THE ENDLESS VOYAGE

"Making the Pieces Fit" Episode 103

When Wegener came along with the idea of continental drift, it really, you know, it took people by surprise, and people didn't want to believe it.

He was the first one who really kind of laid it all out for us. Of course, everybody believed something else was—would fight back.

There are periods in the history of science where there are problems that can't be solved and scientists just say "We don't have an answer for this right now." And that's effectively what Americans did in the 1930s.

NARRATOR:
BY MODERN STANDARDS, THE WORK OF EARLY CARTOGRAPHERS CAN CHARITABLY BE DESCRIBED AS CREATIVE, BUT HARDLY REALISTIC. THE WALDSEEMULLER MAP, PUBLISHED IN 1507, WAS THE FIRST MAP TO IDENTIFY AMERICA BY NAME. BUT ANYONE HOPING FOR AN ACCURATE REPRESENTATION OF THE NEW WORLD WOULD HAVE TO WAIT. EVENTUALLY, OF COURSE, MAP MAKERS WERE ABLE TO REPRODUCE THE NOOKS AND CRANNIES OF THE WORLD'S COASTLINES WITH STARTLING PRECISION. AND CERTAIN UNMISTAKABLE SIMILARITIES BECAME STRIKINGLY CLEAR.

WARREN SMITH, Scripps Institution of Oceanography, UCSD:
Back in the late 1800s it was discovered, and it's almost like any child who looks at a globe can pretty easily decide that Africa and South America look like they fit together, parts of the puzzle. Well, that's how the whole thing started.

ERIC BENDER, Ph.D., Orange Coast College:
This jigsaw puzzle fit was actually recognized 200 years earlier. Sir Francis Bacon had actually recognized that there was this apparent jigsaw puzzle fit as soon as the first accurate maps were made of the coastlines.

TANYA ATWATER, Ph.D., University of California, Santa Barbara:
But also the geology fit very well. A lot of mountain ranges were broken up, the edge of the continents and continued on others.

JOANN STOCK, Ph.D., California Institute of Technology:
And then, of course, the geologists who were working in North America and Europe said, "Well, we've got the same kinds of rocks—you know, similar belts of the same age rocks with the same fossils in them, in these two places, and that looks like it matches up, too." And there was also a lot of good geological evidence from South America and Africa with a similar sort of thing. And so the geologists were a very important part of this

concept after, you know, the map makers, because they had additional points that they could correlate and say, “These pieces must have, you know, started out together.

NAOMI ORESKES, Ph.D., University of California, San Diego:
As early as the mid 19th century, people had recognized that the pattern of fossils around the world didn’t make sense. And the way in which it didn’t make sense was that fossil assemblages in places like South Africa and South America were almost exactly identical in certain parts of the geological record, even though these were environments that were thousands and thousands of miles apart.

NARRATOR:
BY THE EARLY 20th CENTURY, THE INTRIGUING CONGRUENCE BETWEEN DISTANT COASTLINES, ROCKS AND FOSSILS WAS WELL RECOGNIZED. BUT NO ONE HAD YET PROPOSED AN EXPLANATION. IN 1912, ALL THAT WOULD CHANGE.

BENDER:
The idea of continental drift was proposed by Alfred Wegener. This was totally against anything that had been proposed prior to this. His idea was that, at one time, all the continents had been joined into a supercontinent which he called Pangea. And there was ample evidence that he saw that supported this. There was the jigsaw puzzle fit of the continents. There was fossil evidence, climatic evidence, et cetera. All of this kind of led him to believe that the continents were, in fact, drifting over the surface of the earth, and that they’re still drifting today.

NARRATOR:
THE NOTION THAT EARTH’S CONTINENTS, IMMENSELY MASSIVE AND HEAVY SLABS OF GRANITE, COULD SOMEHOW FLOAT AROUND LIKE ENORMOUS CHUNKS OF ICE ON WATER, DID NOT SIT WELL WITH THE SCIENTIFIC ESTABLISHMENT AT THE TIME.

So, in fact, there were many people who denied that the jigsaw puzzle fit was evidence of continental drift. And one of my favorite counter-arguments was one famous American scientist, a man named Bailey Willis, who was Professor of Geology at Stanford, argued that the fact that the fit was so good proved that they couldn’t possibly have been connected, because if they had been connected and broke apart, then during the process of breaking up, the continental edges would get—they’d get kind of bashed about or fractured, busted up—it’d be sort of a mess. And it couldn’t possibly be so good.

Actually, I think the biggest trouble was that we didn’t have a mechanism. We didn’t understand how it could be, because we say that the continents were together and then they pulled apart, and it was just really hard to imagine how the continents could kind of plow through that solid rock.

BENDER:
They looked at his ideas and they said, "Well, your mechanisms don't work." And, realistically, that doesn't work as an excuse simply because of the fact that, well, they're fixist ideas didn't work either. There was no mechanism for explaining how other things happened on the face of the Earth. So, when Wegener came up with this idea, it was simply because they didn't want to believe him more than anything else.

It's not the case that there was no mechanism, because that's something that has often been said about continental drift and you can find that in many textbooks and it's just completely wrong, because, in fact, the exact same mechanism that we accept for plate tectonics today was put forward in the 1920s, and that's the idea that drift was driven by convection currents in the mantle.

NARRATOR:
THE MOST NEGATIVE REACTIONS TO WEGENER'S IDEAS WERE VOICED IN THE U.S., WHERE SCIENTISTS HAD A VERY DIFFERENT VIEW OF SOME FUNDAMENTAL SCIENTIFIC PRINCIPLES THAT DIRECTLY CONTRADICTED WEGENER'S THEORY. ONE SUCH DIFFERENCE CONCERNED ISOSTASY—THE PRINCIPLE OF BUOYANCY WHICH ALLOWS ICEBERGS TO FLOAT AND CONTINENTS TO STAND HIGH ABOVE SEA LEVEL AND NOT COLLAPSE UNDER THEIR OWN WEIGHT. WEGENER'S RADICAL NEW THEORY COULD NOT BE VALID IF U.S. NOTIONS ABOUT ISOSTASY WORKS WERE CORRECT. FOR EUROPEAN SCIENTISTS, WHOSE VIEW OF ISOSTASY WAS QUITE DIFFERENT, THERE WAS NO SUCH CONFLICT.

And, therefore, they were more able to consider the idea of continental drift without having to abandon some other important principles that they adhered to. So, in a sense, what it really was that Americans had to give up more to accept continental drift than Europeans did.

NARRATOR:
BUT THE DISAGREEMENT BETWEEN THE U.S. AND EUROPEAN SCIENTISTS OVER WEGENER'S IDEAS WENT WELL BEYOND ISOSTASY.

NAOMI ORESKES, Ph.D., University of California, San Diego:
One of the reasons why Americans reacted more negatively to his ideas than Europeans did was an argument about scientific method. Essentially, Americans had a very strong view that good scientific method put facts first, that it should empirical in the sense that you should go out into the world, learn about the world, observe, in an objective a manner as possible. And then, only after you had really looked at a lot of things, then you could begin to develop a theory to explain it. A lot of Europeans didn't view it that way, and particularly Germans didn't view it that way. Germans had a view, which is closer to what I think most American scientists believe today, that good science has to be informed by theory, that you have to have an idea that organizes your observations, that if you go out into the world and just collect facts, it's like collecting pebbles at a beach—it's sort of random and disorganized and it won't get you anywhere. So German

scientists tended to be much more theory oriented and they would often begin a book or begin an essay with a theoretical idea. So, Wegener did what was normal for a German scientist in that period to do. Americans read it and said, “This guy is prejudiced. This guy is dogmatic. This is bad science. He’s not letting the evidence speak for itself. He’s got an idea, and then he’s using that idea to force the evidence into his argument.” And so from the American point of view, his work seemed very dogmatic. And so he was extremely harshly criticized, to the point that people said, “This is bad science.”

NARRATOR:
IN 1930, ALFRED WEGENER WENT TO GREENLAND TO TAKE MEASUREMENTS OF CONTINENTAL MOTION—MEASUREMENTS WHICH HE HOPED WOULD FINALLY CONFIRM AND LEGITIMIZE HIS THEORY. BUT IT WAS NOT TO BE. WEGENER DIED OF A HEART ATTACK DURING THAT EXPEDITION. HIS THEORY, HOWEVER, DID NOT DIE WITH HIM. IN 1935, JAPANESE SCIENTIST, KIYOO WADATI, SPECULATED THAT EARTHQUAKES AND VOLCANOES NEAR JAPAN MIGHT BE ASSOCIATED WITH CONTINENTAL DRIFT. FIVE YEARS LATER, SEISMOLOGIST HUGO BENIOFF PLOTTED THE LOCATION OF DEEP EARTHQUAKES AT THE EDGES OF THE PACIFIC. HIS CHARTS REVEALED A CIRCLE OF VIOLENT GEOLOGIC ACTIVITY, KNOWN AS THE PACIFIC RING OF FIRE, SURROUNDING MUCH OF THE PACIFIC. BENIOFF, WADATI AND OTHERS WONDERED WHAT COULD CAUSE SUCH AN ORDERLY PATTERN OF DEEP EARTHQUAKES. WAS IT POSSIBLE THAT WEGENER COULD’VE BEEN RIGHT, AFTER ALL? THAT QUESTION WOULD GO UNANSWERED FOR SOME YEARS TO COME. IN THE MEANTIME, HOWEVER, SEEMINGLY UNRELATED GLOBAL EVENTS PROMPTED SCIENTISTS AROUND THE WORLD TO REVISIT THE THEORY THAT FOR DECADES HAD CONSUMED ALFRED WEGENER.

TANYA ATWATER, Ph.D., University of California, Santa Barbara:
I really think our understanding of the oceans came out because of World War II, ironically, because, in World War II, a lot of new technology was developed. It was mostly for submarine warfare. So we needed to know the landscape down there and we needed to be able to detect metal under the water.

JOANN STOCK, Ph.D., California Institute of Technology:
They developed the ability after World War II to start doing precision depth recording, so they could actually do soundings of the ocean floor with something other than just a line with a rock tied to the end, or, you know, something very primitive that took a long time. So once they had echo sounding, they could actually start surveying the ocean floor and they could see that there were these underwater trenches and mountain ranges and that, where they had underwater mountain ranges sometimes correlated to where they had the earthquakes. And the sort of systematic surveying of the oceans I believe started around or about after World War II.

NARRATOR:
IN 1960, PRINCETON SCIENTIST HARRY HESS AND ROBERT DIETZ OF THE SCRIPPS INSTITUTE OF OCEANOGRAPHY, PROPOSED A RADICAL NEW IDEA TO EXPLAIN THESE UNEXPECTED FEATURES THAT HAD BEEN DISCOVERED AT THE DEPTHS OF THE OCEAN. KNOWN AS SEAFLOOR SPREADING, THIS BOLD HYPOTHESIS PROVED TO BE OF STAGGERING IMPORTANCE. IT SUGGESTED THAT NEW SEAFLOOR DEVELOPS AT OCEANIC RIDGES, OR "SPREADING CENTERS." ACCORDING THE HESS-DIETZ THEORY, AS THIS NEW SEAFLOOR SPREADS OUT SYMMETRICALLY TO EITHER SIDE, IT CARRIES ALONG WITH IT THE CONTINENTS, WHOSE MOVEMENT ALFRED WEGENER TRIED TO PROVE DECADES EARLIER. WHILE THE NOTION OF SEAFLOOR SPREADING WAS WELL RECEIVED, SCIENTISTS STILL NEEDED ADDITIONAL PROOF TO DEMONSTRATE ITS VALIDITY.

ATWATER:
As part of the effort in World War II, we developed magnetometers that you could pull and see if there was a magnetic object under the water. And they developed very good sonars to figure out the depth of the ocean. And after about a decade, we had collected enough data to see the whole basic structure of the oceans and to pick up their magnetism, which turned out to be a complete—a crucial key in the whole thing.

NARRATOR:
IN 1963, GEOLOGISTS FREDERICK VINE, DRUMMOND MATTHEWS AND LAWRENCE MORLEY NOTED THAT MAGNETIC RESIDUE LOCKED IN THE ROCKS ON THE OCEAN FLOOR HAD APPARENTLY BEEN LAID DOWN OVER TIME IN STRIKINGLY SYMMETRICAL PATTERNS ON EITHER SIDE OF OCEANIC RIDGES. THEY ALSO RECOGNIZED THAT THESE PATTERNS COINCIDED WITH KNOWN REVERSALS IN EARTH'S MAGNETIC FIELD THAT HAVE OCCURRED PERIODICALLY.

ATWATER:
When they were measuring the magnetic field of the Earth, they discovered that it reverses, that for a while, the North Pole will be at the north, so if I had a compass here, it would point north. But, at other times, the field dies down and when it grows again, it can be pointing either direction, north or south.

LISA TAUXE, Ph.D., Scripps Institution of Oceanography, UCSD:
People were measuring rocks that they had collected on land, and they found, since the early 1900s, rocks that were magnetized in the wrong direction. They were pointing south, not north. And most rocks, if you heat them up—I'm talking about igneous rocks, so rocks that have come out of a volcano—they're completely different than sedimentary rocks—they start their life very hot—when you do that and then you cool them in the presence of a magnetic field, they become magnetized in the direction of the magnetic field. And these rocks should've been pointing north, and they weren't, they were pointing south, so what was going on here? Either the magnetic field completely flipped,

which nobody could conceive of, or there was some complicated phenomenon called "self-reversal," which is very bizarre, or the entire crust had flipped over. I mean, something weird was going on. So, in order to test what had actually happened, some people went around to all the continents, got lava flows that had been extruded over the last, say, five million years. These were dated with a new technique at the time called potassium argon dating. It uses radioactive decay, and it was pretty new to be able to do this in the early '60s. It took a long time to develop the technology to be able to do this. And they found that rocks all over the world, that with the same age, had the same polarity. They were pointing north if they were less than, say, 800,000 years old, and they were pointing south if they were 1.5 million years old.

ATWATER:
You know, you might say, "Well, so what?" It turns out that's perfect for proving seafloor spreading. When that ground comes apart at a seafloor spreading center, the lava that comes in is basalt, that black lava, and it's full of little crystals of magnetite, and when they cool, they get magnetized in whatever field happens to be there at the time.

And, if the Earth's field was reversing polarity, and the rocks were recording those reversals in polarity, it would serve as kind of a barcode recorder—a symmetric barcode recorder of that history of opening of the ocean basins.

So there are whole stripes of seafloor that are magnetized in one direction and then the other. And they're symmetrical—good for seafloor spreading—and they have a very distinct pattern of widths, which is just dependent on how long each of those intervals of normal or reverse magnetization lasted. And so it's a very, very distinct pattern.

TAUXE:
What you find is a very regular—astoundingly, astonishingly regular pattern of highs and lows, which make these long stripes. If you color all the highs black and all the lows white, what you find is these—what they call lineated magnetic anomalies, which make—they're also known as zebra stripes, because that's what they look like. The people who were studying the seafloor suddenly said, "Oh, that's it." It was one of those eureka moments, because if you have seafloor being formed at spreading centers and spreading out in the presence of a reversing field, you'll get magnetic stripes.

ERIK BENDER, Ph.D., Orange Coast College:
So, it's kind of a tape recorder of…the reversals of magnetic field throughout time. And that's kind of proof for the evidence of seafloor spreading.

NARRATOR:
THE IMPLICATIONS OF THESE MAGNETIC MARKERS FOR THE SEAFLOOR SPREADING HYPOTHESIS WERE PROFOUND, BUT THERE WAS STILL MORE WORK TO BE DONE.

The evidence for seafloor spreading includes the magnetic anomalies, but it also includes this concept of how much sediment accumulates on the ocean floor and how old the sediments are, because the idea is if you're creating new seafloor at the spreading ridge, and then the plates are moving apart, as the seafloor gets away from the spreading ridge, the oldest sediment should be found at the part of the ocean floor that's farthest away from the modern ridge.

NARRATOR:
WITH THAT IN MIND, IN 1968, THE GLOMAR CHALLENGER WENT TO SEA TO CONDUCT FURTHER TESTS AND GATHER MORE DATA.

In the '60s, the scientific community had realized that we would get tremendous value out of drilling into the ocean floor, that the sedimentary pile on the bottom of the ocean saves the history of the Earth in a way that land sediments never do. They're always being eroded and washed around and reorganized. But once you put it on the passive deep ocean floor, it's saved. And so, they all got together and supported this huge project called the Deep Sea Drilling Project, which could go out, hold still in the deep ocean, put down a big long drill string through all that water and then drill into the rocks and get back the sediments and also…get back the sample of the rocky basement rocks underneath. So, when they did that, as soon as the drilling ship was ready to go—this was the very first job it had, was to go out and test seafloor spreading. They went to the south Atlantic where we knew it was very steady, and they just drilled holes at the center and farther and farther out and some on the other side to test the symmetry.

JERRY BOE, Texas A&M University, Scripps University of Oceanography, UCSD:
The way they wanted to prove the seafloor spreading was very simple—is that they wanted to drill to the basaltic basement, the ocean crust, and age-date the oldest sediments sitting on top of the basaltic basement. And if seafloor spreading was indeed a viable theory, then at what they were calling the spreading center, if it was seafloor spreading, that should have the youngest sediments and then further away, you should have the oldest sediments. And they were able to determine this in a few cruises.

ATWATER:
A lot of the scientists who were on that drilling ship actually didn't believe in seafloor spreading when they went out there. And when they came back two months later, I mean, they just, their feet weren't touching the ground. They were so convinced that it was true.

NARRATOR:
WITH THE ACCEPTANCE OF SEAFLOOR SPREADING, CONTINENTAL DRIFT SUDDENLY DIDN'T SEEM LIKE SUCH AN IMPOSSIBILITY AFTER ALL. BUT THERE WAS ONE MORE PIECE OF THE GLOBAL PUZZLE THAT STILL NEEDED TO BE PUT IN PLACE. IT EMERGED FROM WORK DONE THREE YEARS EARLIER BY CANADIAN GEOPHYSICIST JOHN TUZO WILSON. TUZO WILSON HAD SUGGESTED THAT EARTH'S OUTER LAYER CONSISTS OF ABOUT A DOZEN SEPARATE PLATES, WHICH FLOAT ON THE PARTIALLY MELTED ASTHENOSPHERE BELOW THEM. HIS IDEAS PAVED THE WAY FOR THE INTEGRATION OF SEAFLOOR SPREADING AND CONTINENTAL DRIFT.

THE NET RESULT WAS ONE OF THE MOST POWERFUL UNIFYING THEORIES IN THE HISTORY OF EARTH SCIENCE—THE THEORY OF PLATE TECTONICS.

Plate tectonics is really a—is a catch-all for everything that's happening at the surface of the earth. Seafloor spreading—seafloor spreading causes continental drift, if you will. As the fact that the seafloor is opening up—that will drive the continents in motion. All of this goes under the major heading of plate tectonics.

NAOMI ORESKES, Ph.D., University of California, San Diego:
Plate tectonics is a larger theory that incorporates the idea of continental drift. And the main thing that plate tectonics adds to the story is an understanding of the relationship between the ocean basins and the continents. In particular, the most important element that it adds is the notion of subduction, which is what happens when an oceanic plate collides with a continental plate. And what happens in that case is that the oceanic plate actually sinks underneath the continent, back down into the center of the Earth.

BENDER:
The fact that the oceanic crust is so much colder, so much more dense than the continental crust, that that is the reason that it WAS preferentially subducted underneath the continents and why we don't see an awful lot of old oceanic crust all over the Earth.

So this boundary between the two plates is one of the major boundaries on the Earth where large earthquakes take place. So it has important implications for earthquake prediction. And also the frictional heating when the plates slide past each other melts the rock, and so it generates igneous activity leading to volcanoes.

BENDER:
When you talk about a subduction zone, we're talking about the entire region, which would involve the down going slab the deep sea trench, which results from that subduction, the zone of earthquakes, and the volcanism that is associated with that down going slab.

The pattern of earthquakes and volcanoes had been known since the 19th century. People knew that earthquakes were not random, that they mainly occurred in particular belts, often along the western edges of continents. They knew that fact but they didn't know why. With plate tectonics, we have an explanation for why earthquakes and volcanoes occur where they do.

NARRATOR:
DESPITE THE FACT THAT THERE WAS NO DIRECT EVIDENCE OF PLATE MOTION—NO ONE HAD ACTUALLY STOOD ON A PLATE AND MEASURED ITS MOVEMENT—THE THEORY OF PLATE TECTONICS WAS HERALDED AS A BREAKTHROUGH OF STAGGERING IMPORTANCE.

ORESKES:
It was accepted on the basis of the indirect evidence provided by paleomagnetic data, that's not to say the evidence was bad. It was good evidence, but it was indirect. Satellites finally gave us the direct independent measurement of moving plates, because the basic problem with plate tectonics is that you can only ever measure relative motion when you're on Earth, because since everything is moving, if I'm here and you're there, and I want to know how much you're moving, I can only measure your motion relative to my own. There's no independent means of determining my own motion. But, if I can out to outer space, put a satellite in a known fixed orbit, like an Earth stationary orbit, then I can make an objective independent measurement of the plate motion. And that's been done with satellites in recent years. It confirms the evidence that was developed from the surface work. So it's really played a confirmatory role. It's removed any possible doubt that could remain about the idea that these motions aren't really taking place.

DAVID SANDWELL, Ph.D., Scripps Institution of Oceanography, UCSD:
There are a variety of ways that plate tectonics has been confirmed. But, really, the most direct way of measuring plate tectonics is to put geodetic instruments on the individual plates. You put one instrument on the North American plate, one on the European plate, use a system like G.P.S. to measure the divergence of those two instruments over time. They're moving apart at about two centimeters a year. And so now, today, we have really direct evidence that there are these plate motions going on.

ERIK BENDER, Ph.D., Orange Coast College:
The G.P.S. is this fabulous system designed by the U.S. military for use against our enemies. And it's a constellation of satellites which allows to pinpoint on the Earth's surface anything to within a few centimeters, and potentially even a few millimeters. And one of the things that allows us to do as a geologist—or me as a geologist to do—I'm able to do is I'm able to look at someplace on the Earth's surface and see how that spot is moving over time. And that is a verification really of the plate tectonic process.

NARRATOR:
WHETHER THE EVIDENCE IS DIRECT OR INDIRECT, IT'S IMPOSSIBLE TO IGNORE THE IMPACT OF PLATE TECTONICS.

BENDER:
If you look at any of the mountain ranges along the coast of North America, these are direct results of what we call subduction, where we have one piece of lithosphere being driven underneath another. 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. So, there's lots and lots of evidence where we see the results of plate tectonics.

ORESKES:
Plate tectonics is the first global tectonic theory to be widely accepted in the entire history of our sciences. There never was a general tectonic theory that was broadly

accepted by the scientific community before that. So, it's given the earth sciences a kind of unity and a kind of intellectual coherence that it truly never had before, ever, in 400 years of history. So, that alone, I think, is historically and hugely significant, and hugely significant for scientists who now operate in a science that has a unifying framework. So, you could argue that it's given the science a kind of maturity or a kind of depth, a kind of cohesiveness that it didn't have before.

JOANN STOCK, Ph.D., California Institute of Technology:
It was just incredibly exciting that all of these different disciplines—you know, marine geology, marine geophysics, paleomagnetics, the geology of on land—could all contribute to an understanding, a completely new understanding of how the Earth worked. And it was totally different from what people had thought before, and yet it made so much sense. And everyone who was involved in it just got totally excited about how they could make all these new discoveries. And that's why it was so much fun for so many people, because they could use it as a predictive tool for what they should find somewhere else, and then they could go look there and say, "Oh, yeah, that's what's happening here, too." And so it was an amazing revolution.