THE GEOLOGY OF EXOTIC TERRANE

By

Nina Luttinger

a Guide to the Video

EXOTIC TERRANE

EXOTIC TERRANE

27 minute video program
Produced by Doug Prose
Sponsored by the U.S. Forest Service
and the U.S. Geological Survey
Grades7-College, 1992

Available from:
Bullfrog Films, Oley PA 19547
(610) 779-8226
www.bullfrogfilms.com

THE GEOLOGY OF EXOTIC TERRANE

By

Nina Luttinger

Table of Contents

INTRODUCTION

BACKGROUND

An exotic terrane (not "terrain") is a piece of the Earth's crust that has merged with another landmass that usually has a separate and entirely different geologic history. Scientists have concluded that much of western North America is made up of a collage of different exotic terranes that have been geologically moved from where they initially formed, to merge with the continent.

Learning the history of an exotic terrane is a voyage through geologic time. It is a window into the vast field of geology. The long and varied history of an exotic terrane can illustrate major geologic processes and formations, as well as important concepts that are fundamental to understanding geology. The rocks in these terranes are valuable records that document not only characteristics of the regions they are found in today, but also where they came from, how and when they moved to where they are today, and the time frames involved.

Exotic Terrane takes you on a geologic odyssey through beautiful Hells Canyon in the Pacific Northwest, to explore some of the rocks and fossils scientists have used to reach their conclusions about exotic terranes. But it also takes you to the tropical Mariana Islands in the western Pacific Ocean, the volcanic island of Hawaii, and Vancouver Island in British Columbia. Understanding the geology of these islands has been instrumental to understanding the geology of the exotic terrane in this video program. Against the incredibly scenic backdrop of these varied landscapes, this 27 minute documentary focuses on the exciting geologic story of an exotic terrane known as the Blue Mountains Island Arc. Interviews with geologists and paleontologists in the field demonstrate the wide range of different scientific findings or clues needed to understand this terrane's complicated history. Computer graphics of key places and terms, and a 3-Dimensional graphic animation of a geologic process called "subduction" illustrate some of the main geological concepts in the story. As the ancient and dramatic history of the Blue Mountains Island

Arc is revealed, you will implicitly learn another, even larger story that is integral to understanding any geologic phenomenon. Mainly, that the Earth is a dynamic planet, whose segmented crust is endlessly moving and whose history is unfathomably old.

This booklet begins with an introduction to the concept of geologic time, and a brief outline of the time periods associated with the video program. This provides you with a framework, a context, into which the content of the program can be placed. Additional sections include the major concepts and geologic features discussed in the documentary, as well as a more detailed account of some of the laboratory and field techniques scientists employ to study these features. The booklet is arranged to follow the organization of the video program.

Before viewing

Think of the processes that form rocks. For instance, how might the soft mudstone we find on riverbanks be formed?

What are some of the processes that change the size, shape or chemical composition of the rocks we see around us?

Are rocks always found exactly where they formed? Why or why not?

What are some of the processes that move rocks, and how far do you think they can be moved? What are some of the factors influencing how far a rock might be moved?

How are large segments of land, like continents, moved?

Think about the concept of exotic as something that comes from a different place than we find it today. Name some plants or animals that are exotic to where we find them today.

Think of fossils. Have you ever found a fossil? What was it, and where was it found? How do you think it got there?

In what sort of environments would you expect to find fossils?

What sort of organisms, or parts of organisms, have the best chance of being fossilized?

What does studying fossils reveal about the past?

The principle of uniformitarianism is important to the study of geology. This is the principle that the same geologic processes that occur today have not changed in the course of time; such that we can study present day geologic processes in order to better understand ancient geologic processes. In common language this translates into, "the present is the key to the past". Think of how geologists would use this principle to draw conclusions about ancient rocks.

After viewing

What are some of the major concepts introduced in the program?

How does plate tectonics shape the landscape around us?

What major geologic processes created the Blue Mountains Island Arc? How?

What process moved it a long distance to merge with the North American continent?

What were some of the scientific clues that helped scientists understand the history of this exotic terrane?

What are some of the challenges particular to studying exotic terranes?

How does the principle of uniformatarianism apply to scientists' understanding of the Blue Mountains Island Arc?

In what ways are geologic forces still changing this terrane?

What do geologists mean when they say our planet is dynamic?

GEOLOGIC TIME

The Earth is estimated to be about 4.5 *billion* years old. The first life on Earth is thought to be a form of blue-green algae that lived 3.5 *billion* years ago. It is impossible for us to grasp a notion of how old that really is. One of the most amazing things in learning about geology is in understanding the enormous time scales involved. The clocks geologists usually work with measure time not in minutes and hours, but in thousands and millions and even billions of years. To these clocks, our whole lifetime represents only the tiniest fraction of a second. Using these enormous time scales, geologists can examine very gradual processes that include the large-scale movements of continents across an ocean, or the building of gigantic mountains, just to name a few. In learning about any one geologic story (such as the formation of an exotic terrane), it is helpful to understand the time frame involved, and the global events that were taking place during that time. This provides a global context for the story, allowing us to see how it fits in with worldwide events, and the time it takes for some of these events and changes to occur.

The major geologic formations of the Blue Mountains Island Arc were created during a time interval called the Mesozoic Era. Because the Mesozoic Era marks the rise and decline of the dinosaurs, it is also known as the Age of Dinosaurs. It began roughly 245 million years ago and ended about 65 million years ago.

The Earth's surface was vastly different then. In the beginning of this Era, the world's continents were assembled together in one region, forming a supercontinent called Pangaea. This huge landmass stretched from the North pole to the South pole, leaving an enormous ocean covering the opposite side of the globe. Like today, scientists believe that over 70% of the Earth was ocean in the early Mesozoic. And the ocean was not empty. There were already plenty of primitive fishes, sharks, certain shellfish and sea plants, among others. There were also smaller pieces of land out there, such as chains of volcanic islands, that were not part of the supercontinent. As the Mesozoic Era progressed, Pangaea gradually broke up and plate tectonics slowly moved the continents towards their present position.

Simultaneously, some of those small pieces of foreign, or "exotic" lands were moved by geologic forces to collide and merge with the continents. The Blue Mountains Island Arc is one of these. Laboratory tests and field studies indicate that this terrane had an early history close to the equator, but by the middle of the Mesozoic Era, plate tectonics had moved it far northwards, to eventually merge with the North American continent. Since the end of the Mesozoic, many continents have continued to grow in size due to the gradual addition of exotic land fragments. For example, India is an enormous exotic terrane that has merged with Asia since the end of this Era.

The Mesozoic Era consists of three geologic time periods. The earliest of these is known as the Triassic, which spans the time between 245 million years ago and 208 million years ago. The Late Triassic marks the rise of such animals as the dinosaurs, marine reptiles, amphibians, primitive turtles and small mammals. Much of Pangaea at this time is thought to have been flat, dry, warm and dusty, marked with occassional sand dunes and eroded mountain ranges. The brick red color of the Triassic soils we find today in many parts of the world lend evidence to the warm, dry climate that prevailed over much of the supercontinent at this time. At the end of the Triassic, fragmentation of Pangaea slowly began, in an area near the equator known as the Tethyan region. A relatively small embayment on one side of Pangaea became a small sea, the Tethys Sea, that continued to widen by plate tectonic processes and spread farther inland, slowly rifting the supercontinent apart. The Tethyan Seaway became a narrow arm of the ocean, extending westward and eventually separating what is now Southern Europe from Africa. Sea level continued to rise as the Mesozoic progressed. A mass extinction occurred at the end of the Triassic, resulting in the loss of a large portion of the animals that lived during this time.

It was during the Late Triassic that the Martin Bridge Limestone began growing on the sides of volcanoes in the Blue Mountains Island Arc. In some places, coral reefs grew in the limestone. At that time, the Blue Mountains Island Arc was located relatively close to the equator, where similar tropical organisms are growing today. The fossil remains of the Martin Bridge Limestone are now nestled among the inland mountains of this exotic terrane, and they provide evidence for where the terrrane was at one time in its geologic history.

The second time period of the Mesozoic Era was the Jurassic, which began about 208 million years ago and lasted until 144 million years ago. During this time, the Tethyan Seaway continued to spread westward, separating North and South America. By the end of the Jurassic, sea level was very high, creating vast inland seas that flooded North America and Europe. Temperatures are believed to have been somewhat uniformly tropical throughout the fragmenting Pangaea, with a slightly cooler climate near the poles. In the animal world, this period saw the continued dominance on land by the dinosaurs, and marked the beginning of primitive birds, among others. Similar to the end of the Triassic, another major extinction marked the end of this period.

During the Jurassic, plate tectonics moved the Blue Mountains Island Arc farther north in the Pacific, out of the tropical zone. Jurassic plant fossils in this terrane indicate an entirely different environment than that which existed in the Triassic. Temperate zone plant species, such as different types of conifers and gingkoes, indicate that the Blue Mountains Island Arc was now in a cooler climate that had well developed seasons. In the latter stages of the Middle Jurassic, the island arc was probably at the same latitude as it is today.

The Cretaceous Period, lasting from 144 million years ago to about 65 million years ago, was the last period of the Mesozoic Era. Sea level rose much higher than it is today, and the climate continued to grow warmer through the first part of the period. By about 100 million years ago, the average temperature on Earth was higher than it has ever been since. Towards the end of the period, the climate cooled. Continued fragmentation and separation of continents brought landmasses close to their modern day positions, and created some of our present day seas, such as the Caribbean Sea and the Gulf of Mexico. Fossils of the Cretaceous period demonstrate a mixture of ancient and modern features. They include groups such as the dinosaurs, which did not survive through the end of the Cretaceous, as well as modern groups such as snakes, salamanders, modern lizards, and crocodiles, that evolved during this period. Dominance of the plant world by a type of plant called gymnosperms (such as pines) was replaced by the modern type of flowering plant, known as angiosperms. The end of the Cretaceous marks the largest mass extinction ever known. For reasons that remain unclear, a majority of the world's animal and plant species became extinct in a relatively short amount of time.

By the middle of the Cretaceous, the Blue Mountains Island Arc had finished merging with the continent, right about at the present day border of western Idaho. An 80 mile long "suture zone" marks where at least part of the collision ocurred. Various characteristics of these suture zone rocks have helped geologists understand the nature of the suturing event. The exotic terrane is thought to have begun its gradual merge with the continent about 130 million years ago, and completed the merge by 115 million years ago. Just east of the suture zone, the mountains of central Idaho were pushed higher by the geologic pressure of the nearby colliding landmasses. The Cretaceous period marks both the end of the Mesozoic Era and the final endpoint of the geologic odyssey of the Blue Mountains Island Arc across the Pacific Ocean. Now it was part of the continent.

PLATE TECTONICS

The development and general acceptance of a geologic concept called **Plate Tectonics** revolutionized the field of geology in the late 1960s. As a result, the way in which geologists understood geology up to that point changed dramatically. **Tectonics** is a term used to describe the movement of the Earth's crust. Plate tectonics refers to the interactions of segments of the Earth's **lithosphere** called **plates**. The lithosphere is the Earth's rigid outer shell, which includes the crust. It is located above a plastic-like, partially molten layer, called the **asthenosphere**. The theory of Plate Tectonics holds that the Earth's lithosphere consists of 6 major and several minor plates, some of which are up to 60 miles thick, that are moving with respect to each other over the asthenosphere. The plates are formed as material from within the asthenosphere rises to the surface along **spreading centers**. Plates grow at spreading centers and slowly but constantly move across the Earth, in some cases, descending back down into the asthenosphere where plate material was originally produced. Alhough it varies throughout the world, the average rate of plate movement is about 2-3 inches per year. To give you some idea of that rate, it is about how fast your fingernails grow. Like most geologic processes, it is hardly something you can watch happen.

The interactions that occur between plates account for the distribution of earthquakes, volcanoes and many of the mountain ranges around the world. If we could somehow look below the Earth's surface, we would see that the behavior of interacting plates directly influences the physical landscape we see around us, at the Earth's surface.

There are three main types of plate interaction. **Divergence** is the process where plates pull apart from each other, creating a spreading center. As the plates rift apart, molten magma from deep below the Earth's surface rises to fill the newly created space. In this manner, new ocean floor is constantly being created. An example of this is found in the Red Sea of Eastern Africa. The Red Sea started to form as the African and Arabian plates began to pull apart, or diverge, about 23 million years ago. The crust between the two plates collapsed as they diverged, and seawater gradually invaded the newly-created valley. Today, magma continues to rise and create new seafloor, as the rift between the plates grows at the rate of about 1/2 inch each year. At this rate, it will be 100 years before the Red Sea is 4 feet wider.

Plates can also slide past each other along deep fractures that occur on the ocean floor as well as on land. This second type of plate interaction is called a **transform fault**. Large earthquakes are associated with these zones. California's San Andreas Fault is a transform fault, along which the Pacific Plate is sliding north relative to the North American Plate at the average rate of about 2 inches per year.

When plates collide, the denser plate is often pulled under, "subducted", below the less dense plate. This third type of interaction is known as **subduction.** Because subduction was a critical process in forming and moving the exotic terranes mentioned in the video program, this guide goes into a little more detail describing this type of plate interaction.

Subduction

Subduction is the descent of a tectonic plate into the Earth's interior. This process can occur where two tectonic plates come together, or converge. In the case of an oceanic plate converging with a continental plate, the oceanic plate will be subducted because it is typically denser than the continental plate. As the plate descends, material scrapes off and accumulates against the edge of the overriding plate. This is called an accretionary **wedge**, and is characterized by folding and faulting of the rock layers.

Eventually reaching depths greater than 60 miles, parts of the descending plate begin to melt, forming magma that rises towards, and sometimes erupts on, the Earth's surface. During the process of descending and melting and rising to the surface again, the chemistry of the material often changes because rocks in the plates melt and mix with the melted material of other rocks and water. Volcanoes that erupt near these zones form unique lavas. Furthermore, rocks formed near subduction zones are also unusual in their geologic make-up. These rocks are called a **melange**, and generally form along deep-sea trenches. The presence of melanges and other characteristic subduction zone rocks gives geologists important clues about a region's geologic past. For example, the presence of these types of rocks in a part of eastern Oregon, called the Baker Terrane, provided evidence that this area was the site of a former subduction zone, associated with the Blue Mountains Island Arc.

Deep-sea trenches and chains of volcanic islands are also associated with subduction zones. The island chains typically exhibit a rounded, arc shape. They are known as **volcanic island arcs** and are formed by eruptions of lava created during the subduction process. The Mariana Island arc is an example. Geologic activity in this part of the western Pacific Ocean results from subduction of the Pacific plate below the Philipine plate. The site of this subduction zone is marked by the Mariana Trench. In one place, it reaches a depth of 36,200 feet below sea level, the deepest feature on Earth.

Subduction fueled the formation of the Mariana Islands in two ways. First, many of the islands began as underwater volcanoes that were powered by melting of the colliding plate. Over time, enough lava was erupted to break sea level and the underwater volcanoes became volcanic islands. Second, a few of the Mariana Islands, like Saipan, are actually pieces of the sea floor that have been lifted above sea level, as a result of the colliding plates below.

The Cascade Mountain Range of the Pacific Northwest is another example of a volcanic arc associated with a subduction zone, only here the arc formed on the continent, rather than in the ocean. A subduction zone similar to the one that slowly brought the Blue Mountains Island Arc into the western margin of the continent (which at that time was on the border of western Idaho), is located off the present day west coast. Just off the coast of Oregon and Washington, subduction of the Farallon plate beneath the North American plate has given rise to the Cascade Mountain Range. This volcanic arc has been active for almost 35 million years, and some of its volcanoes are still active today, as demonstrated by the recent eruptions of Mt. St. Helens in Washington.

EXOTIC TERRANES

An **exotic terrane** is a block of the Earth's crust, bounded by major faults, that has merged with a continent or other landmass that has a separate geologic history. Exotic terranes exist in varying sizes, shapes and compositions, all of which are a result of the history of their origins, movements and tectonic interactions. The exact history and distance of their movements vary greatly, and are difficult to decipher. Studying each of the rock units in the terrane provides geologists with clues. What *kinds* of rocks, the *chemical composition* of the rocks, and in some cases, the *fossils* in the rocks- all reveal information regarding their origins, what kind of environment they came from, and what kind of geologic processes the rocks have undergone. The laboratory techniques used to examine some of these characteristics are more fully explained in a separate section of this booklet.

Geologic investigations have led to the recent fascinating conclusion that many of the older rocks in western North America are made up of different terranes that have been moved by plate tectonics to merge with the continent. Virtually the entire Pacific coast- from Baja, California in the South, to the tip of Alaska in the North, and extending inland as much as 400 miles- is a collage of different terranes with various histories, and ranging in size from tens to hundreds, even thousands, of miles long. After merging with the continent, some terranes were sheared by faults and drawn out into narrow strips that run parallel to the continental margin. For example, some scientists believe that Vancouver Island, in British Columbia, was once geographically close to, or actually part of the Blue Mountains Island Arc. Plate tectonics moved this part of the island arc far north along the continental margin. Many of the land blocks also rotated in their orientation to the continent, due to the collision and the Northward motion of the Pacific plate. Because of their long, complex and diverse histories, reconstructing the geologic past of exotic terranes includes the coordinating efforts of geologists, paleontologists, geophysicists, and geochemists to piece together the origin, movement, changes in environmental conditions and deformation of these rocks through time.

One of the big challenges in studying geology lies in the fact that the shaping of our Earth is a dynamic process. A rock does not simply stay exactly where it forms, nor does it necessarily remain in the same shape or with the same chemical composition. Furthermore, from the moment a rock is formed, geologic processes continue to take place around it and upon it. For the most part, these processes are not simple, isolated events. They are related to a bigger, complex process, plate tectonics, that is *always* at work. As you read these words- and *every second* of *every day*- whole continents are shifting, mountains are growing higher, valleys are widening, canyons are getting deeper, new seafloor is being created, old seafloor is being subducted, volcanoes are erupting, new islands are being formed- just to name a few. The same natural forces that helped create a landscape are also helping to change it into something new. Therefore, what we see today may represent only a part of what was once there. Much of it may have been eroded away or subducted into the Earth's interior. And some has simply been buried beneath the continuous accumulation of Earth materials, created by ongoing geologic processes. For these reasons, studying any part of the Earth is inherently challenging. In some cases, whole terranes have been covered by thousands of feet of lava that poured over them after they had merged with the continent. Or faults may have fragmented the terrane into many pieces that were subsequently separated and moved long distances from each other. Or oceans may have flooded over them, eroding their features. Some geologists believe that many more exotic terranes probably existed than we see now, but they have either been eaten up in subduction zones or completely buried by lava or sediments, and will never be seen.

For those exotic terranes that *are* accessible to geologists today, present day geologic processes hold a key to understanding the past. Many geologic forces at work today were also acting on the Earth long ago in the past. For instance, the geologic processes creating the present-day, active volcanic islands are the same geologic processes that produced volcanic islands in the past. In this respect, geologists can look to modern day geologic processes to better understand the geologic past of an exotic terrane.

Applying the principle, "the present is the key to the past" has been instrumental in uncovering the truths behind the exotic terranes of the Pacific Northwest. A good example of this is in the conclusion that part of the Baker Terrane in eastern Oregon is actually the site of a former subduction zone. Most of the evidence for this relatively recent conclusion lies in the unusual rocks found there. These types of rocks are principally found at sites of known subduction zones, such as the Mariana Trench. When scientists studying the Baker Terrane compared their ancient rock samples with those from the Marianas Trench, they concluded that the Baker Terrane was also at one time the site of a subduction zone.

PILLOW LAVA

Pillow lava often forms as hot molten magma flows into water. Rapid cooling by water causes the lava to condense into rounded rocks that often have the size and shape of pillows. Their exact shape depends on the shape of the surface onto which they are erupted. On steep surfaces, the magma is thought to form more rounded shapes, that roll down the slope and accumulate at the base. If lava is erupted on more gradual slopes, it rolls longer before solidifying, and the pillow shape is more elongated. As the molten magma cools, any gas inside separates out, bubbling as it escapes. If there is a large volume of water above the lava as it erupts, there is pressure on the lava, and it is difficult for the gas to bubble out. If, however, there is very little overlying water, the lack of pressure will allow the gas to freely bubble out. Geologists can estimate how deep under the water the lava formed by looking at the amount of gas bubbles in the hardened pillow lava.

Pillow lavas provide important clues to geologists trying to decipher a region's geologic past. Pillow lavas found far inland from any present day body of water reveal an active geologic past, different from what is observed today, and/or significant changes in climate that could have led to shifts in sea level or the creation of large, inland bodies of water. The presence of pillow lavas indicates that sometime in the past the region was under water. In the Blue Mountains Island Arc, the presence of ancient pillow lavas in a rock unit called the "Wild Sheep Creek Formation" was one of the clues that told geologists that the island arc formed in an ancient ocean.

FOSSILS

A **fossil** is the remains of an ancient organism that has been preserved in sedimentary rock. **Sediment** is loose material deposited at the Earth's surface by water, ice or air. **Sedimentary rock** is formed when particles of sediment gradually solidify together, or consolidate, to form a hard rock. For example, some of the mud carried in a river is carried to the ocean and eventually falls to the ocean floor. Over time, the mud is buried by more and more sediment. The pressure from the growing weight of the sediments above will gradually compact the mud particles very tightly together, creating a rock called mudstone. Dead animals or plants that have fallen to the sea floor may be trapped in this mud layer and preserved as a fossil as the sediment turns to rock.

Because many other rocks, such as igneous and metamorphic rocks, typically form at very high temperatures, fossils are not preserved in them. For this reason, almost all fossils are found in sedimentary rocks. Generally speaking, it is usually the hard parts of an organism that are preserved, such as the bones and teeth of an animal, or the shell of a shellfish. Plants are preserved because of an internal material called **cellulose** that makes up the rigid cell walls of the plants. After the plant falls into the sediment other, relatively undissolvable materials in the surrounding environment (such as microscopic grains of a glass-like mineral called silica) gradually fill up the spaces inside the cell wall and preserve the structure of the plant. This process produces petrified wood. Sometimes organisms are preserved as **impressions** in sedimentary rock. Impressions include flattened outlines and some of the surface features of the preserved organisms. In rare cases, the fleshy soft parts of an organism are fossilized, but this only occurs in very old, fine grained, dense sedimentary rocks. The *kinds* of fossils we find in an area, as well as the *manner* in which they were fossilized can reveal much about a region's past, such as the kind of environment that existed there (e.g. a lake, an ocean, an ancient forest) or what the climate may have been like (e.g. cold or tropical).

Paleontologists are scientists who study fossils. Fossils provide a few of the many clues needed to piece together the geologic history of exotic terranes. The species of fossils, and the manner of fossilization can help scientists locate possible regions of terrane origin. Paleontologists can compare the fossils found in an exotic terrane to living plants and animals, or to other fossils from rocks of known origins. Since some ancient life forms are only found in certain known areas, any similar fossils found in an exotic terrane are suspected to have a similar history. For example, some coral fossils of the Martin Bridge Limestone, that were found in the Wallowa Terrane of the Pacific Northwest, have never been found anywhere else in North America. In fact, the only other place such fossils *have* been found is all the way around the world in the German and Austrian Alps! Because the coral fossils found in the Alps are the same species as those in the Wallowa Terrane, some paleontologists believe the rocks of this terrane may have been very close to the Eurasian continent at one time.

Examining fossils of different ages from the Wallowa terrane has been critical to understanding its complicated history. Younger fossil remains of an ancient forest that grew in the Wallowa Terrane roughly 175 million years ago suggest the terrane had moved out of the tropical zone by this time, and was probably nearer to where it eventually merged with the North American continent. This is supported by the fact that these fossils were temperate zone species, much like the plant species growing on the Wallowa Terrane today.

LIMESTONE

Limestone is a kind of sedimentary rock. The main mineral in limestone is called **calcite,** which is made of a chemical compound called **calcium carbonate.** Many marine organisms grow shells or skeletons made of calcium carbonate. When they die, this material falls to the seafloor as sediment. Over time, these sediments accumulate and solidify to become limestone. **Corals** can be one of the primary contributors to limestone formation. They are small animals that grow, plant-like, on the seafloor, protected by their external skeletons of calcium carbonate. Corals can grow by themselves, or in large colonies. Colonies of corals that grow together can form a **coral reef**, consisting of skeletal fragments, living plants and animals, and carbonate minerals. A well-known example of a coral reef is Australia's 1200 mile long Great Barrier Reef, which has been growing for many millions of years. Growing directly upon their own fossil record of skeletal fragments, the living corals strive to stay within a few feet of sea level, at an optimum light level needed for growth of the symbiotic algae which they depend on for food. Doing so, reefs represent a continuous cycle- whereby the older organisms die and become the foundation for the younger generation to build on. With time, the dead layers become buried and turn to limestone.

Because the living organisms of coral reefs and other carbonate bodies are largely restricted to warm shallow tropical waters, the presence of limestone made of coral reef material indicates a past environment where these conditions prevailed. Regarding exotic terranes, the presence of this type of limestone indicates the terrane was at one time exposed to conditions critical to coral reef growth. For instance, the discovery of a 210-million-year-old limestone formation called the "Martin Bridge Limestone" in the Blue Mountains Island Arc indicates that the terrane was once out in the ancient tropical Pacific Ocean before becoming a part of the North American continent.

GEOLOGIC INVESTIGATIONS

Most of the geologic investigations concerning the Blue Mountains Island Arc began in the field. Outside, geologists map where certain rock units are found, what specific types of rock they found there, and collect samples for lab analyses. Sometimes, as seen in "Exotic Terrane", field sites are located in rugged backcountry, which requires stenuous hiking and remote camping for the geologist.

In the Blue Mountains Island Arc, collecting adequate rock samples often means using large hammers. This is because some of the rocks there are extremely old and their surfaces have been heavily weathered. Weathering changes the characteristics of the outer rock and confounds the lab analyses. To collect an adequately "clean" sample for the lab, geologists must often hammer deep into the rock.

If paleomagnetic studies are to be be conducted in the lab, scientists need to make drill holes in specific types of rock in order to extract a sample rock core. If fossils are to be be examined in the lab, they can be carefully chiselled out of sedimentary rock in order to preserve their structure and shape. If they are impressions of organisms preserved in rock, pieces of sedimentary rock can be collected.

Rock samples are brought into the lab for a more detailed analyses. This is where geologists test and measure some of the characteristics of the rock samples brought in from the field. A variety of experiments reveal different characteristics about the rocks. Certain laboratory tests only work for specific kinds of rocks. For instance, since the age of fossils can be determined, scientists can estimate the age of the rocks that contain them. Since fossils are an important key to revealing age, as well as past environments and climates, it is useful to be able to examine them very closely. Some fossils can be separated from the rocks they are preserved in. If the fossil has been naturally replaced by the hard mineral silica, it can be separated from the rock it was preserved in by dissolving it in hydrochloric acid. The acid eats away the relatively soft rock, leaving the silica fossil behind. Such a fossil is considered **silicified.** Many of the coral fossils found in the Martin Bridge Limestone were preserved in this manner.

Potassium-Argon dating reveals the age of rocks by measuring the relative amounts of the isotopes of potassium and argon. Because potassium slowly turns into argon at a known rate, the relative amount of these elements contained in a rock gives an estimate of the rock's age. Potassium-Argon dating was used to measure the age of many of the rocks in the Blue Mountains Island Arc.

To learn what kind of tectonic setting a rock may have formed in, geologists can examine a non-sedimentary rock called granite. Granite forms when magma hardens before reaching the Earth's surface. Granite that originates in an oceanic setting has a different chemical composition than granite that formed on a continent. Using a technique called mass **spectrometry**, geologists can measure the particular chemical compositions of the granite samples, and determine if they formed in an oceanic or a continental setting. This kind of data has been used as evidence that much of western North America is made up of oceanic exotic terranes that have merged with, or **sutured** to the existing continent. On the east side of the Blue Mountains Island Arc suture zone, mass spectrometry reveals a continental origin, and on the west side the same test reveals an oceanic origin.

To learn where, geographically, rocks may have formed, geologists examine a property of a certain type of rock called **paleomagnetism**. Paleomagnetism refers to the alignment of microscopic magnetic particles that become part of the rock as it forms. The configuration of this alignment is determined by the local magnetic field where the rock first formed. For geologists, the orientation of the magnetic particles can reveal the position on the globe where the rocks formed, in relation to the equator. But paleomagnetism only reveals the approximate latitude of origin, it does not give any clues about the probable longitudinal position of origin. That is, we can learn how far north or south of the equator a rock may have formed, but we can not use paleomagnetism to determine how far west or east it may have traveled.

Paleomagnetic studies of the Blue Mountains Island Arc complemented paleontological studies which indicated the arc had an early history near the equator. Further investigations strengthened the conclusion of its gradual northward movement towards the continent. Paleomagnetic research has also been instrumental to understanding the geologic history of Vancouver Island. These studies complement paleontological evidence that Vancouver Island may have been part of the Blue Mountains Island Arc at one time.

Chemical analyses of rocks from the Baker Terrane were crucial to scientists' understanding of this region as the site of a former subduction zone. The unique blend of Earth materials that make up the Baker Terrane formed as a crustal plate partially melted and recombined with other chemicals deep within the Earth's crust. Rocks such as shiny, green "serpentine" are the result. As mentioned in an earlier section, scientists compared these rocks to rocks from a modern day subduction zone at the Marianas Trench to formulate their conclusion that the Baker Terrane was once the site of a subduction zone. Comparative studies like this are extremely useful to scientists who are examining a largely unexplored region because the present is often a crucial link to understanding the past.

FURTHER READINGS

GENERAL

Ballard, Robert D., *Exploring Our Living Planet*, National Geographic Society, Washington DC, 1983.

Fortey, Richard, *Fossils: The Key to the Past*, Natural History Publications, London, 1991.

Gregory, K.J., *The Earth's Natural Forces*, Oxford University Press, New York, 1990.

Hamblin, W. Kenneth, *The Earth's Dynamic Systems; A Textbook in Physical Geology* (5th ed.), Macmillan Publishing Co, New York & London, 1989.

Miller, Russell and the editors of Time/Life books, *Continents in Collision*, Time/Life Books, Alexandria, Virginia, 1983.

Moores, Eldridge M., *Shaping the Earth: Tectonics of Continents and Oceans*, W.H. Freeman and Co., New York, 1990.

Plummer, Charles C. and David McGeary, *Physical Geology*, Wm. C. Brown Pubs., Dubuque, Iowa, 1985.

Press, Frank and Raymond Siever, *Earth* (3rd ed.), W.H. Freeman and Co., San Francisco, 1982.

Skinner, Brian J. and Steven C. Porter, *Physical Geology*, John Wiley and Sons, New York, 1987.

Spencer, Edgar W., *Introduction to the Structure of the Earth* (3rd ed), McGraw-Hill Book Co., New York, 1988.

Stanley, Steven M., *Earth and Life Through Time* (2nd ed.), W.H. Freeman and Co., New York, 1989.

The Fossil Record and Evolution: Readings from Scientific American, W.H. Freeman and Co., San Francisco, 1982.

TECHNICAL REPORTS

Ash, Sydney, 1991, A new Jurassic *Phlebopteris* (plantae, filicales) from the Wallowa Terrane in the Snake River Canyon, Oregon and Idaho: Journal of Paleontology, v. 65 no. 2, p.322-329.

Brooks, H.C. 1979, Plate tectonics and the geologic history of the Blue Mountains: Oregon Geology, v. 41, no. 5, p. 71-80.

Brooks, H.C., and Vallier, T.L., 1978, Mesozoic rocks and tectonic evolution of eastern Oregon and western Idaho, in Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the western United States: Pacific section, Society of Economic Paleontologists and mineralogists, Paleogeography Symposium 2, p. 133-145.

Coney, P.J., Jones, D.L., and Monger, J.W.H., 1980, Cordilleran suspect terranes: Nature, v. 288, p.329-333.

Jones, D.L., Silberling, N.J., and Hillhouse, J., 1977, Wrangellia-A displaced terrane in northwestern North America: Canadian Journal of Earth Sciences, v. 14, p. 2565-2577.

Saleeby, J.B., 1983, Accretionary tectonics of the North American Cordillera: Annual Review of Earth and Planetary Sciences, v. 11, p. 45-73.

Stanley, George D. Jr., 1988, The history of Early Mesozoic reef communities: a three-step process: Palaios, v. 3, Reefs issue, p. 170-183.

Stanley, George D. Jr., 1987, Travels of an ancient reef: Natural History, v. 96, no. 11, p.36-42.

Vallier, T.L., and Brooks, H.C., 1986, Paleozoic and Mesozoic faunas of the Blue Mountains Province: a review of their geologic implications and comments on papers in the volume, in Vallier, T.L., and Brooks, H.C., eds., Geology of the Blue Mountains region of Oregon, Idaho, and Washington: geologic implications of Paleozoic and Mesozoic paleontology and biostratigraphy, Blue Mountains Province, Oregon and Idaho: U.S. Geological Survey Professional Paper 1435.

Vallier, T.L., and Brooks, H.C., eds., 1987, Geology of the Blue Mountains region of Oregon, Idaho, and Washington: the Idaho batholith and its border zone: U.S. Geological Survey Professional Paper 1436, p. 196.

Bullfrog Films
Oley, Pennsylvania 19547