by sharp interfaces between the marsh peats and the ocean muds (fig. 5-8). The sand, to mud, to marsh, to sand sequence has been repeated at least seven times over the past 3,000 years (13 times in the past 7,700 years), and each sequence is thought to represent a Cascadia earthquake cycle (Atwater and others, 1987; Adams, 1992; Goldfinger and others, 2002). Stumps left from drowned forests along the West Coast have been discovered, with radio-carbon ages corresponding to those suggested for the past locked zone earthquakes (Jacoby and others, 1995).

Great Cascadia quakes rattle the Pacific Northwest region so much that large blocks of sediment on the continental shelf break lose, get saturated with water, and flow down the continental slope. These turbidity flows leave characteristic deposits, called "turbidites," on the sea floor, which, when retrieved in drilling cores, are dated using radio-carbon techniques. Thirteen such turbidites have been identified in ocean sediment deposited over the last 7,700 years along the Pacific Northwest coast, many correlating with the dates inferred from the drowned marshes and forests (Adams, 1992; Goldfinger and others 2002). The turbidite layers provide an independent line of evidence for extremely large earthquakes shaking the Pacific Northwest (Heaton and Hartzell, 1987).

Clues: investigating paleoseismicity

Let's find out how much of an Earth sleuth you are! You investigate the coastal area from Vancouver Island, British Columbia, to Humboldt County, California, and find much the same pattern over the region's entire length. Here are your clues: you have drowned trees on submerged landslides, you have the juxtaposition of subsided (sunken) tidal marshes and uplifted marine terraces that are the same age, you have correlated sand layers deposited in multiple swamps, you have rock avalanches and debris flows of similar ages blocking stream channels, and you have turbidity current deposits on the continental shelf. Given the evidence, what seems to happen periodically in the Pacific Northwest to cause the pattern of similar features we see up and down the coast? EARTHQUAKES!!!

Scientists in disciplines ranging from geology, to botany, to hydrology have collaborated in their investigation of evidence for past earthquakes (paleoseismicity) in the Pacific Northwest. There has been a significant amount of correlation between the dates (synchronicity) of each disturbance recorded in the history of the landscape. The apparent coincidence leads scientists to conclude that the events initiating the disturbance sets must be of a great enough magnitude to impact the entire region (Heaton and Hartzell, 1987; Adams, 1992).

In addition to physical, geologic evidence of tsunamis, there are also accounts from native American legends and Japanese historical written records that apparently correspond to the last great earthquake, 300 years ago (see "The Flood;" Heaton and Hartzell, 1987).

All these lines of evidence suggest that the average recurrence interval for great Cascadia locked zone earthquakes is roughly 550 years, with the most recent having occurred on January 26, 1700. Hmm.... (fig. 4-1 shows how many earthquakes up to magnitude 7.4 occurred around RNSP between 1975 and 1995.)

"Decade of Terror?"

Perhaps an even scarier thought is what happens if the Earth decides to relieve its stress, not in one single colossal earthquake event, but instead distributes that energy over several very large earthquakes. Think of it this way: we know that it takes 30 magnitude 8 earthquakes to release the same amount of energy as one magnitude 9. Well, what happens if that energy is released in 30 magnitude 8 earthquakes over a span of a few years? We have a true Decade of Terror (Heaton and Hartzell, 1987)!

Intense facts for the visitors:

*If we assume that the Gorda Plate would slip beneath the North American plate at about the rate your fingernails grow, or about 2 inches a year, then in the last 300 years the Gorda Plate should have slipped 600 inches (50 feet, 17 meters). But instead, the plates have been locked for the past three centuries; when the plates suddenly unlock, North America will lunge 50 feet over the Gorda Plate!

*The energy released by a great locked zone earthquake (magnitude 9) in the PNW would be equivalent to about one million atomic bombs exploding simultaneously.

The Last Great Cascadia Earthquake

We know that one of the two largest earthquakes in modern recorded history was on March 27, 1964, off the coast of Alaska, because we have a wealth of direct observation for this event. But most geologic dating techniques are too imprecise to yield exact dates for events. So how can we say so confidently that the most recent Cascadia locked zone earthquake was on January 26, 1700? Stumps of trees that died in marshes when they were submerged and buried by sand are clues. Radiocarbon dating tells us that the trees died about 300 (+/- 10) years ago (Jacoby and others, 1995. There are written records in Japan that tell a story of a tsunami wave hitting that country on January 27, 1700 (Heaton and Hartzell, 1987). Tsunami waves on average travel about 450 miles (700 kilometers) per hour in the open ocean, so it would take about 10 hours for a tsunami generated in the Pacific Northwest to reach Japan's Pacific shore (International Tsunami Information Center, 2002). The waves therefore would have reached Japan's shores the day after the earthquake shook the Pacific Northwest, about 4,500 miles (7000 kilometers) and many time zones away (Atwater, personal communication). Even closer to our own shore, we can turn to Native American legends of "floods" destroying their coastal villages. Both Tolowa and Yurok tribes have such stories (see "The Flood").

The Flood (Lake Earl and North Coastal California)

It was in the fall of the year when there was an earthquake. "Well something not good is happening, you had better watch," he said. The Earth shook again.... "If the Earth shakes east and west the sea will rise up..." he said. The Earth did truly shake from the west and everything on the Earth fell down. The water rose in the streams and came over the banks.

There was among them a girl.... Her brother went with her running up the mountains. They kept looking back as they ran and saw the water coming from the west.... They ran on up the hill and the water nearly overtook them.... The water was also coming up the mountain from the east side because all the streams were overflowing.... "Let us run up along the ridge," the boy said to his sister. When they neared the top, they saw the water covering the whole world.... After ten days the young man went down to look about and when he returned he told his sister that all kinds of creatures both large and small were lying on the ground where they had been left by the sea. "Let us go down," his sister said.... But when they came there, there was nothing, even the house was gone. There was nothing but sand. They could not even distinguish the places where they used to live. (Tolowa story recorded by Goddard; Redwood Creek Tsunami Work Group)

Chapter 5: Tsunami!

Earthquakes from under the seas
Cause big waves to submerge the trees
The first waves are small
Compared to them all
These series we call - tsunami.

A tsunami is often referred to as a "tidal wave," but this is misleading. The term "tidal wave" has several erroneous implications about the nature of the phenomenon: 1) that the waves are caused by the ocean's tides (that is, periodic forces such as the gravitational pull of the sun or moon); and 2) that there is only one gigantic wave that crashes over the shore and engulfs everything in its path. In fact, the occurrence of a tsunami is unrelated to the tides, and a single tsunami barrages the coast in a series of waves lasting hours. A tsunami event is a series of sea waves caused by displacement of the water column. Let us explore what really happens both to cause tsunamis and once a tsunami occurs.

Water Works: Doin' the Wave

Let's do a quick review of the parts (anatomy) of a wave. The distance between the top (***crest***) and the bottom (***trough***) of the curve is the wave's height (***amplitude***). The distance between two successive crests is the ***wavelength***, and the time it takes one wavelength to travel past a fixed point is the ***period*** of the wave (fig. 5-1 A). The relationship between each wave parameter defines the way energy that moves along as the wave.

Have you ever watched a buoy bob up and down offshore? Although we tend to think of water waves moving toward shore, the particles of water that make up waves actually bob up and down (oscillate vertically), in slightly oval (elliptical) "orbits" (fig. 5-1 B). Wind currents blowing over the sea surface drive this movement. The direction (typically with the prevailing wind currents) the water particles are moving at the top (crest) of their orbit determines which way the wave crests travel (propagate) across the sea surface (fig. 5-1 A). The top-to-bottom movement of water molecules does

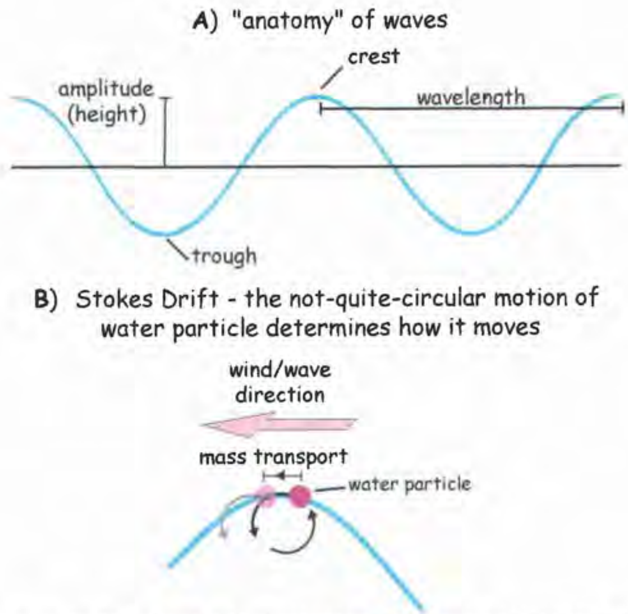


Figure 5-1: Goin' with the flow! (**A**) illustrates the wave parameters of amplitude and wavelength whereas (**B**) shows the mechanics of Stokes Drift. Particles near the surface of ,the ocean bob up and down in accordance with their nearly circular orbits. These orbits become more elliptical under the influence of wind (and water) currents, so the particles slowly drift in a direction parallel to that of the wind. The period of a wave is the time between the arrival of wave crests, and is dependent on the wavelength and speed (velocity) of the wave. To understand better how a wave can propagate through a medium without actually moving the particles of the medium the same amount, visualize a crowd at a sports event doing "The Wave." While the wave moves around the stadium, an individual seated in section 25, row 7, seat 42 moves up and down, but that person stays in section 25, row 7, seat 42.

Figure 5-2: Swell! Although tsunami waves often go undetected in the open ocean, sometimes vessels in shallow waters get front row seats! (Photo courtesy of National Oceanic and Atmospheric Administration)

not continue down a great depth in the ocean. The ability of wind to mobilize water decreases with depth, and the depth at which the motion of water particles is no longer significant is called the ***wave base***. Wave base is an important control of wave height because particle motion is affected by the depth of the water.

When the water is shallow, the particles near the bottom of the wave base are no longer able to fully orbit down into the water column. Because the particles cannot move farther down, they remain shallow, effectively pushing the water column up and increasing the height of the wave. So, as a wave approaches the shore, the water depth shallows. When the height of a wave exceeds the point at which the wave can be stable, the crest spills over, or breaks. This is when we see "white caps," or *breakers*, approaching the beach.

Go With the Flow: Tsunami Mechanics

The mechanics of tsunami waves determines their impact once they reach the shore. Tsunami waves generally have long wavelengths (and periods) and small amplitudes (fig. 5-1 A). Whereas typical storm swells might have a wavelength of about 500 feet (150 meters) and a period of only 10 seconds, tsunamis can have a wavelength over 120 miles (200 kilometers) and periods close to an hour (Johnson and Satake, 1997).

Waves that have small amplitudes (crests only about 3 feet, or 1 meter, high) and long periods (up to an hour) are able to conserve their energy as they travel for considerable distances in the open (deep) ocean (Shuto, 2000). A tsunami may pass beneath a ship in the open ocean without passengers on the ship even noticing! (Sometimes, however, those in shallow waters notice a tsunami disturbance – fig. 5-2) Tsunamis not only retain their wave energy when traversing the ocean, but also they typically reach speeds in excess of 450 miles per hour (700 kilometers/hr) in the open ocean, enabling them to cross vast expanses with both power and speed (International Tsunami Information Center, 2002). In fact, tsunamis commonly travel between 600 and 700 miles per hour (375 to 440 kilometers/hr), faster than the average speed that a Boeing 757 aircraft can travel! So, if you want to know the time it takes a tsunami to cross the Pacific Ocean, think about how long it takes to fly from California to Japan –

about 14 hours! As the tsunami approaches the shore, the water shallows to less than the wave base. This interferes with both the amplitude and wavelength, like a rug being crumpled. Because the trough must shorten, both the wavelength and speed decrease. The amplitude of the tsunami must account for this, so the crest (height) grows from a modest 3 feet (1 meter) to tens of feet (several meters) as it approaches the coast (fig. 5-3).

Tsunami arrival

We can think of it this way: long wavelength waves, such as tsunamis, have a deeper wave base (so the wave extends farther down into the water column) than waves whose crests are closer together. Thus, a massive volume of water is in motion within tsunamis. The front of the wave slows down as it approaches land and "bottoms out" where the sea floor slopes up (fig. 5-3). But the particles behind in the rest of the wave are still traveling at rapid speeds. Like a rug or multiple car crash, the later crests and troughs pile up water behind the slowed initial wave, further increasing the height of the crests as they rush ashore. It is important to realize that it is as likely that a trough of a tsunami will first reach shore as it is likely that a crest will arrive first. So, if you're walking along the coast and the sea suddenly drops and the water goes out, RUN! (See "How to Survive a Tsunami Hazard")

The severity of tsunami impact on shore, or tsunami ***inundation***, is defined by the extent of tsunami run-in and run-up (table 5-1). Tsunami ***run-in*** is the horizontal distance to which tsunami waves rush inland. The maximum land elevation (vertical distance above normal sea level) to which tsunami waves reach is the ***run-up***. Both offshore and coastal features – including reefs, angle of continental slope, and geometry of river mouths and embayments – influence the size and impact of tsunami waves (International Tsunami Information Center, 2002). If the topography of the land is low, tsunami waves can inundate farther inland than if the coast is steep, so local variables have a great impact on the extent of tsunami damage. Seaside communities centered around embayments, such as Crescent City, are especially susceptible because the coastline slope is often low and the geometry of the bay can focus tsunami wave energy.

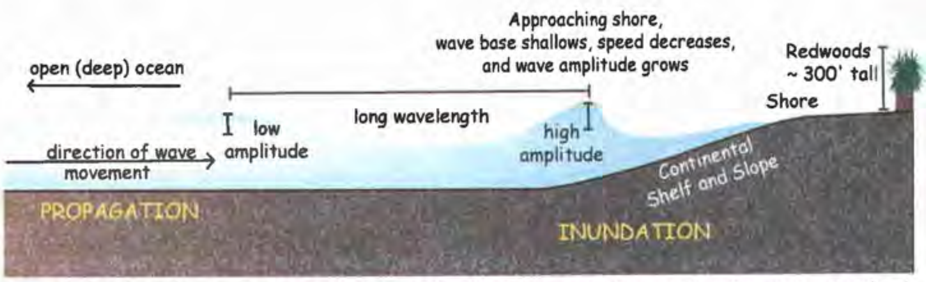


Figure 5-3: Quick, to the trees! Where's the Tsunami Evacuation Route? As the broad tsunami wave approaches shore, the sea floor slopes up, interferes with the wave base, and slows the front wave down. Like a rug or multiple-car crash, the waves behind pile up water behind the front wave, increasing the wave height as the tsunami reaches shore. Tsunami waves have been reported at 100 feet (30 meters) high and have flooded inland more than a quarter mile!

Figure 5-4: Crinkled coastline. Curved coves and crescent-shaped embayments are characteristic features of RNSP's shore. Similar to water sloshing in a rounded tub, incoming waves can be focused and amplified by coastal geometry. (Photo courtesy of NPS)

Figure 5-5: Pacific pond? Think of the pattern of ripples made by a pebble thrown into a pond, then look at this model of the 1964 tsunami travelling toward Crescent City. The displacement of the sea floor from the Alaskan earthquake shoved the water column enough to generate the ensuing teletsunami. (Modified from the National Oceanic and Atmospheric Administration)

Port towns are built next to natural harbors that are commonly crescent-shaped (fig. 5-4). Whereas the embayment normally provides ideal harbor conditions, this shape can also focus incoming tsunami wave energy and amplify the run-up depending on the direction from which the tsunami waves arrive. Magnification of the tsunami inundation is, in fact, an unfortunate aspect of the 1964 tsunami that hit Crescent City (see "North Coast tsunami history;" figs. 5-8, 5-9).

Tsunami Height	**What you notice (near source)**	**Damage (near source)**
3 feet (1 meter)	If the bottom slope is steep, tsunami resembles tide that doesn't break. If bottom slope is shallow, its rapid swell is often not recognized	Some partial damage to wooden houses
6 ft (2 m)	For steep slope, tsunami resembles breaking tide. For shallow slopes, it initially resembles a wall, then breakers spill	Most wooden houses demolished, fishing boats damaged, possible loss of life
8 ft (2.5 m)	Continuous wall with tell-tale spilling breaker front, continuous roar (like storm or truck) generated	
13 ft (4 m)	Similar to 7.5 ft, more pronounced spilling breaker	Some stone houses demolished, many fishing boats damaged, concrete houses withstand
16 ft (5 m)	If tsunami hits coastal cliff, loud sound like thunder or explosion generated and heard for long distance	
25 ft (8 m)	No tide-like rise of water level, first tsunami wave is plunging breaker	Stone houses demolished, all fishing boats damaged, reinforced concrete buildings may withstand

Table 5-1: What tsunami run-up means for people on the coast. "Average" to "moderate" size tsunami waves typically surge up onto the coast without breaking (similar to how high tide comes in). However, commonly, the higher the tsunami wave, the more likely it is to break and the higher its potential for damaging coastal structures. (After Shuto, 2000)

What happens when you throw a pebble into a pond? Is there just one wave generated from the disturbance, or is a series of ripples generated? Digital model images of tsunami events show a remarkable resemblance to ripples propagating over a pond, so we can think of the Pacific Ocean as a "Big Pond!" (fig. 5-5) Just as there is a **series of ripples** that spreads from where the pebble sinks into the pond, a **series of waves** is emitted when the water column is displaced enough to generate a tsunami in the ocean (see "What causes tsunamis").

One of the most unfortunate misconceptions the public has about tsunamis is that a tsunami is simply one giant wave that crashes into the shore and that is the end of the tsunami. In fact, the giant ripples that propagate out from the tsunami source besiege the coast in a series of waves, and the first is often not the largest or most destructive (see "brass knuckles"). The lengthy period between waves (up to an hour) can fool people into thinking that the tsunami has ended, but the barrage of waves can last up to 12 hours. Because of the public's misconceptions, people have returned to the "danger zone" before the official "all clear" has been issued (see "How to survive our tsunami hazard").

Tsunami: The "Brass Knuckles" of the Ocean

The awesome power of nature is often difficult for people to grasp without concrete physical examples to which they can relate. During a demonstration, I like to pull someone (typically a Junior Ranger) from the audience and hand my volunteer a liter water bottle, which weighs about 2 pounds when full. I begin by saying, "Folks, think about how much water weighs. Any of you who've ever backpacked, hiked on a hot day, or even cleaned a fish tank can testify to the heft of water. So [insert volunteer's name] is holding this bottle of water and can feel its two pound stationary weight. But now I'd like [volunteer] to please catch the bottle as I lightly toss it toward [him/her]. How does the bottle feel when it hits you now that it's in motion? (Heavier, or more forceful.) How fast do you think the bottle was traveling? [A few miles per hour.] Imagine if I were to throw this at you at about 40 miles per hour. How would those two pounds feel then?"

At this point, we can define the potential for a single tsunami wave. Water weighs about 8 pounds per gallon, or 62 pounds per cubic foot (about 8 gallons). Instead of a little water bottle, we imagine the weight of a standing wave of water 100 feet tall, 1,000 feet long (which is only one fifth of a mile, but we can use this length for the example), and we can pretend the wave is 100 feet wide (even though tsunami wavelengths often exceed 100 <u>miles</u>). That *stationary* wave weighs about <u>300 million pounds</u>! (Note: Remember that tsunami waves can impact hundreds of miles of coastline, so they would weigh much more than a wave just 1,000 feet long and 100 feet wide.) In the open ocean, tsunami waves can travel at speeds up to 600 miles per hour, but they slow down to about 40 miles per hour by the time they slam into the coast. So, using our hypothetical wave, we have 300 million pounds of water crashing into the coast at about

40 miles per hour. That kind of "knock-out" knuckle sandwich would punch out anything in its way!

Have the audience think about the kinds of structures near the waterfront of coastal communities. Ships, docks, boathouses, jetties, pubs, markets, beach houses, residential homes, and piers are all built along the shore. How many of those structures will survive a swell that weighs more than 300 million pounds inundating the community at 40 miles per hour? (table 5-1) The force of the surge can easily damage or tear apart even solidly built concrete structures. When the first wave withdraws back to sea, it drags with it much of the debris from the buildings lining the shore – almost as if the wave were putting on "brass knuckles." So when the second wave comes in, it returns armored with its "brass knuckles" (the debris from the first surge), and then slams back into any structures that survived the first assault. Typically, the second, third, and fourth waves have more extensive run-ins, so they surge farther into the waterfront community and pick up more debris with every successive "punch." This is why tsunami events are called the "Brass Knuckles of the Ocean" (fig. 5-10).

What Causes Tsunamis?

Few events introduce enough energy into the water column to cause a tsunami. Large meteorite impacts, which are quite rare, and landslides both disrupt the water column from above. But the amount of water mass responsible for the energy from such above-the-water processes is often small, so that the waves generated commonly dissipate quickly and have little impact on distant shores.

Submarine landslides (sometimes accompanying large earthquakes) and submarine volcanic eruptions may be massive enough generate sufficient uplifting force from below to displace the water column significantly (Pinet, 2003). Submarine landslides are more commonly triggered in regions of tectonic activity, such as the volcanism of the Hawai'ian Islands or the earthquakes associated with plate movement at boundaries like the San Andreas Fault or the Mendocino Triple Junction. Considering how close plate boundaries are to the continental shelf, submarine landslides do pose a significant tsunami threat to the California coast south of Cape Mendocino. The single most common cause of giant tsunamis is **movement of the seafloor caused by earthquakes** (Satake and Tanioka, 1999).

Let's think about throwing a pebble into a pond of water again. Now, imagine instead that the pond spits the pebble back out from the bottom and you'll have a pretty good analogy for how most tsunamis are generated by earthquakes. Although seismic

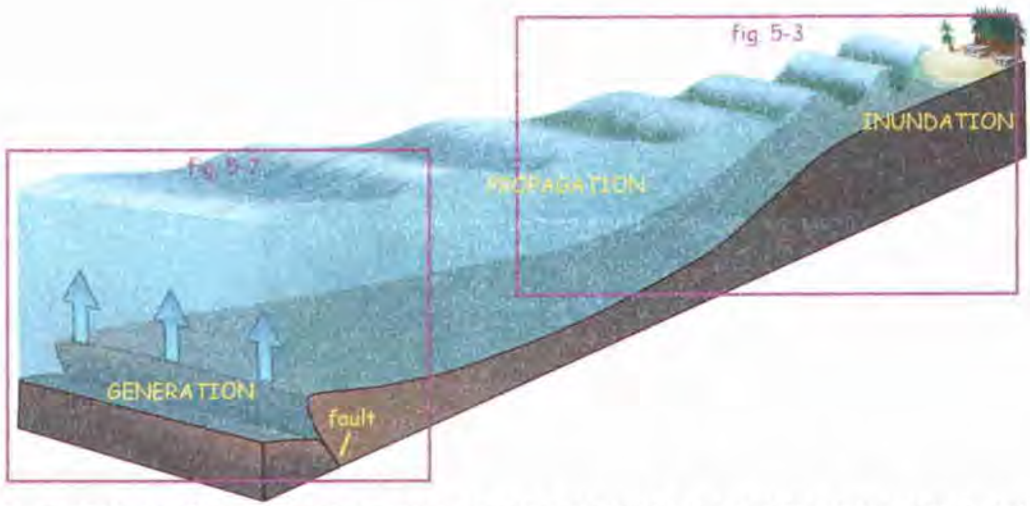


Figure 5-6: Surf's up! The three steps to make a tsunami are generation, propagation, and inundation. To generate a tsunami, the water column must be vertically displaced, which can be accomplished by faulting the sea floor (fig. 5-3). Then, once the broad "ripple" starts, the energy propagates out from the source toward shore. As the series of waves approaches the shore, the sea floor slopes upward, forcing the waves to slow down and the water behind to pile up (fig. 5-4). Once the tsunami reaches the shore, the local topography has great influence on how far inland the tsunami inundation extends. If the shore is flat (like at a river mouth or bay), the effects of the tsunami are often more severe. (Modified from National Oceanic and Atmospheric Administration)

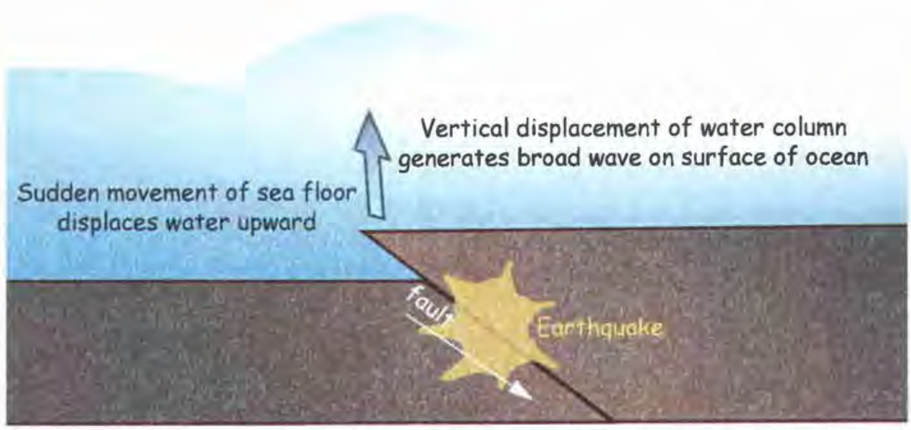


Figure 5-7: Shake it up, baby! Earthquake seismic waves can produce a fault that offsets (displaces) the sea floor. The up or down displacement of the sea floor then shoves particles in the water column upward or downward. This action generates a broad surface wave with a deep wave base and low amplitude and period that then propagates outward toward shore (fig. 5-6).

waves may vibrate the sea floor, it is important to recognize that it is the whole scale displacement of the sea floor, NOT the much smaller-amplitude earthquake seismic waves themselves, that causes a tsunami (fig. 5-6). Sudden displacement (up or down movement) of the sea floor energizes the water particles to a much higher level than movement produced by the wind, thus increasing the wave base. The magnitude and depth of an earthquake influences the amount of displacement of the sea floor, thus determining whether or not a tsunami occurs and how big it will be (fig. 5-7; Sokolowiski, 1999).

Where Tsunamis Come From: Local vs. Distant Sources

The most pertinent control over the severity of tsunami inundation is how close the at-risk shoreline is to the source of the tsunami. An earthquake on our Cascadia Subduction Zone would have a greater impact on RNSP than an equal-sized earthquake on the Southern Alaska Subduction Zone or the Japan Subduction Zone. There are important safety and response implications affecting RNSP's tsunamis hazard depending on whether the tsunami source is local (on the CSZ) or somewhere more distant (on another subduction zone, such as Southern Alaska).

A tsunami from a local source has the most potential for causing severe damage. Although people in the region may be "warned" by feeling the shaking associated with the earthquake, the first tsunami waves can inundate the shore within just a few short minutes after the earthquake. Severe local source tsunami run-ups can reach more than 100 feet (30 meters), about double of the most severe recorded distant source run-ups (up to 50 feet, or 15 meters; International Tsunami Information Center, 2002).

Distant source tsunamis afford more warning time (between 3 and 22 hours), but their severity is more difficult to forecast. Not only are tsunamis from distant origins subject to the same offshore and coastal features that impact local waves, but also the severity of distant source tsunamis is more sensitive to tidal fluctuations. Should a distant source tsunami hit the coast during low tide, it will have much less of an impact than during high tide, because the run-in and run-up distances will be less. Tsunami events can last more than 13 hours, so the change in tide levels during the tsunami event can either mute or amplify the waves (table 5-2; Johnson and Satake, 1997).

Characteristic of tsunami-causing event	**Effect it has on severity of tsunami**
Longer length of area displaced	Longer length of coastline affected
Wider area displaced	Smaller run-up; slightly smaller inundation
Larger total displacement (slip)	Larger total run-up and inundation
Bigger submarine landslide	Larger local run-up and inundation

Table 5-2: How the way the sea floor moves affects the characteristics and potential severity of a tsunami. In general, if a rupture is long, the tsunami "ripple" will have a large diameter (just as throwing a large cobble into a pond makes a larger initial circle than that of a smaller pebble). If the sea floor ruptures by a large amount (think of a really big cobble), the tsunami "ripple" will have a higher wave height (larger run-up). (After Priest, 2000)

North Coast Tsunami History

We've learned that tsunamis are generated by the sudden displacement of a broad area of sea floor. We've also learned that the Cascadia Subduction Zone is capable of great earthquakes as the Gorda Plate grinds beneath North America. So, if Gorda were to suddenly slip, the coastal areas would experience vertical displacement, a process that has the potential to generate large, local-source tsunamis (fig. 4-9, 5-6). Tsunamis leave identifiable sediment layers behind after they inundate the shoreline. The 1964 tsunami from the distant Alaskan earthquake deposited about 0.4 inches (1 centimeter) of sand in Northern California lagoons and other low-lying coastal areas (Redwood Creek Tsunami Work Group). For comparison, the local-source tsunami generated from the Great Cascadia Earthquake of 1700 deposited 6 inches (16 centimeters) of sand (fig. 5-8; Redwood Creek Tsunami Work Group). In addition to the tsunamis evidenced by such sediment deposits in the stratigraphic record, there have been distant source (less-severe) tsunamis recorded in the last century (Redwood Creek Tsunami Work Group). The most infamous was that of the spring of 1964.

At 7:36 pm on the night of Friday, March 27, 1964, the largest earthquake ever recorded in North America struck Alaska near Prince William Sound, 1,700 miles (2,700

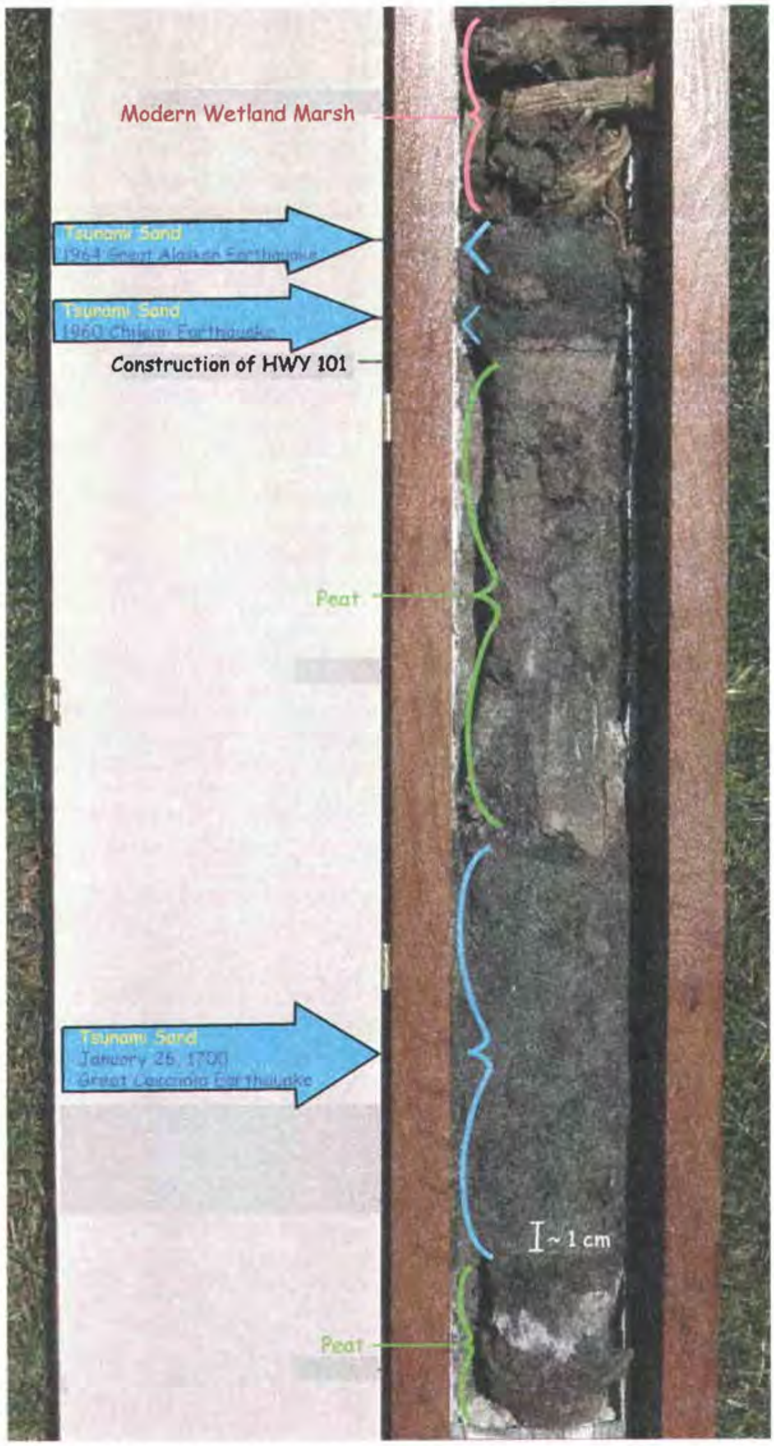


Figure 5-8: For Pete's sake! As seem in this sediment core, the 1964 Alaskan magnitude 9.2 earthquake generated a tsunami that deposited 1 cm of sand near RNSP. The tsunami from the 1960 magnitude 9.5 Chilean earthquake deposited slightly less sand. Sand with the same characteristics of other tsunami deposits has been identified underneath the younger deposits, but this older tsunami sand is over 16 cm thick! Such a large difference in sand thickness can be explained if the source of the tsunami had been local, generated by the January 26. 1700 Cascadia Subduction Zone earthquake. (Photo by V. Ozaki)

kilometers) northwest of Crescent City, California. The magnitude 9.2 earthquake was generated on a "locked zone," between the subducting Pacific Plate and overriding North American Plate. Within 8 minutes, seismic waves had already alerted scientists 2,900 miles (4600 kilometers) away in Hawaii of the event, and by 11 pm a tsunami had been reported by authorities in Kodiak, Alaska, to the California Disaster Office. The message was relayed to the Crescent City sheriff's office. In 1959, 1960, and 1963, tsunamis had caused minimal damage to waterfront merchants, so perhaps officials did not fully appreciate the extreme nature of the impending series of tsunami waves, or perhaps the inadequate information dispersal resulted from poorly orchestrated communication connections.

The only news of a tsunami to arrive around midnight had reached those businesses and residences in the downtown area, so residents were unprepared for the ensuing disaster. At almost 1:45am, the fourth and most destructive wave took Crescent City by surprise. Homes were demolished, split in half by the waves, and the local Pontiac dealership caught fire, which spread to both the Texaco and the Union gas stations whose gas tanks exploded. The waves carried out groceries from the local Safeway store and sank 26 ships moored in the harbor (fig. 5-9). The tsunami destroyed 29 blocks of Crescent City, cutting off communications and leaving the city in a state of emergency, a status that was elevated to that of a disaster area by President Lyndon Johnson on April 2 (fig. 5-10). All in all, in Crescent City, the '64 tsunami claimed 11 lives and cost $16 million in damages, but it promoted a complete revision of Crescent City's community tsunami preparedness plan (see "How to survive our tsunami hazard;" United States Geological Survey).

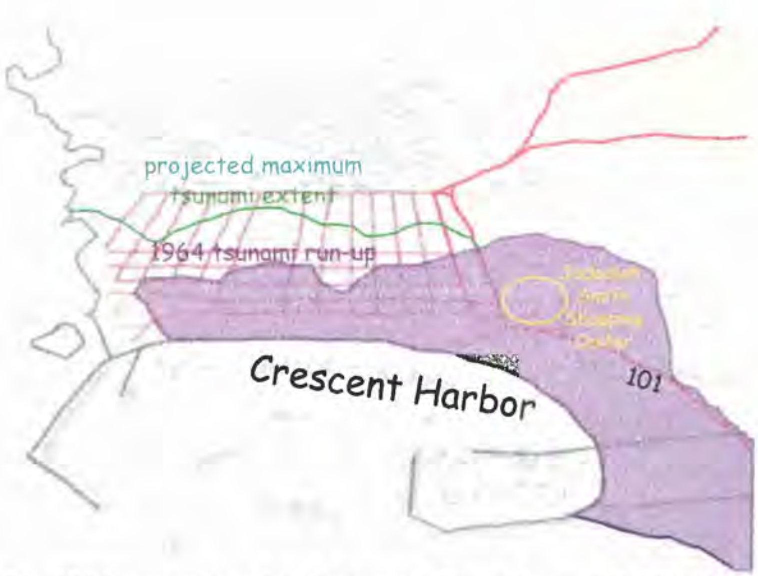


Figure 5-9: The 1964 tsunami inundated Crescent City as far as 5th Street (purple area). The waves were focused by the shape of Crescent Harbor, so the furthest extent of water surged up past where the Jedediah Smith Shopping Center is now located. The green line is the predicted maximum tsunami inundation extent and includes all of downtown Crescent City as far as 9th Street. (Modified from Dengler and Moley, 1999)

A B

Figure 5-10: "Brass knuckles" of the ocean. The photograph of F and G Streets in downtown Crescent City (**A**) was taken two days after the 1964 tsunami surged onto the North Coast. Note the house in the upper left corner, shoved at an angle from its foundation. The semi-truck at the bottom center was shoved from the street onto the adjacent lawn. A close view of the streets of downtown Crescent City (**B**) also shows a car thrown onto another and a house ripped off its foundation (arrow). (Modified from Dengler and Moley, 1999)

Tsunami Hazard	Defenses
Human life	*Defense structures: sea walls, tsunami breakwaters, tsunami gates, tsunami control forest
Buildings	
Coastal Structure	
Traffic: railway, highway, harbor	
Lifelines: water supply, electricity, telephone	*City planning: relocation of residence, tsunami resistant building zone and codes
Fishery	
Commerce and Industry	*Defense system: evaluation, forecasting, evacuation, drills, continuation of disaster culture, rescuer operation
Agriculture and Forest	
Oil Spill	
Fire	

Table 5-3: Implementing a defensive preparedness plan can mitigate all hazards of living on a tsunami-prone coast. (After Shuto, 2000)

What can we do?

Risk analyses of the hazards associated with large earthquakes have produced recommendations for mitigating the threats posed, especially tsunamis. For the RNSP region to be prepared, several stages of evaluation are ideal. We, as interpreters, recognize the importance of "knowing the resource" to best inform visitors about RNSP, and the same principle applies when informing the public about natural hazards. Given clues from past earthquakes, we now recognize that areas of the coast are prone to subsidence, and we can identify areas susceptible to landslides. We can target developed areas at risk of tsunami inundation, coastal subsidence, or landslide hazard, and establish warning systems and evacuation routes. Even more effective, once we have identified areas of great risk, we can take <u>preventative</u> measures toward mitigation. Mitigation of earthquake hazards for coastal communities is possible with thorough evaluations, development and implementation of evacuation strategies, and restriction of further construction near at-risk areas (table 5-3; fig. 5-11; Main, 2000).

California's North Coast: How to Survive Our Tsunami Hazard:

Remember:

* Tsunamis can occur at any time, day or night. They can travel up rivers and streams that lead to the ocean.
* Never go down to the beach to watch for a tsunami!
WHEN YOU CAN SEE THE WAVE YOU ARE TOO CLOSE TO ESCAPE.
Tsunamis can move faster than a person can run!
*Tsunamis are not surfable! They are not curling waves. Large tsunamis most frequently come onshore as a rapidly-rising turbulent surge of water choked with debris.
* A tsunami is not a single wave, but a series of waves. Stay out of danger until an "ALL CLEAR" is issued by a competent authority.
* Approaching tsunamis are sometimes heralded by noticeable rise or fall of coastal waters. This is nature's tsunami warning and should be heeded.
* A loud roar that sounds like a train or aircraft usually accompanies approaching large tsunamis. If a tsunami arrives at night when you cannot see the ocean, this is also nature's tsunami warning and should be heeded.
* A small tsunami at one beach can be a giant a few miles away. Do not let modest size of one make you lose respect for all.
* Sooner or later, tsunamis visit every coastline in the Pacific. All tsunamis - like hurricanes - are potentially dangerous even though they may not damage every coastline they strike.

If you feel a strong earthquake when you are on the coast:

1. Drop, cover and hold on and watch for falling objects until the earthquake is over.
2. Move to higher ground or inland away from the coast immediately. A tsunami may be coming. Go on foot if at all possible.
3. Go to an area 100 feet above sea level, if possible, or go 2 miles inland, away from the coastline. Every foot inland or upwards makes a difference. Over the past century, the average height for the largest tsunami waves has been between 20 and 45 feet at the shoreline, but a few waves have exceeded 100 feet locally.
4. Do not wait for an official warning. If the earthquake generating the tsunami was local, you are likely to have felt shaking, but officials are unlikely to have enough time to issue a warning. Distant source tsunamis may allow officials enough time to issue a warning, but those announcements may not get to everyone. Although no shaking will accompany distant source tsunamis, a noticeable and sudden drop or rise in seal level or loud roar from the ocean may serve to warn you of the approaching waves.
5. Stay away from the coast; do not return to shore after the first wave. Waves may continue to arrive for hours. Listen to your radio for an official "all clear" before returning to the beach.

(compiled from Humboldt Earthquake Education Center, USGS, and the Red Cross)

A

B

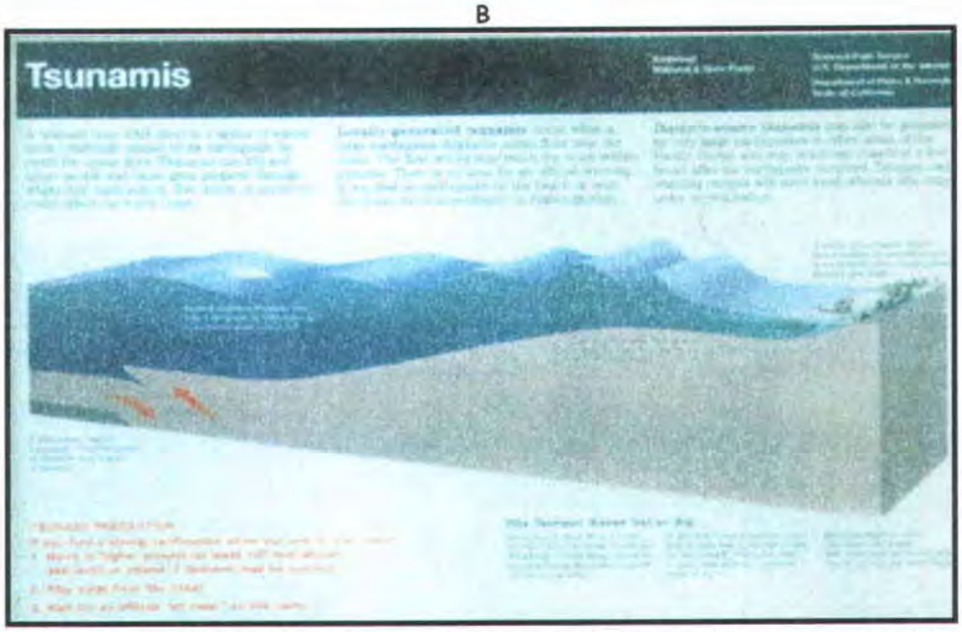


Figure 5-11: It's a sign! Tsunami evacuation route signs have been controversial for reasons ranging from cost of replacement (they are actually the most stolen signs on the West Coast!), to cost of scaring away tourists (**A**). For RNSP, interpretive panels and signs help remind visitors that the coast is active and a part of daily life (**B**). ("**A**" modified from National Oceanic and Atmospheric Administration, "**B**" courtesy of RNSP)

Chapter 6: Geologic Time

Time…we're apt to speak in cosmic terms when we think about "deep time." But, for our purposes, knowing exactly how old rocks are is usually not as important as recognizing the sequence of events responsible for developing the landscape and materials of RNSP.

We can think about the relative ages of rock layers and other geologic features to some extent by using our powers of deduction. For example, if a group of people walks into the visitor center, you will likely be able to tell which members of that group might be able to become Junior Rangers (7-12 year olds) and which might be interested in the Golden Eagle Pass; that is, you can distinguish between adults and children simply based on *relative* ages. If you had a rock with a dinosaur skull fossil and a rock with a human skull fossil, which rock would you say is older? Fossils of once-living things we know to have gone extinct much longer ago than others can be used to determine the age of one layer of rock *relative* to another. Similarly, if we see one layer of rock on top of another layer of rock, which layer is older? We can answer by thinking about deposition: could we deposit rocks on top of other rocks if the other rocks were not already there? The rocks on the bottom must therefore be older than the rocks deposited on top. Think of a stack of pancakes – the one on the bottom was made before the next that is slapped on top. Geologists recognize this relationship as the ***Principle of Superposition***, enabling them to determine the ***relative age*** of the rock layers. Relative time is one way of thinking about geologic time.

At RNSP, our national park Junior Ranger program is designed for specific age groups: those 7-9 year old need to complete less of the Junior Ranger activity newspaper than 10-12 year olds. If parents ask us about the Redwood National Park Junior Ranger program for their children, we are going to need to find out how old the siblings are to know how much of the national park Junior Ranger newspaper each sibling will need to complete to get their Junior Ranger patch. We need to find out each child's exact, or ***absolute***, age. Geologists sometimes need to know the absolute age of rocks to find out more precisely how much time the rocks represent. ***Absolute-age dating*** of rocks involves using radioactive isotopes of certain elements found in the rocks to discover how many years ago the rock formed, but this level of detail is unnecessary for most interpretive talks at RNSP. Both relative and absolute dating methods have been used to refine the ***geologic time scale***, a chart classifying when rocks formed (see table 6-1).

From molten glurp to national park: A comparative time scale to make the Earth in just one single year (and RNSP...in *13 days*)

First, let's take the Earth's entire 4.5 billion year history and cram it into just one single year, beginning at midnight on January 1. "During January and part of early February, the Earth is organized into core, mantle, and crust. Sometime near February 21, the very first primitive life appears. All of spring, summer, and early fall sees the development of continents, and ocean basins akin to those of today start opening. On October 25, at the beginning of the Cambrian Period (543 mya), complex organisms (including critters with shells) evolve. On December 7, reptiles emerge. Thirteen days later (on December 18), subduction of the ancestral Gorda plate begins (150 mya). In another 4 days, the Coastal terrane has formed at the ancestral Gorda Ridge, but less than a day later, it has already started to be accreted onto the North American continent. By Christmas day, the dinosaurs are extinct (65 mya). The next day, around December 26, the Franciscan assemblage is accreted onto the coast. Four days later, the King Range has formed at the Mendocino Triple Junction. Our modern human species, *Homo sapiens*, appears on the scene at 11 pm on New Year's Eve, but the glaciers make it too cold to party until 11:58:45 pm, when the last glacial age ends. Just three-hundredths of a second before midnight, Columbus lands on San Salvador Island in the Bahamas. With a few thousandths of a second remaining, you are born." (Adapted from Press, 1994)

Geologic time may seem incomprehensible for most people because it is so vast. Events that happened in the geologic past were so long ago that we have trouble grasping the "closeness or distance of events" and how one event impacted another. One way to present the geologic history of Redwood National and State Parks is in a geologic time line (see table 6-1). It is important to recognize that there are dangers in condensing the geologic "story" into this format: we may lose sight of the vastness of the time represented, as well as the idea that geologic processes often link visitors to their natural world. Unfortunately, time lines omit the time lapsed for all the processes that are still altering the dynamic North Coast. However, as references, time lines highlight events and allow us to quickly note when important processes sculpting RNSP occurred.

Geologic Time Scale		
EON	**ERA**	**PERIOD** Epoch
Phanerozoic Eon (543 million years ago to today)	**Cenozoic Era** (65 mya to today)	**Quaternary** (1.8 mya to today) Holocene (10,000 years ago to today) Pleistocene (1.8 mya to 10,000 yrs ago) **Tertiary** (65 to 1.8 mya) Pliocene (5.3 to 1.8 mya) Miocene (23.8 to 5.3 mya) Oligocene (33.7 to 23.8 mya) Eocene (54.8 to 33.7 mya) Paleocene (65 to 54.8 mya)
	Mesozoic Era (248 to 65 mya)	**Cretaceous** (144 to 65 mya) **Jurassic** (206 to 144 mya) **Triassic** (248 to 206 mya)
	Paleozoic Era (543 to 248 mya)	Permian (290 to 248 mya) Pennsylvanian (323 to 290 mya) Mississippian (354 to 323 mya) Devonian (417 to 354 mya) Silurian (443 to 417 mya) Ordovician (490 to 443 mya) Cambrian (543 to 490 mya)
Precambrian Time (4,500 to 543 mya)		
Legend mya = million years ago Age of rock layers at RNSP (150 mya to today)		

Table 6-1: The Geologic Time Scale divides Earth's history into distinct segments according to wise-spread evidence (like fossils) for important geologic events. (Aadapted from "http://www.ucentimetersp.berkeley.edu/help/timeform.html")

Geologic Time Division	Date (years ago)	Event(s)	Description of event (common name of geological formation)	Park Outcrop
Quaternary Period	1992	Cape Mendocino earthquake	Uplifted tide pools at Cape Mendocino	
	1980s	RNSP restoration efforts		Ah-Pah Trail - Newton B. Drury Scenic Parkway
	1964	Great Alaskan Earthquake, tsunami		Historical photos of Crescent City; tsunami sands in lagoons
(Holocene Epoch)	1950s	Logging, erosion, sedimentation	Redwood Creek gravel bar and sediment "slug"	Redwood Creek
	1850s	Gold rush	Ancestral Klamath River gravel and sediments (Prairie Creek Formation)	Gold Bluffs Beach
	January 26, 1700	Cascadia Subduction Zone earthquake		Tsunami sand deposits
Pleistocene Epoch	150,000 ya	Formation of St. George Formation	Fossiliferous sandstone and siltstone (St. George Formation)	Pebble Beach, Crescent City
	~1 mya	Movement along Grogan Fault	Slicken-lines in Franciscan rocks of Redwood Creek	Redwood Creek
Pliocene Epoch	1-2 mya	Erosion leading to formation of gravel bar deposits at ancestral Klamath River mouth	Ancestral Klamath River gravel and sediments (Prairie Creek Formation)	Gold Bluffs Beach
Eocene Epoch	14 mya	Completion of accretion of youngest Klamath terrane onto N. America	(King Range)	Cape Mendocino, Lost Coast, MTJ
	50 mya	Completion of accretion of Franciscan assemblage onto N. America	Metamorphosed ocean sediments, Redwood Creek schist (Franciscan assemblage, Coastal terrane)	Enderts Beach, Redwood Creek

Mesozoic Era (Cretaceous Period)	90 mya	Start of accretion of Coastal Terrane onto N. America (pg) Heyday of Redwoods, 13 different species	Metamorphosed ocean sediments (Coastal Terrane) Sequoia sempervirens only remaining redwood species native to RNSP region.	Enderts Beach, Wilson Creek, Klamath Overlook Any state park or grove
	100 mya	Formation of youngest Klamath Mountain terranes at ancestral Gorda Ridge	(King Range) (Coastal Terrane)	Cape Mendocino, Lost Coast, MTJ Enderts Beach, Wilson Creek, Klamath Overlook;
(Jurassic Period)	150 mya	Subduction of ancient Gorda/Juan de Fuca Plate (part of larger, ancient "Farralon Plate") beneath North American Plate	Oceanic sediments - sandstone, mudstone, and shale (Franciscan assemblage). Some deeper ocean crust and mantle rocks - basalt, gabbro, and peridotite. Continuous subduction metamorphoses those rocks locally to schist, quartzite, and serpentinite (Franciscan assemblage, Redwood Creek schist, Josephine Ophiolite)	All along North Coast of California and southern Oregon, Enderts Beach, serpentine and peridotite exposed along Smith River
	160 mya	Formation of oldest Klamath Mountain terrane	(Smith River Terrane)	Jedediah Smith Redwoods State Park, along hwy 199

Table 6-2: "So, how did *this* form?" This chart lists the timing of some significant geological processes in the past 160 million years and what we see in RNSP because of the events. Over time, geological processes formed the landscape of RNSP, and we can see evidence of different geological events in the exposures of rock in RNSP.

The Story

In order to impart excitement about geology to visitors, we as rangers must understand and appreciate the Earth processes involved. Let us travel back in time 150 million years to a time period called the Jurassic.

> Nerdy Jargon Alert!
>
> To provide ourselves with universal references, geologists have developed an intricate nomenclature for everything from time periods, to Earth processes, to rocks. Such technical terms, when used too early or without appropriate introduction and explanation, can often be the impetus for those listening to "tune out" because they do not immediately understand this foreign language. Careful placement of quasi-familiar words helps to explain the concepts and retain the visitors' attention.

Once visitors realize that RNSP is nestled in an uplifting mountain range, the geologic past may be revealed using various outcrops within RNSP. The oldest rocks exposed in the park belong to the Jurassic and Cretaceous-age Franciscan assemblage and are dominant along the northern California coast (Blake and others, 1985). Their story begins 150 million years ago (during the Jurassic Period), when subduction scraped oceanic sediments off the top of the ancestral Gorda Plate and jammed them beneath the seaward edge of the North American plate (Blake and others, 1985). Metamorphism further altered the rocks as the units continued to be "smooshed" beneath the continent. In the same way a pressure cooker changes (cooks) food, the temperature and pressure at depth altered the minerals of the original sedimentary rocks.

The Jurassic saw the "heyday" of Redwoods, with 13 different species flourishing in the Northern Hemisphere (Harris and others, 1995; Kiver and Harris, 1999). The time when Redwoods were prolific is actually 90 million years into the Jurassic, about the same time the Coastal terrane began accreting onto North America (Blake and others, 1985). During accretion, the Franciscan assemblage was forced about 11 miles (18 kilometers) deep into the Cascadia Subduction Zone, a depth at which the rocks experienced enough heat and pressure from high degrees of metamorphism to become schist (Beaudoin et al., 1996).

Cranky Gorda shoves things around

To bring to life the geologic processes that have created the landscape at RNSP, you can have members of the audience reenact the plate movements as you recount how they should move. You'll need three volunteers (typically Junior Rangers, fig. 6-1) to stand in a row facing the audience. You should instruct the actors (from left to right) to affect the following demeanors: one who can ignore people (Pacific Plate), one who can be mean (Gorda Plate), and one who can be stubborn (North American Plate). (I have the Pacific JR on the left hold a blue paper plate labeled "oceanic plate," the Gorda JR hold another blue oceanic plate, and the - typically bigger - North America JR on the right hold a green continental plate; fig. 6-1 A.) Ask Pacific and Gorda to pretend they were best friends (put their arms around each other), and then pretend that they fight (they stretch their arms, pushing away from each other). I explain that this is what happened to the Pacific Plate: it got ripped apart when a small piece (the Gorda Plate) "decided" to break away (fig. 6-1 B).

To help people remember the name "Gorda," I explain that Gorda is a rebellious trouble-maker, and I employ a "rogue" accent (Australian, for instance) and ask the audience to say the name "GORDA" with me in gruff voices. I demonstrate how, if the plates are all touching, then when the Pacific and Gorda plates move apart, the Gorda and North American plates get shoved together (fig. 6-1 B). I then remind people that Gorda has crust that is thinner (less buoyant) and ask them what will happen as it pushes against the North American Plate (it will sink beneath - behind, in the demonstration - North America). Introducing the term "subduction zone" at this point is appropriate, vis-a-vis a violent natural process. Adding to the circus (yet learning) atmosphere, the Junior Rangers like to push against each other, and often North America's right arm and Gorda's left arm get "smooshed" up in front of them (you, the ranger, can help this effect happen every time because it's helpful; fig. 6-1 C). Telling the stressed duo to "freeze," I make note of the "smooshing" effect and ask the audience to think about what that might represent (the Coast Range). Once you've walked the actors through the process once, you can stand back and just dictate the events and let your actors demonstrate how the Coast Range formed.

About 14 million years ago, in the Pliocene, the rocks we see today began being uplifted to the surface into the present Coastal Range (Blake and others, 1985). These ongoing geologic events dictate how the rocks now respond to current environmental conditions. The rocks have been "cooked" and "smooshed" and are therefore weak and prone to landsliding and erosion, especially when destabilized by human activities such as logging (Marron, 1995; Jones, 2000).

Visitors often are better able to relate to human history, which is often perceived as being more "recent" than ongoing geologic processes. Geology becomes

A

B

C

Figure 6-1: Recipe for a (fun) disaster: 1 aloof Junior Ranger (Pacific Plate), 1 mean and violent Junior Ranger (Gorda Plate), 1 stubborn Junior Ranger (North American Plate), and 1 determined Ranger. Set aside aloof Junior Ranger for garnish. Mix mean Junior Ranger beneath stubborn Junior Ranger until stiff. Add force and rogue accent. Serves 200-300 park visitors. (Photos by T. Parshall) much more applicable to people's lives once they recognize the "human elements" dependent upon Earth processes. Connecting surface processes and their subsequent cultural impacts, as well as cultural activities and their resulting affects on the landscape, is vital for effective interpretation. Pleistocene sedimentation formed thick packages of conglomerates, which are exposed in the Gold Bluffs. The Klamath River imported small concentrations of gold from the nearby Klamath terrain, which was found in the Bluffs in the 1850s (Trexler, 1989). In telling this kind of story, perhaps people will walk away not only knowing the origin of the name of the Bluffs, but also understanding a little about how the Bluffs themselves came to be.

Another way to tell the tale

We can take the entirety of Redwood National and State Parks' 150 million year geologic history and compact it into a day (kind of like your average vacationer trying to experience a National Park in an hour). This means time is moving at over 1,700 years per second (6,250,000 years per hour)! We'll start at midnight with the onset of subduction of the ancestral Gorda plate 150 mya. Just after 9:30 am, the Coastal terranes begin to be accreted and form the Coast Range. By 4 pm, the Franciscan assemblage has been emplaced along RNSP's coastline. At a quarter to midnight, the Gold Bluffs Beach sediments have been deposited at the mouth of the ancestral Klamath River. Seconds later the Grogan Fault first cuts across RNSP, creating a conduit through which Redwood Creek flows. At 11:59:59.98, the last Great Cascadia Earthquake, in the year 1700, shakes RNSP.

The Balance

Now that we have an understanding of the tectonic processes that have occurred near the North Coast over the past 150 million years we can begin to appreciate the rates at which rocks change at rock/water and rock/air interfaces. We know that subduction scrapes oceanic sediments from the Gorda Plate and smashes them underneath the Coast Range, essentially adding air to the beachball (fig. 1-7). Subducton and accretion thus tend to make the Coast Range rise, a process known as ***uplift*** (fig. 6-2 A). We know that the North Coast is being uplifted at an average rate of about 1 inch (3 centimeters) per year (the rate gets much faster near the Mendocino Triple Junction; Wilson, 1989). But once rocks are exposed at the surface, they are besieged by the actions of wind and water, which erodes the surface. If erosion were dominant, any topographic relief would soon be leveled and we would have a flat coastline and no Coast

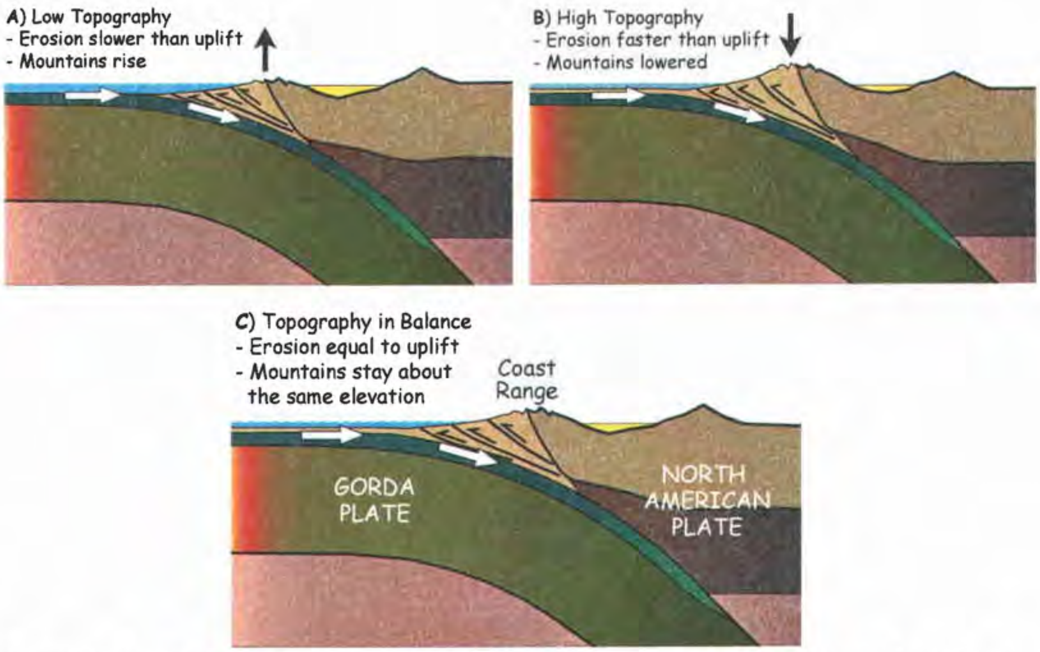


Figure 6-2: Slowly but steadily keeping pace. The balance of the landscape depends on the rate of uplift and the rate of erosion. If one rate exceeds the other, the height of the mountains changes accordingly. So, the King Range (southern part of the Coast Range near Cape Mendocino) is being uplifted at one of the fastest rates in the world, but that means it is also being eroded much more quickly than other, lower lands.

Figure 6-3: Sandy beaches of the East Coast. National Seashores on the East Coast are treasured for their gentle slopes, which are in stark contrast to the rocky shorelines of RNSP. The West Coast is near active plate boundaries, which uplift rock faster than the rock can be eroded. Given enough time, erosion can level steep sea cliffs like those in RNSP to the gentle slopes of the East Coast. (Photos courtesy of NPS)

Range (fig. 6-2 B). For any topographic relief to be maintained, the rate of erosion cannot exceed the rate of uplift, or the topography would be flattened over time (fig. 6-2; Whipple and others, 1999). So, the fact that we indeed have a breathtaking rocky shoreline and backdrop of mountains indicates that layers are being uplifted at least as fast as they are being eroded (fig. 6-2 C).

Let me describe what Redwood National and State Parks would look like in the future if some common Earth processes we take for granted daily (namely, *uplift* and *erosion*) were suddenly and inexplicably to stop happening. We'll first look at something that theoretically could happen: stopping plate convergence. If we stopped subduction, uplift of the Coast Range would also be halted. This would tilt the balance of the system in favor of erosion, which would then become the dominant force sculpting the North Coast. We'll begin at the northern end of the Redwood coast, specifically at Endert's Beach, where tidepool walks are typically held. Beginning at the trailhead from the parking lot (which seems to have been shifted to the east), we no longer need to prepare visitors for the short, but somewhat steep descent to the water because we are already at the water's edge.

The combined action of waves and weathering has slowly worn the impressively sheared rocks of the coastal cliffs into the very sand at which we are now looking. Having gained independence from the coastline through erosion, our characteristic sea stacks, once jutting majestically out of the surf, have now been completely consumed by the unchecked erosive power of the ocean. With the loss of the coastal cliffs, natural buffers to the high winds and salinity of ocean storm systems, none of the sitka spruce or juniper that had been growing on the trail high above the ocean remain. Blackberry patches (which can grow in sandy soils) constitute the only vegetation on what is now a coastal plain similar to beaches of the East Coast. As we walk to the water, looking for the rocky crags between which all the creatures of the intertidal zone make their existence, we find that they are gone, replaced by a bed of sand dipping gently toward the deeper Pacific (like national seashores and beaches on the East Coast, figs. 6-3, 6-4).

This trend of leveling our dramatic coast line would continue as we ventured farther south. Damnation Creek trail (once "Hell and Damnation Creek" trail), named for its steep 1,000 foot (300 kilometer) descent over just 2.2 miles (3.5 kilometers), would be transformed from a strenuous level 6 hike into an easy, flat level 1. The spectacular section of highway 101 leading south to Wilson and Lagoon Creeks and the Yurok Loop trail, bordered to the east by vertical cliffs and to the west by the rocky Pacific, would lose its majesty. No longer would there be a Klamath Overlook from which to spy migrating whales and other sea life. In fact, such sea life would be scarce along our coast without coves and sea stacks to provide them with habitat. Assuming the erosion rate is about 1 inch (3 centimeters) per year, Gold Bluffs Beach would lose its 180 foot (60 m) bluffs within 2,000 years. The transformation of the North Coast of California into a landscape and ecological system similar to that seen along much of the East Coast of the United States would take approximately 2,020 years.

Now let's consider how we could transform the North Coast of California into the Himalayas! Instead of throwing a wrench into the subduction machine, let's stop the erosion cycle and allow uplift from subduction to continue unchecked. (This is, of course, even more impossible than stopping the process of subduction.) At an uplift rate of 1 inch (3 centimeters) per year, within 350,000 years, our lovely little Coast Range would rival peaks like Mt. Everest and K-2, which rise to over 26,000 feet (8,000 m) above sea level! So ranger "hikes" at Redwood might require an expedition of 50 team members establishing a base camp and ferrying supplies up to snow-capped summits!

Being as we've considered each process individually, we must understand that, in this natural system, the processes of uplift and erosion are not independent, but inextricably connected. In fact, should the rate of one process change, the rate of the other would respond by changing accordingly in a feedback mechanism. The system is thus in a balanced or ***steady state*** (sometimes called *dynamic equilibrium*; Schumm and Lichty, 1965). There are numerous examples of other physical, biological, ecological, and other systems that reach steady states.

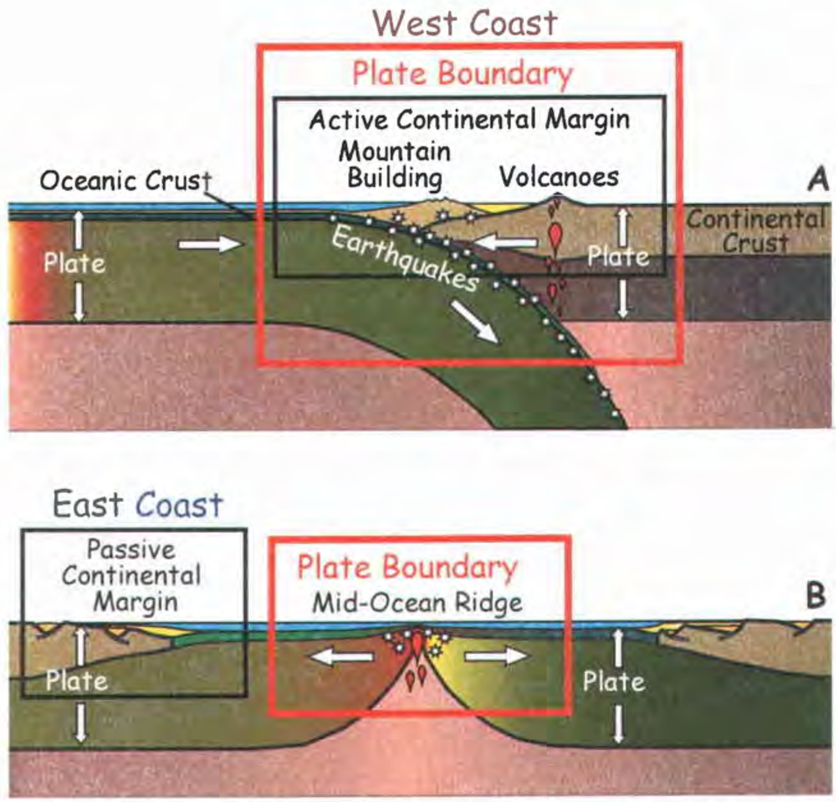


Figure 6-4: West side vs. East side! The West Coast of the United States is actively being uplifted by ongoing subduction processes (**A**), whereas the East Coast has not been active for about the past 300 million years (**B**).

Tipping the Balance

There are other factors beside rates of uplift and erosion that influence this natural balance. Natural factors, such as rock strength, slope gradient, climate, and seismicity, limit the topographic relief of mountains (Schmidt and Montgomery, 1995; Whipple and others, 1999). Most of the rocks in the region have enough pores and cracks to allow water to permeate, which weakens the units' integrity. The rocks interact chemically with the water and become more clay-like, and are easily broken down by erosional processes. Both the intensely "smooshed" Franciscan formation and the overlying fluvial/alluvial sediments contribute to bedrock instability. Additionally, although the average hillslope gradient is 26%, steep inner gorges have slopes greater than 65% (Madej and Ozaki, 2001; Pitlick, 1995). Unstable ground materials amplify the effects of earthquakes, as we learned in Chapter 4. In other words, we have fractured bedrock forming steep mountains in a region that gets about 80-100 inches (200-250 centimeters) of rain annually (Pitlick, 1995). RNSP has mild winters (between October and April) with frequent low-intensity storm events that account for more than 90% of the annual precipitation (Pitlick, 1995; Merritts and Vincent, 1989). Also, because three plates converge at the Mendocino Triple Junction just 270 miles (170 kilometers) south of Crescent City, there is relatively rapid regional tectonic uplift (at a rate sometimes more than 1.5 inches – nearly 4 centimeters – per year; Merritts and Vincent, 1989). So, the *natural* conditions of the region – steep, weak bedrock being frequently seismically shaken and rapidly uplifted while being attacked by erosion from high amounts of precipitation – make RNSP extremely prone to landslides and excessive erosion. However, the instability of the slopes of RNSP is even further exacerbated by none other than ourselves.

We humans magnified the effects of erosion via logging and road construction within this delicate and dynamic system. There are records of logging around Redwood Creek basin at least as far back as 1936. In the seven decades since 1936, over 65% of the original canopy of redwood trees in Redwood Creek basin has been harvested. To fell a redwood, loggers needed to build roads not only to groves of trees, but also roughly 300 feet (100 meters) out from the base of each individual redwood. These "landing pads" cushioned the redwood's landing and prevented it from exploding under the impact of its own weight. The combination of timber harvesting and road construction had a devastating impact on erosion and subsequent sediment delivery to Redwood Creek. In fact, landslides occurring on slopes that have been modified (by harvest or roads) accounts for 80% of the total erosion related to landslides (Pitlick, 1995; Madej, 2001). The resulting extreme rates of erosion and high frequency of landslides not only raise concerns for public safety and property damage, but also cause concern for the welfare of the giant water-dependent Redwoods.

By understanding the processes of uplift and erosion, visitors can begin to see how the steep landscape through which they hike was formed through time, that it is continually forming, and that human activities can impact the landscape and ecology.

Appendix A: The Answers!

Five Geology-Related Questions Commonly Asked by Visitors:

1. *Why is the coast so rocky/steep here?*

Related Questions: Wasn't there a tsunami here years ago…?

Do earthquakes happen around here?

This question affords rangers the chance to connect the landscape with the geologic processes that sculpt the landscape (specifically, tectonic and erosional processes).

Breathtakingly rugged, the rocky North Coast offers dramatic views down steep slopes to the crashing waves below. But why is the northern coast of California so unique? Le'ts think about beaches on the East Coast (fig. 6-3). In particular, let's focus on the beaches stretching from Cape Cod in Massachusetts to the tip of Florida. What's the first image that comes to mind? Sand! Expansive white sand beaches tilting ever-so-gently into the Atlantic attract millions of people every year. Now look around and think of the West Coast, particularly, the Pacific Northwest. The images are quite different: rocky shores and crashing waves abound in the west. The differences between the landscape of the two coasts relate to plate tectonics.

The entire West Coast of the Americas is an active region of the Earth. With the exception of a few places like the famous San Andreas fault in California, the entire western coastline is the result of the convergence of two plates of Earth's hard outer shell. In South and Central America and most of Mexico, the oceanic Pacific Plate subducts beneath the continental north American Plate (see Nature's Messy!). North of the San Andreas fault, the Juan de Fuca plate (and, just off the Redwood coast, the Gorda plate, which is the southern extension of the Juan de Fuca plate) subducts beneath North America. Let's take a closer look at the zone where the Gorda plate subducts beneath North America.

Nature's Messy!

Whereas it is true that nearly the entire "Pacific Rim" (edge of the Pacific Ocean) is actively subducting, there are places where the relative motion between the Pacific Plate and its neighbor varies. For example, the Pacific Plate is actually "tearing away" from North America (diverging) at the Gulf of California, and there are boundaries where the two plates simply slide past one another, namely the San Andreas Fault in California and the Queen Charlotte/Fairweather fault system along the coasts of British Columbia and southeastern Alaska.

The thin crustal material beneath the ocean is less buoyant than the thicker crustal material of the continents; therefore, the ocean crust tends to "sink" lower into the underlying mantle (fig. 1-7). When the oceanic plate converges with the continent, the buoyant continent is able to ride higher; thus the Gorda Plate dives or "subducts" beneath North America. This process tends to uplift the edges of the continent (our coastline) as sedimentary rock layers are scrapped off the top of the Gorda Plate and smooshed onto North America. The tectonic activity creates earthquakes and uplift, exposing new rock to the forces of ocean wave erosion. The forces of erosion actively sculpt the cliffs as they rise, creating a rugged, rocky boundary between the land and the sea.

Now let's compare this active tectonic setting to the East Coast. The oceanic crust underneath the Atlantic Ocean is part of the same plate as the North American continent; therefore, unlike the West Coast, the East Coast is *not* a boundary between moving plates, but is instead a passive margin between land and sea. This means that the tectonic uplift raising our Coast Range against the waves of the Pacific Ocean is not present to exhume any rocks for the Atlantic to erode. So the coast on the eastern margin of North America is dominated by deposition of sand along gentle beaches, instead of jagged cliffs caused by uplift and erosion.

Of breathtaking beauty we boast
But it's danger we fear the most
Through active uplift
The coastline does shift
Becoming the <u>rocky North Coast.</u>

2. How do sea stacks form?

*This question is a typical "rock" question; that is to say, erosion is the main process responsible for the rock formations known as **sea stacks.***

Stalwartly withstanding the powerful waves, sea stacks jut majestically out of the sea, but only for a while. Eventually, erosion will win out as the particles that comprise the hard rock will return to the sea: "...Earth becoming fluid as the sea itself" (Carson, 1955). A new interpretive panel at the Redwood Creek overlook describes how Split Rock is forming (fig. P-1). Recall that the Coast Range forms from sedimentary rock layers that are scraped from the floor of the Pacific Ocean (the top of the Gorda plate) and crumpled onto the coast (fig. 1-9). Most of the "stuff" on the ocean floor is sand and mud, which become sandstone and mudstone (shale), respectively. These sediments typically form layers of various thickness depending on the environment where the sand and mud accumulated. As the Gorda Plate subducts, the layers are dragged down and experience a lot of heat and pressure (even more stress than your typical vacationer!). These poor layers are scraped off and attached or "accreted" onto North America (creating an "accretionary wedge," fig. 1-9). As they uplift along the coast, the rocks are attacked by the relentless erosive power of the Pacific Ocean. The ability of the fine-grained mudstone or shale to resist erosion can be compared to that of the more robust sandstone by looking at the very rocks themselves. The shale and mudstone layers crumble much more quickly than the sandstone, so that the sandstone layers begin to form prominent cliffs (fig. A-1 A). Tiny cracks in the sandstone, called joints, serve as planes of weakness along which blocks of rock break off (fig. 3-1). The cliffs crack and erode into smaller pillars that eventually stand alone in the surf as sea stack (fig. A-1 B).

Our coast cliffs are riddled with cracks
And weakened as sea water hacks
Eroding the rocks
The waves leave some blocks
The pillars of rock called <u>*sea stacks.*</u>

3. Why are there so many green rocks?

This question ties the processes of subduction and weathering to the chemical makeup of some of the rocks in the park.

The state rock of California is serpentine (*serpentine* is actually the mineral comprising the rock, *serpentinite*, but shhh! ...we won't tell anyone they got it wrong.) Serpentine is a mineral that forms under pressure when water interacts with rocks that contain elements like iron and magnesium, such as the "mantle rock" *peridotite*. Serpentine has a distinctive "soapy" feel and "waxy" look, and you might notice many tiny wavy layers if you look at a chunk from the side (fig. 2-3). These are characteristic features that develop because of the environment in which the rock formed: the waxy sheen and soapy feel come from the minerals changing form (metamorphosing) in response to high temperatures and pressures at depth within the Earth. Specifically, *serpentinite* forms when heat and pressure metamorphose the minerals ***olivine*** and ***pyroxene*** in the mantle rock ***peridotite*** to *serpentine*. The intense convergent plate process that drags rocks down to such depths is happening just off our coast!

The Gorda Plate smashes against North America as it plunges down into the Cascadia Subduction Zone (figs. 1-9, 1-10). The oceanic plate resists the extreme force behind this collisional process, and sometimes even deep parts of the oceanic plate are shoved up onto the edge of North America. Whereas the top of the Gorda Plate is laden with layers of sand, mud, shells, and other muck (the "stuff" of most of the rocks that form the Coast Range), the hard underlying crust formed from magma that cooled and hardened. The densest of the minerals from the cooling magma crystallize at the greatest depths. So the bottom of the oceanic crust is composed of some of the same iron-rich minerals that make up Earth's mantle. The sequence of rocks representing mantle and the overlying oceanic crust is called an ***ophiolite*** (fig. 1-17). The intense pressure and shearing forces involved in smashing the ophiolite up onto the continent combine with hot water to alter the iron-rich minerals into serpentine. The Smith River has cut down through the ***Josephine Ophiolite***, whose highly fractured green serpentine cliffs easily weather and erode, making them prone to landsliding. Redwood National and State Parks offers kayak tours of the Josephine Ophiolite and its impressive geologic features during the late spring and early summer (until the Smith River becomes too low sometime in August). So visitors can take a "magical kayak ride" through the very crust and mantle of the ocean! (And rangers don't need to invent an imaginary mineral such as "unobtainium" to drill into the center of Earth, like Hollywood promoted in the Spring 2003 disaster flick, "The Core.")

I'm known for slope failure, not might
I can't put up much of a fight
I break down in toil
And make orange soil
I'm our state rock - serpentinite.

4. Why are the soils orange near the Smith River?

This question is directly related to the iron-rich serpentine rocks of the Josephine Ophiolite (figs. 1-17, 2-2). We know the North Coast is very moist. Think for a moment about many of the older boats or other vehicles we might see around the Crescent City area. What happens to metal when it is exposed to water for an extended period of time? It ***oxidizes***, or rusts! What color do those boats and vehicles turn as they are exposed to the elements? An orange rust color! We know that serpentine is a mineral that has the metal element iron in it, so guess what happens to serpentine in the North Coast, where we have plenty of rain and fog? That's right, even rocks can rust! Thus, the orange soil is essentially rusted serpentine and is likewise rich in iron oxide. Iron-oxide minerals give the soil nutrients allowing unusual plants, such as *darlingtonia* (a pitcher plant that eats insects) to grow (fig. A-4).

Smith River gorge rocks are green
Over time rain dulls their sheen
Like your car left outside
Rusts to iron oxide
Here we form soil from serpentine.

5. Why is there a sand bar (spit) on the Klamath River?

This question relates to the balance between surface processes, specifically between erosion and deposition of sediment.

The Klamath River carries sediment accumulated from drainage systems reaching far inland. As the sedimentary grains tumble along the river, they are slowly rounded into smaller and smaller particles. New grains are deposited into the river system with every tributary. By the time the sediment reaches the ocean, a variety of grain sizes meet the waves in a large pulse. Despite the powerful action of sea waves, the Klamath River dumps enough sediment out at its mouth that the waves cannot remove it all. Because they are more easily mobilized, the smaller particles (silt and mud) are kidnapped by the ocean and whisked out to sea, leaving the coarser sand and gravel grains behind. Too big to be flushed out to sea, the sand and gravel get trapped between the Klamath current and the Pacific tides, forming the dynamic spit (fig. A-2). (Program ideas for communicating the process of river transport, erosion, and deposition are described in Appendix B, Young Naturalist interpretive program.)

Once established, the spit serves as a portal for salmon during spawning season. Also, because of the interplay between saltwater and freshwater, a quasi-estuary is established for animals less tolerant of complete marine saltiness. Both the salinity and the sediment carried to the ocean are important resources for Pacific coastal sea life, such as the grey whale. Because the mineral and nutrient rich sediments are flushed out of the Coast Range by the Klamath in such a large volume, the mouth of the Klamath becomes a place of concentration for plankton, algae, and other small marine life on which bottom filter-feeding ("benthic") grey whales feed. After birthing near Baja California around December each year, pods of whales return along the West Coast, reaching the Redwood coast in the spring. Occasionally, the young are unable to make the rest of their first 6,000 mile (10,000 kilometers) migration back to the Bering Sea, and so are forced to stop along the way for a season until their pod returns in the fall. The high concentration of nutrients makes the mouth of the Klamath an ideal place for the whales to remain for a season.

Ranger Bob's analogy

One might say, as the whales move from inlet to inlet looking for food to munch on and female whales, pods of whales "bar hop" along the coast!

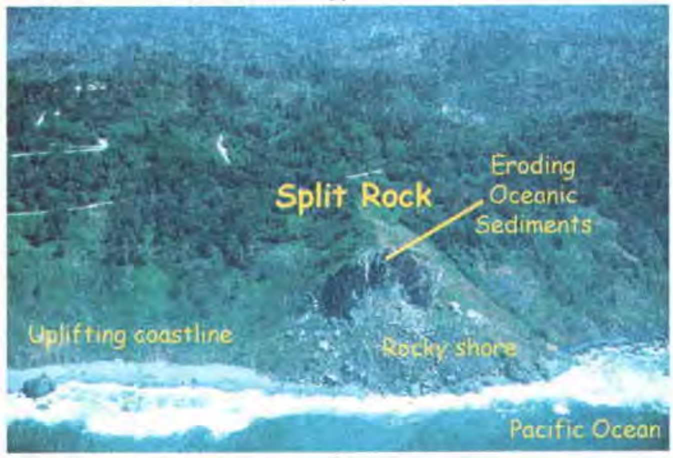
Beyond whale watching from the Klamath Overlook and camping on the Klamath spit, visitors can sometimes observe Yurok and Tolowa fishers either posed with spears or hovering in canoes for salmon catching at the spit's edges. Native American tribes often host festivals (such as the Salmon Festival and the Brush Dance) on their reserved lands adjacent to the spit.

The Klamath River mouth grains
Form a spit that waxes and wanes
Coarse nutrient sand
Forms dynamic land
To shield the mouth it remains.

Yurok Legend

Gazing up at the north bank cliff, we see the figure of a woman carrying a basket on her back. Yurok tribal legend portrays the rocks at the Klamath mouth as benevolent spirits guarding the river. The Oregos spirit manifested herself as the north bank cliff, summoning fish for sustenance of the river mouth people, while her sister dwelled in the south bank rock. Disturbances on the sandspit wake the sisters, who stretch their legs across the mouth of the Klamath, shifting the current to the opposite side of the mouth until new turmoil arises.

A



B

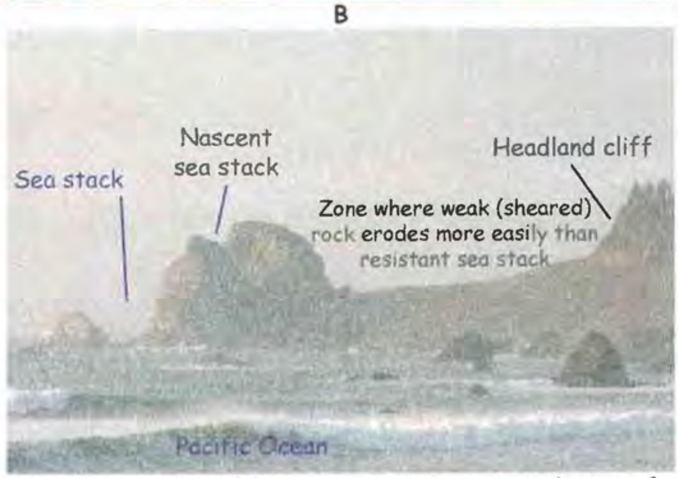


Figure A-1: The battle between uplift and erosion is raging at the interface between land and sea. Split Rock (**A**) is a crumbling seacliff that will eventuallybecome a sea stack. Near Wilson Creek, visitors can enjoy picnics while watching waves crash against the rocks, gradually carving sea stacks (**B**). RNSP has about 42 miles of protected coastline preserving this dramatic balance. ("**A**" courtesy of NPS, "**B**" by J. Natoli)

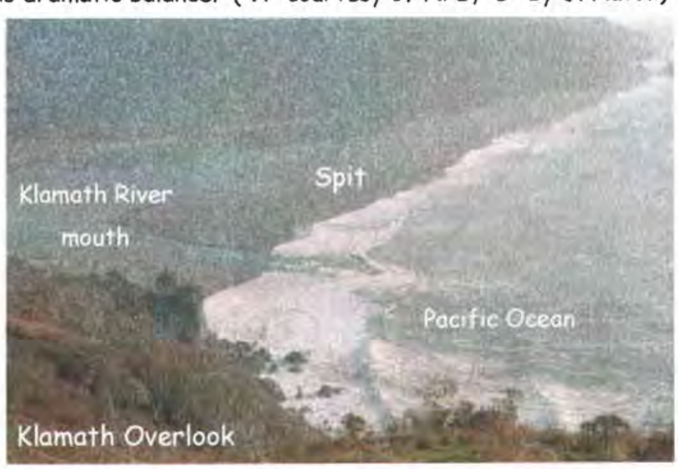


Figure A-2: Thar she blows! Visitors looking to get close to the sea can enjoy ocean mammal life and Native American rituals near the Klamath River spit, but few realize the uniqueness of the sand spit and its importance to the success of both ocean and land systems. A delicate balance between sand carried to the ocean and waves whisking the sand out to sea must be achieved in order to maintain the spit. (Photo by J. Natoli)

<u>Common questions that can be related to geology when asked by visitors, or used as provoking questions by rangers:</u>

6. Is this fog typical?

One of the characteristics of the North Coast of California is the fog. Moist air rolls eastward from the Pacific and encounters the Coast Range, collecting among the redwoods (fig. A-3 A).

The Coast Range acts as a sort of "squeegee" for the moisture systems rolling inland from the Pacific, causing abundant coastal fog and rainfall (Densmore and Hovius, 2000). For the moisture-laden systems to surmount the Coast Range and continue east, they must first lighten their load and drop their moisture, a process that usually takes the form of precipitation during the winter months or fog during the summer.

In fact, RNSP get about 800 inches (200 centimeters) of rain per year (Pitlick, 1995), nearly as much as a temperate rainforest. If visitors grumble about the moisture, remind them that, were the North Coast any less rainy, RNSP would not exist. Redwoods act like sponges in that they soak up enormous quantities of water in order to keep more-than-300-feet of tree healthy. In the summer, when rain is not as common, redwoods have adapted by developing specialized flat needle structures that act as "fog catchers." When the morning fog begins to burn off, the fog catchers provide surfaces on which the evaporating fog can instead condense (fig. A-3 B). The condensed fog droplets then either get soaked up directly by the needles, or "rain" back down onto the base of the redwood. (So, amazingly, redwoods create their own rain!) Were the Coast Range not jutting up, the climate of Northern California's coast would be quite different and probably not moist enough for our beautiful redwoods to grow.

7. Why are the trees so tall?

This question relates directly to the amount of moisture characteristic of the Coast Range of northern California, and the subsequent adaptation of redwood needles to be adept "fog catchers" (see answer to question 1 above). Redwoods are fairly tolerant of shady areas and can compete for sunlight by growing *up* before they grow *out*.

Towering redwoods among the fog provide inspiration for many photographers, but few realize how dependent these giants are on the droplet of moisture hanging within the dense fog (fig. A-3 B). The fog would not exist without the Coast Range, which would not exist without the geologic process of subduction.

8. Why do such unique plants grow here?

The old-growth (trees over 500 years old) redwood forests are said to have among the highest density of biodiversity in the world, even surpassing that of tropical rainforests. The incredible diversity is owed in part to the high levels of precipitation of RNSP, and in part to the unique soils weathered from our iron-rich rocks (fig. A-4; see answer to #4 in "Five questions commonly asked by visitors"). Without the geologic processes of subduction and accretion, the iron-rich rocks of the Josephine Ophiolite would never have reached the surface, where they are weathered into "rusty" soils.

9. What are tide pools?

Here's where you the ranger get to promote not only interpretive programs, but also our gorgeous rocky coastline (fig. A-5 A)! Coastal areas on the East Coast of the U.S. have not been tectonically active for several hundred million years, which is a lot of time for ocean waves to erode a once-rocky shoreline down to the gently-sloped sandy beaches we see there today. The coast of the Pacific Northwest, by contrast, is on an active plate boundary (the Cascadia Subduction Zone), and thus it is actively being uplifted (see answers to questions 1 and 2 in the "Five questions commonly asked by visitors"). We have active uplift of rock at the coast, and this rock is scoured down to tide pool levels by the same wave erosion that sculpts sea stacks (fig. A-5 B). Sea creatures, such as seat stars and sea anemones, then attach themselves to the rocks and crags to survive in the harsh, inter-tidal zone. The rocky areas that are submerged during high tide and exposed during low tide along the coast are known as ***tide pools***.

Figure A-3: Is it always this foggy here? The fog rolling in from the Pacific Ocean encounters the Coast Range and collects among the Redwoods (**A**), providing essential moisture. Redwood needles are specially adapted to act as "fog catchers" and condense moisture into droplet, which are then either absorbed or "rained" down onto the tall trees' roots (**B**)! (Photos courtesy of NPS)

Figure A-4: Carnivorous herb? The darlingtonia, a pitcher plant, eats insects (somewhat like a Venus Fly Trap). A unique species, it only grows in serpentine (iron-rich) soils near the Smith River in California. (Photo courtesy of NPS)

Figure A-5: Let's see what the tide brought in! Coast walks and tidepool programs are wonderful opportunites to interpret how coastal geology impacts ecology (**A**). Tidepools are special places within the rocky intertidal zone of the shore because they hold ocean nutrients and shelter the creatures brave enough to live there (**B**). (Photos courtesy of NPS)

10. Why can you find agates on the beach here?

With this question, we return to the balance between erosion and uplift on our coast. Agate is a form of silica that forms when critters with silica-rich shells die in the ocean and sink to the bottom, forming layers of ooze. By the time the marine sediments are uplifted via subduction and accretion processes, the silica-rich layers have become a form of microcrystalline quartz known as *chert*, and agate is simply a semi-translucent variety of chert. Flint Ridge, south of the Klamath River, is almost entirely chert. For centuries, Native Americans have used flint for arrowheads and trade. In fact, Flint Ridge is considered a holy place for the Yurok and Tolowa tribes.

Appendix B: Interpretive Programs

Young Naturalist Program (Ages 3 to 6)

Topic: Geology
Theme: Rocks in RNSP move along streams and become small and round through erosion.
Goal: Young Naturalists will begin to appreciate some natural processes that shape the world around them (specifically, RNSP).

Materials: ~10 foot length of blue material; 2 large, angular rocks; 4 smaller, more rounded rocks; 8 or so rounded pebbles; about a cup of sand; hand lens; optional: brick of clay/play-dough; Everyone Needs a Rock book

Objectives:

By the end of the program, the Young Naturalists will:

*Identify rocks as a park resource (something they can find in the park)

*Use a hand lens to closely examine the different "colors" (minerals) in rocks

*Recognize that rocks move; list water and at least one other method of transport (people, animals...)

*Describe the way rocks get smaller and rounder downstream and eventually turn into sand at the river mouth at the ocean

*Perform the "life of a river rock" journey down a cloth "river" toward the sea

Outline:

Young Naturalist programs are difficult simply because of the different stages of children involved. Although there does not initially seem to be much of a difference between children of age 3 and those of age 6, the intellectual and deductive reasoning skills developed between those ages cover an incredible range. For this reason, as usual, the ranger must accommodate a mixed level of understanding in his/her audience.

Youth programs require special effort at the beginning of the program to grab the audience's attention. Children need to have their interest piqued by feeling a connection with both the ranger presenting the material and the subject, and rocks may not seem interactive. For this reason, attention needs to be drawn toward unique characteristics of rocks, such as their color, shape, and even taste. A connection can also be made between small rocks and small children, keeping in mind that a young child's scope of the world is at a different scale than ours.

For my own Young Naturalist program, I stretch a length of blue material along the ground so that a narrow end is at the higher part of a slight slope than the wider (lower) end. Along this length of "river," I place rocks I found in RNSP, starting with larger, angular chunks near the "headwaters," grading to smaller, more rounded pebbles farther "downstream," and finally reaching lots of sand at the "mouth" (beach end) of the material. After introductions, I commonly do a mini "Ranger Says" game and ask the kids to "look up" (what do you see?), "stand up," "jump up and down," "sit down," and finally "look down" (what do you see?). Here we spend more time inspecting the needles, soil, and bits of rock on the ground using hand lenses. Then, once all are sitting around with bits of rock in our hands, I read Everyone Needs a Rock (by Byrd Baylor, available in the RNSP Visitor Centers). At certain passages in the book, I pass out rocks that had interesting colors and smells for the kids to experience.

Once we've read the book, I ask what the difference is between the rocks in the kids' hands (or sand I show them) and the chunks of larger rocks (size and "sharp edges"). I ask what would have to happen to make one of the larger rocks turn into sand. We think about sharing a chunk of play-dough and how we might be able to give everyone a little bit to play with (break it into pieces). We then think about what happens as more and more people handle the play-dough (the pieces get rounded). Then I ask if rocks can move. We think about what can move rocks and we decide that water (in the form of rivers and ocean waves) do a pretty good job. If you feel comfortable, this is a good point in the program to take the group to a real body of moving water (like the Smith River, Mill Creek, or Redwood Creek) to look at the actual rocks that are in the water.

Once we've looked at a real RNSP example of moving rocks, I ask for a volunteer to enact the "Life of a Rock." My volunteer and I both start at the top of the blue blanket "river," standing tall with our hands on our hips so that our elbows make nice angular points. We all decide that the very beginning of rivers do not have as much water running as their huge mouths that meet the ocean. We think about how much a little trickle of water could move rocks compared to a larger volume of water. We take a slow step "downstream," thinking about what happens as more and more water flows into our "river." We think about what might happen to our sharp elbows as other rocks get pushed into us. We take another step, lowering our elbows and bending our heads. We continue in this manner downstream, quickening our pace and crumpling ourselves into smaller and smaller "balls," until we reach the "mouth" completely curled into tiny "grains of sand."

Junior Rangers Program (Ages 7 to 12)

Topic: Geology

Theme: Rocks at RNSP move in earthquakes because Earth's tectonic plates converge near our coast.

Goal: Junior Rangers will begin to appreciate that landscapes form because the Earth is dynamic.

Objectives:

By the end of the Junior Ranger Program, the Junior Rangers will be able to:

*Identify at least two ways in which rocks move (earthquakes, water, etc.)

*Name at least two of the three plates involved in North Coast tectonics (Gorda, North America, Pacific)

*Name the specific type of convergence between the Gorda and North American Plates (subduction zone)

*Name the mountain range RNSP is situated on (Coast Range)

Outline:

One of the first questions I always ask my JRs is "what is this silver thing dangling around my neck?" At first, they all think it's a whistle. Once I open it, someone often guesses that it's a magnifying glass, and I tell everyone it's called a hand lens. I ask them to figure out what kind of person would want to carry a hand lens around, and they guess someone who wants to make small things look bigger. I agree and have them start thinking about what things are small in the park, eventually leading them to look by their feet (where there are usually little rocks). I have them think about why anyone would want to look at rocks and ask whether or not rocks move. At first, they all say no, but at my reaction, someone usually thinks of earthquakes. This is where we develop the rock star yell: "earthquake!!!" I prime them so that every time I ask the question: "and then what happens??" they all respond with the yell. This is an attention-keeping technique that keeps their interest throughout most of the program.

I then ask if any of the JRs have ever been in an earthquake. They usually want to volunteer their experiences, so we listen to a few brief stories. Then I have the kids who have been in earthquakes come up and huddle around me. I whisper that we're going to have the other kids all stand on an amphitheatre bench that shakes when you stop and their job is to stop really hard. Once in position, I have everyone start jumping (I always join in), and then I tell each JR who hadn't been in an earthquake to stop jumping one-by-one so each can feel the shaking caused by the movement of everyone else. (This is also a great technique for dispersing excess energy.)

I ask if anyone has ever seen a cracked egg. Then we all close our eyes and picture Earth from space. We decide it would be blue, green, and white. Eyes remaining shut, I ask what color Earth would be if we took away all the clouds. (Blue and green.) Then we take away all the plants (blue and brown), followed by all the water (brown). Then I reveal that if we really did remove everything covering the crust of the earth, it would look just like a cracked eggshell. We define the pieces of shell as plates that move, but I explain things in the context of preparing for a skit we'll do at that evening's campfire program. I ask who of the JRs has ever been in a pool (everyone) and if they've ever played with a beach ball. I ask if pushing the beach ball down into the pool is easy. I then make the analogy of a beach ball and a tennis ball in a pool to explain the two different types of crust (continental and oceanic). The North American continent is the beach ball and thicker and more buoyant than oceanic crust (tennis ball). Trying to push a tennis ball down in the pool is much easier because it's thinner and less buoyant. I announce that I'll need several volunteers for the skit.

Here's where we use the demonstration described in the text box "Cranky Gorda shoves things around." This excites the JRs about playing the "GORDA" plate (I usually have a "bushman's" hat for the JR who acts the role of Gorda). Once we've smooshed Gorda into North America, I get out the Oreo® cookies to further drive home the point that subduction forms the Coast Range (demonstration described "Using Oreo® cookies").

By this point, JRs realize that plates of the Earth move, but we need to instill a sense of how much and how often they move. Here's where the fingernail activity comes in (see "Fingernail Tectonics") to help the JRs understand that the longer plates do not move, the larger the likely earthquake. I usually amend the fingernail activity by having us all jump the distances (1 inch, 4 feet, 24 feet) and think about which one requires more energy. This leads into the concept of earthquake magnitude.

Earthquakes are the focus of the program, so I gather the JRs around the make-shift seismograph (construction described in "Rollin' with seismic waves"). On top of the "seismograph" I set up two cups, one with dry sand and the other with packed wet sand. I then ask the JRs what buildings are usually made out of, and we set pieces of wood or rock up in both cups to represent buildings. I ask people to watch what happens to the buildings during an "earthquake." I have two JRs start turning the rolling pin while two others start tapping on the top of the box. I instruct the "violent tappers" to gradually tap harder and harder until they're almost punching the box (or until the cups start to overturn). I ask which "buildings" fell over first. (The ones in the loose sand.) We then examine the "seismogram" we've made and look for the "blips" where the "tappers" shook the "ground." I pick a blip that is about half an inch (1 centimeter) and we decide the "buildings" probably fell over with that "'quake." Assuming the "buildings" were on some sort of sandy ground, a magnitude 6 earthquake would make them fall over. If the half-inch blip represents a magnitude 6, and we need to shake the ground 10 times as much to get a magnitude 7, then we'd need a blip the size of the entire rolling pin. For a magnitude 8 earthquake, the ground would shake 10 times more than that of a 7, so we'd need 10 rolling pins. (I usually have a JR walk several feet away from the group to represent the amount of ground shaking for a magnitude 8.) A magnitude 9 earthquake requires the ground to shake 10 times more than in a magnitude 8, so I have the JR walk across the amphitheatre to illustrate the degree of shaking.

To end the program on a dramatic note, I drive home the fact that the earthquakes around RNSP that happen every 200 to 600 years have probable magnitudes between 8 and 9 (pausing for effect). I then pose the question: "So, if earthquakes happen an average of every 500 years, and the last one was in 1700, when's the next one?"

Rollin' with seismic waves

First, cut out a hole width-wise out of the top of your Stratton "flat hat" cardboard box. Then cut notches into the side of the box where you cut the holes. Cover a plastic rolling pin with white paper and set the pin in the notches so you can easily turn the rolling pin from the sides. Attach a pencil to an edge of the box so that the lead is just barely touching the white paper and leaves a mark when you turn the pin (you may have to hold the pencil). Voila!

Campfire Program (All ages)

Topic: Geology

Theme: Earthquakes and tsunamis have shaped Redwood National and State Parks and can be understood using sandwich cookies!

Goal: Park visitors will be able to appreciate that Earth systems are connected and that plate tectonics is a powerful force that shapes landscapes (especially RNSP).

Objectives:

By the end of the Campfire, the audience will be able to:

*Know how rocks move during earthquakes

*Understand what the magnitude of large earthquakes really means

*Understand that RNSP has an active coastline at the boundary of 2 plates

*Understand that the Coast Range results from the process of subduction

*Understand that great subduction zone earthquakes cause tsunamis

Outline:

Following tradition, I officially welcome everyone to the campfire and make announcements. I have my Junior Rangers help start the campfire, announcing which Junior Rangers have achievements. I then get them involved and focusing their energy by doing the "campfire yell": "Campfire!! C'mon down!" rings out in all directions from the amphitheatre. After leading the audience "warm up" in more traditional campfire songs (like "on top of a redwood," lyrics originally adapted by state park ranger Doug Gordon and later amended), I have them refer to their lyrics sheets (which the Junior Rangers have helped to pass out) and sing "The Coastal Bunch (Range)," to the tune of "The Brady Bunch." (see "Campfire warm up songs") The song introduces them to a few of the terms we learn throughout the course of the program, but in a "silly" (non-threatening and non-intimidating) way.

To encourage audience interaction, I have people from the West Coast raise their hands and then ask who's from east of here. I call on individuals to specify where they call home. I ask the person from coastal North Carolina how they like all the rocks on our shoreline. I try to check the locations of recent earthquakes so I can tell the person from Indiana, "hey did you know you had a magnitude 5.0 earthquake while you were on vacation this week?" The flow of questions affords me the all-encompassing question: "so, who's here on vacation?" Every hand is raised (this is good because everyone feels involved). I tell them I love people on vacation because everyone is always so relaxed and no one is ever stressed-out. People guffaw. I then ask who has ever been stressed out. Virtually all hands go up. I call on individuals to tell me what they do when they're stressed out. I collect the answers and then launch into the main part of my program.

"Rocks have personality, too, and the Earth gets stressed-out just like all of us. But, unlike us, the Earth can't [fill in audience responses, such as "eat chocolate" or "work out"]. What do y'all think happens when the Earth gets too stressed-out?" Of course, I have primed my Junior Rangers to shriek "EARTHQUAKE!" at this point. I inform the rest of the audience that they are expected to rumble the very ground I stand on as they do likewise every time I ask "...and then what happens...?" The yell becomes an attention-keeping "inside joke" among campfire attendees as they look for the opportunity to shout at the Ranger.

This is generally how I delve into my introduction: To understand why the Earth gets stressed in the first place, we must understand that rocks move, and even more germane, the Earth itself moves. "The Earth's surface is like a cracked eggshell." The hard outer shell of the Earth is broken into pieces we call plates. Below that is a less solid layer of the mantle on which the plates can slide. There are two different types of crust that cap the plates, oceanic and continental. Continental crust is thicker and more buoyant than oceanic crust. We can think of it this way: imagine a beach ball and a tennis ball in a pool. "Has anyone here ever tried to push a beach ball under water?" It's really hard because the beach ball is so thick and buoyant. "What about a tennis ball, though? You won't have such a hard time pushing that down underwater. Why? Which one is thicker, or more buoyant? I need several volunteers to show you how this works on Earth."

Three Junior Rangers stand in a row facing the audience. From left to right, I have a (preferably smaller) JR hold a blue paper plate labeled "oceanic plate," a (again, smaller) JR hold another blue oceanic plate, and a (preferably bigger) JR on the right holds the green continental plate. I then follow the demonstration technique described in the "Cranky Gorda" text box.

At this point, I follow the skit with the Oreo cookie demonstration described in the "Using Oreo® cookies" text box, and your JRs can help you pass out cookies. (Remind the audience not to eat them yet!) Remind your audience that those cookies are high in calories and fat, and so there is an activity to burn off all that energy. Making sure to caution people about being over-zealous (this can be especially necessary when giving this program in late August to campers at Jedediah Smith State Park), involve folks in the earthquake and tsunami activity described in the "Crowd surfing" text box.

Now your audience gets to rest as it's finally dark enough to show your slides. I have found success in reviewing the idea of Earth's surface as a cracked eggshell, plate tectonic motions, and subduction zone earthquakes (make sure they yell!) leading to catastrophic tsunamis. I describe the scary idea of moment magnitude (see "Hands on" demonstration text box) and how much energy (magnitude 8-9 on the North Coast) the Earth needs to release during an earthquake, and I employ the story of the 1964 Crescent City tsunami (see "North Coast tsunami history") that accompanied the Great Alaskan subduction zone earthquake.

To conclude, I remind everyone that our gorgeous rocky coastline and impressive Redwoods could not exist without Earth processes, and I read from Rachel Carson's "The Edge of the Sea" to say goodnight.

Campfire warm up songs with a nerdy twist!

The Coastal Bunch (Range)

It's the story, of a plate named Gorda
Who was being smooshed by two other plates.
All of them are near the coast, by the water,
Making many earthquakes.

It's the story, of the North A.P. *(American Plate)*
Scraping over Gorda all alone.
Most of Gorda sinks beneath, but some accretes,
Creating a subduction zone!

'Til this one day when Pacific met the others
And we knew earthquake motions would be strange
That this triple junction shoves mountains over,
And that's the way this became the Coastal Range!

The coastal range! The coastal range!
That's the way this became the Coastal Range!

<u>Sample "Kid's Letter" Response to School Inquiries about RNSP Geology</u>

Every fall, as school sessions begin, RNSP headquarters starts receiving letters from kids all across the nation, asking for information so that they can write reports on National Parks. Sometimes these letters are more specifically aimed at certain aspects of RNSP, and, in my experience, young students are often interested in RNSP's geology. We can help these interested students by including our brochures about tsunami and earthquake hazards, and there are often extra "Living on Shaky Ground" pamiles per hourlets that Vicki Ozaki (RNSP Geologist with the USGS) supplies us with after the Humboldt County Fair in August. When I personalize our "kid's letter" template, I try to include slightly more in-depth information, but I'm careful not to include too much or go over their heads. Of course, we need to be sure our information is accurate and, if in question, make sure to show it to your district's interpretation supervisor. The following is an e-mail response I sent to one student in September of 2003.

" We are pleased that you are studying the redwoods! Regarding the geology of our parks, in addition to our focus on groves of redwood trees and their ecology, there is an additional focus on the coast. Redwood National and State Parks (RN&SP) not only protects 75% of the last remaining stands of old-growth coastal redwoods, but RN&SP also protects 37 miles of rocky coastline. The Pacific Northwest coast is world renown for being rocky and steep, a stark contrast to the beaches on the East coast. The difference between the East coast and the West coast can be explained by the geologic processes active in each area. Whereas the East Coast has not been active for the last 200 million years, the West Coast is presently being "smooshed."

If you're in 8th grade, you've probably learned about plate tectonics. Off the coast of our park, the Gorda Plate (an oceanic tectonic plate) is subducting (diving beneath) the North American Plate (a continental plate). They stick together for 200 to 600 years, building stress and pressure, and uplifting and deforming the rocks at the coastline into the CoastRange mountains. When the stress becomes too great, they suddenly lunge past each other, grinding rock against rock in devastating earthquakes (magnitude 8 to 9). If the Earth beneath the ocean moves enough, these earthquakes can generate giant sea waves ("tsunamis"), like the 1964 tsunami that demolished the downtown area of Crescent City, CA, including where RN&SP headquarters is today. This is why you can see "tsunami evacuation route" signs all the way down the coast from Washington state to Cape Mendocino, CA.

As far as rock types in RN&SP, we have all of the 3 major rock types (sedimentary, igneous, and metamorphic). Specifically, at the coast we have mainly sedimentary rocks such as sandstone, siltstone, mudstone, shale, and chert, all with cracks that are filled in with quartz (these are called quartz "veins"). There are some *places where these rocks have been metamorphosed (changed because of high heat and pressure, in non-science lingo, "cooked") into metamorphic rocks like slate and schist. In the north end of RN&SP, all along the Smith River in Jedediah Smith Redwoods State Park, there is green rock known as serpentine, which came from far below the ocean floor (it's part of an old ocean plate). It's full of iron and weathers into unique iron-rich soils (just like your bike, it "rusts").*

Our fossils are mostly marine fossils that once lived in the Pacific Ocean. Some of the youngest (most recent) fossils can be found near Point St. George in the siltstone and sandstone rocks exposed along the coast near Crescent City.

Enclosed is a package of information to help with your studies. If you read the various brochures and map carefully, you will find some of the answers to your questions about the park. You can also find more information on our website at ***www.nps.gov/redw.*** *When you bring up our home page, click on "In Depth" (http://www.nps.gov/redw/home.html) and when the next page comes up, choose the subject that you want to know more about on the left-hand side. You will want to click on "natural resources" and then "geology." You have our permission to print out and use any of the photos or information you can find on the website for your report."*

Appendix C: Geo-Limericks

Basalt

I form rock from volcanic assault
Aligned along a submarine fault
Pillow lava cools fast
And sometimes forms glass
But usually it just forms basalt.

Conglomerate:

Along a river rocks sit
Next to each other we fit
Sand gets in our cracks
We're stuck back-to-back
Together we're conglomerate.

Earthquakes

Stressing our rocks makes them break
During the rupture they shake
North America scrapes
O'er the thin Gorda Plate
That's when we get an earthquake!

Gabbro

From liquid hot magma I grow
I stay in the Earth far below
My dark crystals shine
They form over time
I'm the intrusive rock - gabbro.

Klamath River Spit

The Klamath River mouth grains
Form a spit that waxes and wanes
Coarse nutrient sand
Forms dynamic land
To shield the mouth it remains.

Peridotite

Forming deep in the Earth far from sight
Iron minerals add to my might
I'm called mantle rock
I form rusty blocks
Smith River gorge - peridotite.

Rocky North Coast

Of breathtaking beauty we boast
But it's danger we fear the most
Through active uplift
The coastline does shift
Becoming the rocky North Coast.

Sandstone

Above the subduction zone
By currents and winds we are blown
Our grains settle down
In water we drown
And harden into sandstone.

Sea stacks

Our coast cliffs are riddled with cracks
And weakened as sea water hacks
Eroding the rocks
The waves leave some blocks
The pillars of rock called sea stacks.

Serpentinite

I'm known for slope failure, not might
I can't put up much of a fight
I break down in toil
And make orange soil
I'm our state rock - serpentinite.

Serpentine/Smith River Cliffs

Smith River gorge rocks are green
Over time rain dulls their sheen
Like your car left outside
Rusts to iron oxide
Here we form soil from serpentine.

Schist

With pressure and heat rock can twist
Its particles caught in the midst
Smooshed sandstone and shale
Quartz and mica prevail
Transforming the rock into schist.

Shale

Look closely and see my detail
My layers are broken and frail
In still waters I form
From clay bits well worn
I'm rock on the coast now called shale.

Sweating plates

The top of the plate is quite wet
But deeper and hotter it gets
Hot water melts rock
The magma goes up
Volcanoes form when the plate "sweats."

Tsunami

Earthquakes from under the seas
Cause big waves to submerge the trees
The first waves are small
Compared to them all
These series we call - tsunami.

Appendix D: Visitor Survey

During my summer season of 2003, I was able to conduct a survey of visitors who came to my July and August Saturday night campfire programs. The number of attendees ranged from around 75 to over 200, with an average attendance of about 120 people. My objective was to evaluate the effectiveness of an interpretive approach to imparting geology education to the public. I developed a survey form intended to reach both adults who attended the campfire program and their Junior Rangers (ages 7-12) who attended the Junior Ranger program earlier the same afternoon. Both surveys were one page, and arranged so that the Junior Ranger survey was on the back of the adult survey. The surveys were designed keeping in mind that my audience and potential participants were non-captive and likely to be disinclined to fill out any survey that required much time.

The adult surveys consisted of four questions, three of which had three parts, and the Junior Ranger surveys consisted of seven questions, three of which had three parts. The first question identified the level of geology background of those attending my programs (both adults and Junior Ranger age). The purpose of discovering the visitors' geologic background was to determine how much potential my program had to increase the visitors' understanding of geology. Both surveys then asked three questions about geologic concepts, arranged in order of increasing difficulty. Because program logistics prevented a "before-and-after" survey, the survey relied on participants' honesty to determine in part how the interpretive program affected their answers to the concept questions. In surveys of adults, each concept question was accompanied by a question as to whether the person had known the answer before the program, and to what degree s/he felt the program enhanced his/her understanding of the answer. Junior Rangers also were asked about their prior knowledge of the answer to the questions, and they were asked two general questions about the helpfulness of the program at the end of the survey.

At each of six campfire programs, approximately 30 surveys were handed out to those interested in responding. A total of 53 surveys – 46 adult and 22 Junior Ranger (some overlap was expected and occurred when families completed the surveys on both sides as intended) - were returned, at an average of 6-7 surveys per program. Because participation in the survey was strictly voluntary, survey participants were self-selecting, which perhaps introduced an inherent bias toward positive responses: those who responded were those who were interested (or provoked) enough to want to respond.

Due to National Park Service survey regulations, while in uniform I could not directly associate myself with the survey. Instead, volunteers familiar with my project helped by announcing the survey during the "announcements" portion of my evening campfire program. The volunteer (1) spoke twice at my program (once before, once after), thereby disconnecting the surveys from the NPS, and (2) distributed the surveys to the attendees at the campfire. Survey participants were asked to return completed surveys to the Jedediah Smith State Park campground entrance kiosk at their convenience. I collected the completed surveys from the Jed Smith kiosk later in the week.

At each campfire program, I introduced the volunteer, who then paraphrased my written suggestion for how to announce the survey. "*Hi folks. I'm an assistant for the Oregon State University Research Team, which is gathering data for developing geology training manuals in National Parks. We'd appreciate your participation. If you're interested and willing, after Ranger Jen's program tonight, you can come up here and grab a survey from me. They are anonymous and designed simply to see if programs like these are effective interpretive techniques. If you had any Junior Rangers at Ranger Jen's program this afternoon, feel free to take a survey for each of them as well. You can do the surveys back at your campsites, and return them to the Jed Smith campground kiosk when you leave. Oregon State University would really appreciate your participation -- thanks!*"

Survey data were tabulated in a spreadsheet format using Microsoft Excel™. The various responses to each question were assigned numerical values corresponding to categories of increasing geologic understanding, as shown in the survey samples (tables A-1 - A-6). For example, a response indicating that a survey participant had an advanced course in Earth Science was rated "4," whereas having no formal Earth Science education was rated "0." Similarly, for concept questions, both "I don't know" and leaving the answer space blank (lack of response) were ranked "0," whereas correct answers were assigned a value of "2." Ideal correct answers to content questions are indicated in the survey "key," included in original format, but responses were liberally interpreted.

The data querying functions of Microsoft Excel™ were used to address questions regarding the percentage of respondents who demonstrated significant improvement in their understanding of the concepts presented. From the data, the following set of observations emerged. Key concepts are underlined.

Adult survey:

Of the 46 adult surveys returned, 70% indicated some sort of formal Earth Science training (question 1). After the campfire program, all respondents correctly answered that "earthquakes happen near/in RNSP" (question 2a), and 11% said they had not known that earthquakes happen around RNSP before the (2b). Eighty nine percent of respondents said that the campfire program enhanced their understanding of earthquake occurrence near/in RNSP, either a fair amount or a lot (2c).

Seventy-six percent of respondents were able to adequately answer that California's North Coast is "so rocky and steep" because of the active processes of uplift and erosion (3a). Of those who correctly answered 3a, 20% had neither had an Earth Science course nor known the answer before the campfire program (3b). Ninety-four percent of those who responded correctly also said the campfire enhanced their understanding of why the coast of RNSP is rocky and steep either a fair amount or a lot (3c).

Prior to distribution of the survey, question 4a had been identified as the most challenging; however, 80% of respondents adequately understood that the Coast Range is formed from the process of subduction (and coeval accretion of oceanic sediments onto the edge of the North American continent). Of the 37 respondents who correctly identified subduction as the process forming the Coast Range, 16% reported that they had not had formal Earth Science training nor had they known the answer before the program (4b), and 86% said that the campfire enhanced their understanding of how the Coast Range formed either a fair amount or a lot (4c).

Survey responses based on participant honesty have an innate error risk. To illustrate the degree of error possible, of the 15% of respondents who did not adequately understand how the Coast Range formed, 29% (4% of total respondents) claimed they knew the answer before attending the campfire program (4b).

Junior Rangers survey:

Of the 22 Junior Ranger (JR) respondents, 68% said they had never had a "real" class in Earth Science/geology. All Junior Rangers correctly responded that rocks move (3a) and that earthquakes occur when rocks suddenly move a lot (4a). Twenty-seven percent of the JRs said they had not known that rocks move before attending the JR program (3b), and 23% said they had not known that earthquakes happen when rocks suddenly move a lot before attending the JR program (4b).

Prior to distribution of the survey, question 5a had been identified as the most challenging concept that was presented in the JR program. Fifty-nine percent of the JRs responded correctly that the continents are above the water because they are thicker and more buoyant than the oceans. Of the JRs who answered 5a correctly, 32% reported that they had not had a "real" class in Earth Science/geology nor had they known the answer before the campfire. (However, this statistic is potentially misleading because the survey was administered following the evening campfire program, which itself followed the afternoon JR program. Some respondents, therefore, may have felt they knew the answer before attending the campfire because they attended the JR program. Therefore, perhaps an important distinction is noting that 62% of those who answered 5a correctly said they had never had a real Earth Science/geology class.)

Eighty-two percent of Junior Rangers said the JR program helped them understand the way the Earth moves either a fair amount or a lot, and 77% of JRs said the JR program helped them understand the way geology shapes RNSP either a fair amount or a lot.

Oregon State University's Geologic Interpretation Survey

Please answer the following questions honestly to the best of your ability (or to the extent you feel like while vacationing). These data will be used to develop a geology training manual for future rangers and visitors to Redwood National and State Parks. Feel free to add any comments or suggestions! **Junior Ranger** questions are on the **back**. When you're done, simply **return the survey(s) to the Jed Smith Campground Kiosk when you leave.** Thank you so much!!!

ADULTS:

1. Have you had any formal course work in geology or Earth Science? (*circle one*)

   Yes **No** 0

   If yes, then please indicate the highest level course:

   __1___ Course in grades 1-8. ___2__ Course in high school.

   __3___ Introductory course in college. ___4__ Advanced course in college.

2. **a) Do earthquakes happen near/in Redwood National and State Parks?** (*circle one*)

   yes 2 **no** 1 **I don't know** 0

   b) Did you know this before attending the geology campfire program? (*circle one*)

   no, not at all 0 **a little** 1 **yes** 2

   c) How much do you think the campfire program enhanced your understanding of earthquakes around Redwood National and State Parks? (*circle one*)

   not at all 0 **a little** 1 **a fair amount** 2 **a lot** 3

3. **a) Why is the North Coast of California so rocky and steep?**

   0 = *blank*

   1 = *incorrect*

   2 = *correct – active uplift and erosion*

   b) Did you know this before attending the geology campfire program? (*circle one*)

   no, not at all 0 **a little** 1 **yes** 2

   c) How much do you think the campfire program enhanced your understanding of the rocky, dramatic Northern California coast? (*circle one*)

   not at all 0 **a little** 1 **a fair amount** 2 **a lot** 3

4. **a) How is the Coast Range formed?**

(*don't worry if you think the answer is <u>related</u> to # 3a*)

0 = *blank*

1 = *incorrect*

2 = *correct - scraping off of oceanic sediments from subduction*

b) Did you know this <u>before</u> attending the geology campfire program? (*circle one*)

no, not at all 0 **a little** 1 **yes** 2

c) How much do you think the campfire program enhanced your understanding of the <u>reason there is a Coast Range on the West Coast</u>? (*circle one*)

not at all 0 **a little** 1 **a fair amount** 2 **a lot** 3

JUNIOR RANGERS:

Please have the Junior Ranger in your family respond to the questions below. If you have more than one Junior Ranger in your family, please have **each** respond on a **separate** survey form.

1. How old are you?

2. Have you ever had a "real" class/course in Earth Science or geology? (*circle one*)
yes 1 **no** 0

3. **a) Do rocks move?** (*circle one*)

yes 2 **no** 1 **I don't know** 0

b) Did you know this before attending the geology Junior Ranger program? (*circle one*)

no, not at all 0 **a little** 1 **yes** 2

4. **a) What happens when rocks suddenly move a LOT?**
0 = *blank*
1 = *incorrect*
2 = *correct - earthquake!!*
b) Did you know this before the geology Junior Ranger program? (*circle one*)

no, not at all 0 **a little** 1 **yes** 2

5. **a) Why are the continents above the water and the oceans below the water?**
0 = *blank*
1 = *incorrect*
2 = *correct - continents are thick and more buoyant*

b) Did you know this before my Junior Ranger program? (*circle one*)

no, not at all 0 **a little** 1 **yes** 2

6. How much do you think the geology Junior Ranger program helped you understand the way Earth moves? (*circle one*)

not at all 0 **a little** 1 **a fair amount** 2 **a lot** 3

7. How much do you think the geology Junior Ranger program helped you understand the way geology shapes Redwood National and State Parks? (*circle one*)

not at all 0 **a little** 1 **a fair amount** 2 **a lot** 3

Table A-1: Raw data from adult survey responses

Adult ID	Date (2003)	1	2a	2b	2c	3a	3b	3c	4a	4b	4c	Comments
1	?	0	2	2	1	2	2	1	2	2	2	Rick Heizer
2	7/26	3	2	0	3	2	0	3	2	0	3	Anne Natoli
3	7/26	3	2	2	2	1	1	2	2	1	2	
4	7/26	0	2	1	3	2	1	3	2	0	3	
5	7/26	0	2	0	3	0	1	3	0	0	3	Jetta from Germany "In understand but my English is not good enough to explain -- sorry. We had a great time with Ranger Jennifer and she did a great job in explaining us everything!! Well done the ranger of social actions!!
6	7/26	0	2	0	3	1	0	3	2	0	3	
7	7/26	2	2	2	3	2	1	3	2	1	3	"Jen did an awesome job -- <u>loved</u> the Oreo analogy! She made it <u>very</u> entertaining! (Not easy to do!)
8	7/26	2	2	1	3	2	1	3	2	1	3	
9	8/2	0	2	1	3	2	0	2	2	1	2	
10	8/2	2	2	2	3	1	0	1	2	1	1	
11	8/2	1	2	2	2	2	0	2	1	1	2	
12	8/2	2	2	2	3	2	1	2	2	1	2	
13	8/2	0	2	1	3	2	1	3	2	1	3	
14	8/2	2	2	2	1	2	2	1	2	0	1	
15	8/2	3	2	2	2	2	1	2	2	1	2	
16	8/2	3	2	2	2	2	1	2	1	1	2	
17	8/2	2	2	1	3	2	1	2	1	1	2	
18	8/9	3	2	1	3	2	0	3	1	1	2	
19	8/9	3	2	2	1	2	2	2	2	2	2	I enjoyed the engaging & entertaining resentation. Ranger Jen was great!
20	8/9	3	2	2	1	2	2	2	2	2	1	
21	8/9	3	2	2	2	2	2	3	2	2	1	<u>Fun</u> & Informative - Good repetition creative presentation.
22	8/9	2	2	0	3	2	0	3	2	0	3	

(Table A-1 continued)

Adult ID	Date (2003)	1	2a	2b	2c	3a	3b	3c	4a	4b	4c	Comments
23	8/9	2	2	1	2	1	2	2	2	1	2	
24	8/9	3	2	1	3	2	1	3	2	2	3	
25	8/9	0	2	2	3	2	0	3	2	1	3	
26	8/9	0	2	2	3	2	0	3	2	0	3	
27	8/9	0	2	2	3	2	1	2	1	1	2	
28	8/9	0	2	1	2	2	0	2	2	0	2	
29	8/9	2	2	1	3	2	2	2	2	0	2	I've taken a number of Geology classes in my day as a student at the Monterey Academy of Oceanographic Sciences (a charter high school) and thusly was extremely surprised to learn of the existence of the Gorda Plate, something I was previously completely unaware of.
30	8/9	3	2	0	3	1	1	1	2	1	2	
31	8/9	3	2	1	3	2	1	3	2	2	2	
32	8/17	3	2	2	2	2	1	2	2	1	2	
33	8/17	4	2	2	2	1	1	2	2	1	3	
34	8/17	1	2	2	3	2	1	3	1	2	3	
35	8/17	1	2	1	3	0	1	3	0	1	3	
36	8/23	0	2	2	3	2	1	3	2	1	3	
37	8/23	3	2	2	3	2	1	3	2	1	3	
38	8/23	0	2	1	3	2	0	3	2	0	3	What a fabulous presentation! From a learning point of view, Jen engaged all our senses and faculties. She's an outstanding educator.
39	8/23	0	2	2	3	1	2	3	2	2	3	Jen -- best ever -- well done -- most informative.
40	8/23	2	2	2	3	2	1	3	2	1	3	Jen was spectacular! This was by far the Most informative educational & fun campfire program I've attended (over the past 55 years!)
41	8/23	3	2	1	3	2	0	3	2	0	3	
42	8/23	2	2	2	2	1	0	2	2	1	2	Ranger Jen was very informative on all subjects.

(Table A-1 continued)

Adult ID	Date (2003)	1	2a	2b	2c	3a	3b	3c	4a	4b	4c	Comments
43	8/23	0	2	2	1	1	0	2	2	1	1	
44	8/23	4	2	2	3	2	2	2	1	2	2	You are an awesome teacher! If students had the opportunity to learn from you in schools they would learn a whole lot more! Actually you should be training teachers how to teach. In your lesson you brought in real life, kinesthetic, modeling, music and more. That is how to become a highly effective teacher!
45	8/30	3	2	2	3	2	1	3	2	1	3	Excellent job!
46	8/30	3	2	1	3	2	1	3	2	0	3	

Table A-2: Adult survey response tally

	Number of adults responding with listed value					Percentage of adults responding with listed value				
Question	**0**	**1**	**2**	**3**	**4**	**0**	**1**	**2**	**3**	**4**
1	14	3	11	16	2	30	7	24	35	4
2a	0	0	46			0	0	100		
2b	5	15	26			11	33	57		
2c	0	5	10	31		0	11	22	67	
3a	2	9	35			4	20	76		
3b	14	23	9			30	50	20		
3c	0	4	48	24		0	9	39	52	
4a	2	7	37			4	15	80		
4b	12	25	9			26	54	20		
4c	0	5	19	22		0	11	41	48	

Table A-3: *Analysis of combined responses from adult surveys*

Responses	Total raw numbers	Percent	Percent who correctly answered content question	Percentage of those who hadn't known answer before *CF*
2a (2) & 1 (0)	14	30	30	
3a (2) & 1 (0)	10	22	29	
4a (2) & 1 (0)	12	26	32	
2b (0) & 1 (0)	2	4	4	40
3b (0) & 1 (0)	7	15	20	50
4b (0) & 1 (0)	6	13	16	50
2a (2) & 2b (0)	5	11	11	
3a (2) & 3b (0)	10	22	29	
4a (2) & 4b (0)	11	24	30	
2a (2) & 2c (2) or (3)	41	89	89	
3a (2) & 3c (2) or (3)	33	72	94	
4a (2) & 4c (2) or (3)	32	70	86	
4a (1) but 4b (2)	2	4	29	

Table A-4: Raw data from Junior Ranger survey responses

JR ID	Date (2003)		1	2	3a	3b	4a	4b	5a	5b	6	7	Comments
1	7/26		12	1	2	1	2	2	2	1	3	3	Christopher Glenn
2	7/26		7	0	2	1	2	1	2	1	2	2	
3	7/26		10	0	2	2	2	2	2	2	2	2	Trevor Glenn
4	7/26		11	0	2	1	2	0	2	1	2	2	
5	8/2		8	1	2	2	2	2	2	1	3	3	
6	8/2		8	0	2	2	2	2	0	0	3	2	
7	8/2		8	2	2	1	2	2	0	0	3	3	
8	8/2		6	0	2	0	2	0	0	0	1	1	
9	8/2		9	0	2	0	2	1	0	0	3	1	
10	8/9		7	0	2	0	2	1	1	0	1	2	
11	8/9		14	1	2	2	2	2	1	2	1	1	
12	8/9		9	0	2	0	2	0	2	0	3	3	
13	8/9		10	0	2	1	2	0	2	0	3	3	
14	8/9		7	0	2	0	2	1	0	0	3	2	
15	8/17		6	0	2	2	2	1	2	0	3	2	
16	8/17		7	1	2	1	2	1	2	0	3	3	
17	8/17		10	0	2	2	2	1	2	1	3	3	
18	8/23		13	1	2	2	2	2	2	1	2	2	
19	8/23		16	1	2	2	2	2	2	0	2	3	p.s. Ranger Jen is extreamely entertaining & helped me better understand and appreciate geology!
20	8/23		6	0	2	0	2	0	0	0	0	0	
21	8/30		7	0	2	2	2	2	1	0	3	1	
22	8/30		10	0	2	2	2	2	2	0	3	3	

Table A-5: Junior Ranger survey response tally

	Number of Junior Rangers responding with listed value				Percentage of Junior Rangers responding with listed value			
Question	**0**	**1**	**2**	**3**	**0**	**1**	**2**	**3**
1								
2	15	6			68	27		
3a	0	0	22		0	0	100	
3b	6	6	10		27	27	45	
4a	0	0	22		0	0	100	
4b	5	7	10		23	32	45	
5a	6	3	13			27	14	59
5b	14	6	2			64	27	9
6	1	3	5	13	5	14	23	59
7	1	4	8	9	5	18	36	41

Table A-6: *Analysis of combined responses from Junior Ranger surveys*

Responses	Total raw numbers	Percent	Percent - correctly answered content question
3a (2) & 2 (0)	15	68	68
4a (2) & 2 (0)	15	68	68
5a (2) & 2 (0)	8	36	62
5a (2) & 2 (0) & 5b (0)	4	18	31
3a (2) & 3b (0)	6	27	27
4a (2) & 4b (0)	5	23	23
5a (2) & 5b (0)	6	27	43
6 (2) or (3)	18	82	
3a (2) & 6 (2) or (3)	18	82	82
4a (2) & 6 (2) or (3)	18	82	82
7 (2) or (3)	17	77	
4a (2) & 7 (2) or (3)	17	77	77
5a (2) & 7 (2) or (3)	13	59	100

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