THE ENDLESS VOYAGE

"World in Motion" Episode 104

If there were no plate tectonics on the Earth, the Earth would be a lot like Venus.

All the features of Earth are there for a good reason, and usually a plate tectonic reason.

The volcanoes, the earthquakes, all of that is somehow tied into tectonics. It's hard to look at anything on the Earth's surface without actually thinking about plate tectonics.

NARRATOR:
LIKE A PAINTER WITH A LIMITLESS PALETTE, NATURE REMINDS US FROM MOMENT TO MOMENT OF ITS UNIQUE ABILITY TO TRANSFORM THE WORLD AROUND US. OFTEN, THESE REMINDERS ARE GENTLE AND SERENE…

BUT THEY CAN ALSO BE EXTRAORDINARILY DESTRUCTIVE. AT ONE TIME, CATACLYSMIC EVENTS LIKE THESE WERE SIMPLY VIEWED AS MYSTERIES THAT DEFIED EXPLANATION. BUT, WITH THE ADVENT OF PLATE TECTONICS THEORY, IT'S BECOME APPARENT THAT EPISODES OF EXTREME GEOLOGIC UPHEAVAL, WHILE NOT EXACTLY PREDICTABLE, ARE MUCH MORE THAN SIMPLY RANDOM EVENTS.

JOANN STOCK, Ph.D., California Institute of Technology:
Because we know where the plate boundaries are, we know where most of the movement is going to be. That doesn't mean that we couldn't have an earthquake in the middle of plate, because every once in a while there's a big earthquake in the middle of North America, Australia, some continental plate. But those don't happen very often compared to the earthquakes at the plate boundaries. So, if you're looking for numbers of earthquakes, most of those earthquakes are going to be at the plate boundaries.

DAVID SANDWELL, Ph.D., Scripps Institution of Oceanography, UCSD:
There's really two types of earthquakes. There's the very shallow earthquakes. These occur at the seafloor spreading ridges where the plates are moving apart. Plates are rather thin, so the earthquakes are shallow. Now there's a completely different type of earthquakes at the subduction zones. This is where the plates are getting subducted back into the earth.

ERIK BENDER, Ph.D., Orange Coast College:
The most violent earthquakes that we see anywhere on the earth are always associated with subduction zones, where you have these two pieces of lithosphere grinding away on one another and pushing into one another. You have tremendous amounts of strain and pressure building up. And when these finally slip, all that pent up frustration—for lack of a better term—all this pent up strain energy is suddenly released in an earthquake.

PAUL JOHNSON, Ph.D., University of Washington:
When ocean crust gets old and heavy and sinks down into the mantle, several things happen to it. We know this because of earthquake tomography. Seismologists will look and see where they are. You can actually image these plates as they sink into the mantle. And some of them sink down about 600 kilometers and flatten out. And some of them sink all the way down to the core.

SANDWELL:
The interesting thing about deep earthquakes is that no one really understands why they occur. The Earth shouldn't really be brittle at depths of 600 kilometers. Yet, there is a lot of evidence for deep earthquakes…not only is there this good evidence for deep earthquakes, but that's really the primary evidence that these plates are being subducted into the mantle. The deep earthquakes follow a particular trajectory. You can look at the trajectory of the deep earthquakes, it's called the Benioff Zone, and figure out where all the subducting plates are going.

NARRATOR:
WHETHER STUDYING EARTHQUAKES OR OTHER GEOLOGIC EVENTS, SCIENTISTS USUALLY FOCUS THEIR ATTENTION ON PLATE BOUNDARIES.

STOCK:
The boundaries of the plates are where we have the active deformation. That's where we have the active mountain building or the active basin subsidence—the active faulting that produces the earthquakes that are damaging to populations. It's where we have the active volcanoes—so it's intimately tied into the whole issue of those sorts of natural hazards for the global population.

NARRATOR:
WHEN THEY'RE MOVING, PLATES CAN BE DRIFTING APART COMING TOGETHER, OR SLIPPING PAST EACH OTHER. THE THREE TYPES OF BOUNDARIES THAT RESULT FROM THESE INTERACTIONS ARE CALLED DIVERGENT, CONVERGENT AND TRANSFORM BOUNDARIES, DEPENDING ON THE NATURE OF THE PLATE MOTION.

If we start at the beginning, we have divergent plate boundaries, areas where the lithosphere literally is being rifted apart. And we have new seafloor filling up that void and allowing the seafloor to spread. There's lots and lots of geographic examples, and the most obvious one is the mid-ocean ridge system. This is the area where you have these high mountain chains, you have lava welling up along those rifts and the seafloor actively spreading. They also occur on the continents as well, however. If we look at probably the classic continental example, we look at East Africa. We have an example where the African continent is literally being broken up along the East African rift zone, the Gulf of Aden, and also the Red Sea. These are areas where the continent is literally breaking up and we see new seafloor growing in these areas. In the United States, we have what's referred to as the Rio Grand rift, where the area of the Rio Grande is actively opening up. And Albuquerque actually sits right in the middle of what would potentially someday become a small ocean basin.

The spreading centers are extremely important tectonically, because they produce most of the world's volcanism, even though you don't see that because it's all under water, except for rare places.

NARRATOR:
WHILE VOLCANOES CAN BE VERY DRAMATIC, THE MOST STRIKING RESULT OF SEAFLOOR SPREADING IS PROBABLY WHAT OCCURS OVER THE LONG HAUL.

STOCK:
If you start off with a narrow rift system and there's seafloor spreading going on, after millions of years you'll end up with a really big ocean—that's what happened in the Atlantic Ocean. It took it 180 million years or whatever—but that how the ocean basins get built, by seafloor spreading at the mid-ocean ridges. For the rate of plate movement, we often give people the analogy of how fast your fingernails grow, which seems pretty slow. It's a few centimeters a year. And it depends on which boundary you're talking about.

The East Pacific Rise mid-ocean ridge spreading center forms it pretty fast. Mid-Atlantic Ridge forms it very slowly. You're moving plates apart on the order of centimeters per year. And that requires that you form this crust continuously. It's formed at different rates in the past, a hundred million years ago during the Cretaceous, it formed two or three times faster than it is now. It seems to have slowed down a little bit now.

If we look at convergent boundaries…where one piece of lithosphere is diving underneath another, we have all of the world's largest mountain chains, really. We look at—here in North America, we have the Cascades, where we see active subduction of the Juan de Fuca plate underneath North America. As that plate dives down, generates large earthquakes and we also have the volcanism associated with it. And at the surface, we have this deep-sea trench.

TANYA ATWATER, Ph.D., University of California, Santa Barbara:
The subducting plates are so heavy, they're actually being pulled into the earth by their own weight. And right at the top, there's a big trench there. Those are the deepest places in the ocean. It's right where the plates being pulled down. It's actually being held down against its will. If you would just cut off that sinker that's pulling it down, it would actually float back up and fill in the trench.

If we work our way down to South America—the Andes Mountains. The Andes are the result of this subduction. If we work our way over to the western Pacific, we have Japan. The island of Japan sits right over one of these subduction zones, and it's the result of the volcanism and the earthquakes there. The Philippines—all of these are examples of that subduction process. Then, lastly we have what we refer to as transform boundaries, where we have one piece of lithosphere simply sliding by another one.

JOANN STOCK, Ph.D., California Institute of Technology:
The transform faults under the oceans can have earthquakes on them. They don't usually have volcanism on them. They're more better known to us in continental settings. For example, the San Andreas Fault is the transform fault between the Pacific plate and the North American plate in California. And there's a similar fault like that between the Australia plate and the Pacific plate in the south island of New Zealand. So, those settings can also have big earthquakes.

Basically, the three types of plate boundaries—the ridges, the transform faults and the trenches—each have a topographic expression.

ERIK BENDER, Ph.D., Orange Coast College:
If we go to the ocean basins, we see the massive mid-ocean ridge system, basically a large 10,000 foot high mountain chain which completely runs down each of the major oceans in the world. And this mountain chain is almost entirely volcanic…and it's really where we see the seafloor actively opening up.

SANDWELL:
The transform faults are scars in the earth, where the plates slide past one another. They're deep, topographic expressions. You have a lot of earthquakes there. And then the trenches are deep areas where the plates are getting subducted back into the planet. The subduction zone depths can go up to—trench depths can go up about six kilometers. The other prominent features of the ocean basins are seamounts, and island arcs, and volcanic activity. So after the plates are generated at the seafloor spreading ridges, occasionally, you'll have a hot spot or a mantle plume come up and drive through the lithosphere, releasing volcanism and creating a seamount or volcano on the ocean floor.

NARRATOR:
SEAMOUNTS ARE ESSENTIALLY THE SAME AS VOLCANOES, EXCEPT THAT THEY ARE INACTIVE AND DO NOT EXTEND ABOVE THE SURFACE.

DEBORAH KELLEY, Ph.D., University of Washington:
Seamounts can form in different environments. Along the major mid-ocean ridge system, the seamounts are typically associated with the spreading environment. That is where the plates are spreading apart, and basaltic volcanism—it allows basaltic material to rise up through the seafloor. However, in other places, like Hawaii—for reasons that aren't entirely clear—volcanism can occur in a place where the plates are not spreading apart, as in the case of Hawaii, it's in a center of a plate. And we think, for several thousand years, there's been upwelling of deep crustal mantle rocks, basically melted mantle material, that forms those large volcanoes there.

NARRATOR:
A VARIATION ON THE SAME THEME IS THE GUYOT, WHICH IS TALL ENOUGH TO BE ERODED BY WAVE ACTIVITY, AND THEREFORE HAS A FLAT TOP. SOMETIMES THESE VOLCANIC STRUCTURES OCCUR IN CHAINS.

DAVID SANDWELL, Ph.D., Scripps Institution of Oceanography, UCSD:
Like the Hawaiian Emperor Chain, where you have the Pacific plate riding over the mantle. There's a fixed mantle plume and it leaves behind a trail of volcanoes forming the Hawaiian—the present day activity is at Hawaii, but then you have the chain of volcanoes going all the way out to the Emperor Chain. Eventually, this chain gets subducted down the trench at the Aleutian Trench.

NARRATOR:
THE ISLAND ARC IS A CURVING CHAIN OF VOLCANIC ISLANDS AND SEAMOUNTS ALMOST ALWAYS FOUND PARALLELING THE CONCAVE EDGE OF A TRENCH.

You have the plate subducting at the trench. When the plate gets to a depth of about 100 kilometers below the surface of the Earth, the water and the crust there interacts with the mantle, starts to melt the overlying mantle material, and forms a chain of volcanoes that's directly behind the trench, forming an island arc. So island arcs always occur in combination with subduction zones and trenches.

In some sense, the trenches can be thought of as the destruction of the plates, in contrast of the mid-ocean ridges where over 60, 80% of our Earth's surface is formed. So what happens as these plates spread apart, because of upwelling mantle material down below, they move away from the zones of spreading, and in places—because they're driving upwards and outwards at some point to conserve mass—there has to be a downwelling limb of the convection cell. In places in off of, say, the western coast of the United States, or off of Alaska up in the Aleutian Islands, the tectonic plates downwell deep into the mantle and form trenches.

SANDWELL:
Another example of an island arc is the Marianas Trench, where you have the Marianas Islands behind the trench. The Puerto Rico Trench forms a nice island arc with vacation spots on the landward side of the subduction zone.

NARRATOR:
CLEARLY, THE GLOBAL IMPACT OF PLATE TECTONICS IS HARD TO MISS. WHAT IS FAR LESS OBVIOUS, HOWEVER, IS WHAT CAUSES TECTONIC ACTIVITY. MANY SCIENTISTS BELIEVE THE PROCESS BEGINS DEEP WITHIN THE EARTH. THE CHALLENGE IS TO SOMEHOW GATHER RELIABLE DATA ABOUT AN AREA THAT NO ONE HAS EVER ACTUALLY EXPLORED, AT LEAST, NOT DIRECTLY.

There's still a raging debate that goes on to this day as to exactly what the interior looks like, what the composition is, etcetera. We have a good handle on the composition of the upper mantle from things called mantle xenoliths—portions of the mantle which are ripped up and brought to the surface during volcanic eruptions.

STOCK:
You can look at the compositions of those rocks and determine something about the pressure and temperature conditions and what the mineral assemblages are that are stable down at mantle depths.

Otherwise, the way we know everything we do about the Earth's interior really comes from seismic waves. As an earthquake occurs, seismic waves are sent outwards in all directions.

The wave speed changes quite a bit at as it passes from the crustal rocks into the mantle rocks, and then again from the mantle into the outer core.

And as those seismic waves travel with different velocities through the interior, as they bounce off of different boundaries within the Earth's interior, that's how we really know what the interior looks like and what its composition is.

If you think of the layering in terms of composition, then we have essentially three major layers, and those are the crust, the mantle and the core. The crust is very thin, it's about up to 10 kilometers thick in the oceans, maybe, typically, 30 or 40 in the continents. It could get a little bit thicker under some of the major mountain ranges—60 kilometers, something like that. Beneath the crust is the mantle. The mantle is composed mostly of olivine, which is a silicate mineral that is not found so much in the crust. The crust is composed more of quartz and feldspar—kind of less dense minerals, less dense rocks. And then below the mantle is the core, which is mostly iron. The outer part of the core is actually fluid, and then the inner part is solid. And of course the temperatures get really hot as you get into the interior.

NARRATOR:
GEOLOGISTS RECOGNIZE THAT HEAT GENERATED FROM EARTH'S INTERIOR IS CRITICAL TO PLATE TECTONICS.

STOCK:
Heat plays a role in plate tectonics in several fundamental ways. First of all…the earth is cooling, and the process by which it's cooling involves convection, and so that's what's driving the plates.

NAOMI ORESKES, Ph.D., University of California, San Diego:
Convection is the turnover of a material when it's heated. It's controlled by density. So, when you heat a material, it becomes less dense, in general. And when things are less dense, they rise. So convection is the rising of a material that's been heated. Then, as it rises and begins to lose that heat, it cools off, it tends to sink back down, and so you get a

circulation set-up caused by the heating from below, the heat comes from the Earth's interior, and because the mantle is partially melted it's able to convect the same way that soup in a pot convects when you heat it from below.

The interior of the Earth is incredibly hot. If you go down towards the core of the earth, you're reaching temperatures that are approaching that of the surface of the sun. It's hot down there.

And the overall reason is the Earth is still cooling from when it was first formed four and a half billion years ago. It was really hot, and it's cooling slowly—and the way it's cooling is part of what drives plate tectonics, but it hasn't cooled completely yet. So plate tectonics is still going on as part of the cooling process.

TANYA ATWATER, Ph.D., University of California, Santa Barbara:
In its most fundamental sense, what plate tectonics does is get heat out of the inside of the Earth. It's getting hotter and hotter in there all the time because of radioactive decay, and somehow you have to get it out, and plate tectonics is the way you do it. When the plates come apart, they draw up hot material. Some of it melts and comes to the top, and others just plasters on underneath. It cools by losing its heat to the surface. At the subduction zones, these big, cold plates dive back in, and that's taking cold back into the Earth. It's a big convection cell of bringing heat out and putting cold in.

DAVID SANDWELL, Ph.D., Scripps Institution of Oceanography, UCSD:
Basically, all the planets are driven by internal heating. This internal heating comes from disintegration or radioactive decay of isotopes. The main isotopes are uranium, thorium and potassium. Now the mantle—the volume of the mantle is very large. Even though there are small amounts of these radioactive isotopes in the mantle, over geologic time they generate a tremendous amount of heat. And plate tectonics is just the response of our planet to shedding that extra heat. You could shed the heat from the Earth in a number of ways. You could do it by volcanism. That'd be a direct pipe from the mantle up to the surface of the Earth. You could do it by conduction of heat across a boundary layer, where you go from a high temperature to a low surface temperature. But the third way, the most efficient way to shed the Earth of its heat, is through plate tectonics.

STOCK:
The heat is also important because it produces volcanism. It produces the melts within the mantle that allow the new seafloor to be created by the eruption of magma filling in the gap between the old parts of the plate as they move apart, And then, of course, it produces the volcanism in the subduction zones. The down-going plate has water, and sort of wet sediment and stuff on it, as that goes down into the Earth, the heat is sufficient to melt volatiles off, out of that part of the down-going plate, and those come up and then trigger melting above them in the mantle. And so that causes big chains of volcanoes. If the Earth wasn't cooling, we would not have plate tectonics. So other planets, some planets, don't have plate tectonics, because they've already gotten cold. They might have had it the past, but they don't anymore.

NARRATOR:
WHILE MOST SCIENTISTS AGREE THAT HEAT AND CONVECTION PROBABLY PLAY A MAJOR ROLE IN PLATE TECTONICS, MANY QUESTIONS REMAIN.

ERIK BENDER, Ph.D., Orange Coast College:
Many geologists today are thinking about convection, where we have hot mantle material, hot asthenospheric material rising up, that spreads laterally and then sinks down at subduction zones, and then as a return flow. Some scientists believe this convection acts like a conveyor belt driving plate tectonics. Other scientists believe this convection is merely a thermal effect, where you have hot material rising…the colder crust is then sinking in different areas. Heat we know has something to do with it. We have to have some sort of hot material rising up which is going to cause the rise of the spreading ridge. As for what exactly happens after that, you ask 100 geologists, you're probably going to get 100 different answers.

JOANN STOCK, Ph.D., California Institute of Technology:
If you think of what's happening in the mantle below the plates, that's where the convection's taking place. And the plates themselves are—the top layer of the convection system—they're kind of riding around on top of the convection cells. But one of the big controversies right now really is how closely are they coupled to convection, because the way the convection patterns are occurring at depth may not exactly mimic the plate geometries at the surface. Plate geometries are partly inherited from the earlier history of where the spreading ridges were. It seems as if spreading ridges can shut off and they don't have necessarily an active source after they die. They just kind of stay there. So there's a degree of differential activity between the convection system and the plates that people don't completely understand, and it's one of the topics that are being researched at the moment.

The main things I think aren't understood well mostly have to do with continental deformation. Plate tectonics explains the ocean basins, the motion of the ocean floor and the creation of ocean crust extraordinarily well, but the details of continental deformation still are not all that well understood, and there are still significant arguments about whether or not the rigid plate model really works in the continents.

NARRATOR:
ANOTHER VEXING ASPECT OF PLATE TECTONICS CONCERNS PLATE HISTORY. WHILE SCIENTISTS KNOW SOMETHING ABOUT EARTH'S TECTONIC PAST, THERE ARE STILL MANY MORE QUESTIONS THAN ANSWERS.

NAOMI ORESKES, Ph.D., University of California, San Diego:
There are places on Earth where certain features have persisted for hundreds of millions, or even billions of years. This is an interesting problem because if plate motions are basically controlled by mantle convection then as a plate moves across the mantle, you might expect its regime to change. So, let's say something's going on in the mantle over

here. Now my plate moves away from that area into some other area. You might expect the effect of that mantle "thing" to migrate along, and you do see that, for example, in Hawaii. This is a famous example, where the Hawaiian Islands represent a chain of islands, a chain of volcanoes that are generated as the plate moves over a mantle hot spot. So, as they move, new islands crop up over that spot. But there are other places on Earth where instead of seeing a chain of islands or a chain of events, the same feature stays with the crust, and so moves with the crust. A good example of this is the mid-continent rift in the United States, which has been active geologically for over two billion years. Now how is that possible when this plate, this piece of continental crust has been all over the Earth in two billion years? So, either the crust is somehow controlling the mantle, which is possible, or there's just something going on that we don't understand.

NARRATOR:
SCIENTISTS ATTEMPT TO RECONSTRUCT EARTH'S HISTORY, SO AS TO BETTER UNDERSTAND THE CURRENT STATE OF GEOLOGIC AFFAIRS. THOSE SAME SCIENTISTS ALSO LOOK AHEAD AS THEY WRESTLE WITH QUESTIONS ABOUT THE FORCES THAT CAUSE PLATE MOVEMENT.

There are still these things we don't understand about the dynamics of the Earth. How are plates actually driven? Are do we start subduction? We understand the kinematics, the way things move pretty well now. What we need to focus on now are the forces that cause that movement, and also the long-term evolution of mountain belts in the context of those forces. Gaining a better understanding of the forces will then allow us to predict other things better, including things of great relevance to humanity, like earthquakes and volcanoes.

BENDER:
There are a lot of computer models which predict what the surface of the Earth will look like—at least in terms of the continents—50, 100, 150 million years into the future. There's a lot of things that—basically just looking at present day motions—we can predict what's going to happen. The problem is that a lot of those models don't take into account what potentially could happen in something like the Atlantic Ocean. As the eastern seaboard is weighed down under tremendous amounts of sediments coming off the Appalachians, we potentially could open up a new subduction zone on the eastern seaboard, which would then cause everything to slide back the other way. So we may have the Atlantic Ocean closing. We can do these computer models, but as to whether or not they're really accurate, only time will tell.

NARRATOR:
WHILE IT MAY NEVER BE POSSIBLE FOR SCIENTISTS TO PREDICT OUR GEOLOGIC FUTURE WITH ABSOLUTE CERTAINTY, THE DRIVE TO UNDERSTAND THE INNER WORKINGS OF PLANET EARTH CONTINUES.

BENDER:
There's no really accurate representation of how this all works. We're still trying to figure this all out. It is such an incredibly new idea and a new science that's

revolutionized everything. We've got to go back and rethink everything now. We're really not even sure about how this all works—what is the driving force behind plate tectonics? Ever since the idea of plate tectonics has been devised, people have been arguing about the driving forces. What is really causing the seafloor to spread? And we may never know, but someday, we hope to. That's really what we're driving towards. And as we find out new things, we keep having to revise the plate tectonic theory. So, it's really a work in progress.