Chapter 1: ***Hatching Plans for Hitchhiking with a Hatch, Pursuing Plate Tectonics***

Backdrop of a standard classroom, with lecture-room seats for the actresses.

Janna: Hey, Jordan, I see that you are back in your "Starbucks mode", just using college as a place to get an occasional intellectual caffeine rush, or is there some other reason for you to be reading a French book here in our Differential Equations class? You have probably been reading it all morning because you were certainly not in our Sadistics class. I suppose that you want my notes again.

Jordan (*still reading*): That would be nice. Say, Janna, how would you like to go for a trip around the world with me?

Janna: If anyone else asked me that question, I would know that they were kidding, but **you** just might be serious. The last time you mumbled a bizarre question like that, it came from something you were reading, so I had better look at your book … "Vingt Mille Lieues sous les Mers". *(Vahn meal lee-you sue lay mare)* My mediocre Spanish tells me that "les Mers" *(lay mare)* relates to the ocean, el mar, but that is as far as I can get. Unlike you, I have not enjoyed Paris for a couple of years. Microsoft did not send my dad and his family to enjoy Parisian culture, so I will have to use Babel Fish to translate your title. Oh, I should have spotted it, "Twenty Thousands Leagues under the Sea". Let me guess, you want me to accompany you on a submarine voyage around the world. Should I be concerned that you are not smiling?

Jordan: Look, Janna, we both get our Computer Engineering degrees in a few months, thanks to you, but the IT business is on Skid Row. We could not get a job right now running a company's paper shredder. When my dad started twenty years ago, he was able to become phenomenally wealthy, rising like a rocket through the IT world. As a result, he has become so busy that he will buy me anything to divert me from bothering him. He keeps telling me to become unique. Maybe I could become the first ordinary citizen to build a submarine that circumnavigates the world. With robots, we would not need the big crew on Jules Verne's submarine. You and I could manage just fine.

Janna: If a sub becomes our home, would I have to do all the homework for both of us, like this past year? If my parents ever knew how strange you can be, Jordan, they would never have let us become roommates. What am I supposed to tell them? Hey Mom and Dad, I am just going off with Jordan for a little submarine trip around the world. While some excursions are plainly abysmal, ours will include a tour of abyssal plains. We hope to be back in a year. Oh, by the way, could you lend her some wrenches? She is building the submarine herself. I really doubt if they will go for that story. Perhaps I could tell them that our Study Abroad Office is sending me to the University of Outer Mongolia for a year, a place where "Internet" still means, "between nets" so I will be *incommunicado.*

Jordan: So you **will** go with me !! Tell me that you are not just saying that because my dad has offered you a big prize to help me graduate.

Janna: To tell you the truth, your dad has been paying me to keep you on track for graduation, but then I discovered that we had become good friends, so now I am winning both ways. Nonetheless, neither one of us had better say anything to him about your submarine project. Within your parents' mansion, you have created such intricate metallic furniture for your electronic equipment that your dad could be convinced that he is funding another iteration of the ultimate nerd cave.

Jordan: Great idea !! My dad is so neat that he **did** find the right roommate for me !! There are rooms in our house that my parents do not even know exist, so I could work on it there. However, the assembly room will have to be a rented garage that is big enough to hold a power boat. While I am working on the design and construction, you could take a couple of oceanography courses to identify what we will find in the deep blue sea.

Janna: To improve our chances of survival, you should start attending our Sadistics class again because each component of our submarine is going to have a finite probability of failure and we need to add up all those probabilities to calculate how much life insurance we should buy. My cat will need an annuity.

Jordan: An annuity for your cat would be cheap but not for my African gray parrot. My parrot will probably live longer than me, even if I stay off submarines. To improve our odds, I will include lots of safety features. Moreover, we will have a land-based team continually feeding us relevant information about shifting currents and shifty politicians. Any of our agreements to come ashore in foreign countries or even to receive supplies would be subject to political change, so that would have to be monitored.

Janna: I suppose that you could raise our periscope as we glide into harbor and see if some mob is toppling the president's statue. In any case, it is time for our Diffy Q class to start, so we can continue this when we get together at Subway® for lunch.

Backdrop of a Subway® sandwich shop

Janna: You have not touched your submarine sandwich.

Jordan: I am trying to think where a sea monster would take the first bite.

Janna: Just how small is this baby submarine going to be?

Jordan: Well, it needs to be big enough that it will not become anybody's midnight snack.

Janna: I hope you know that every girl expects to have a walk-in closet. OK. OK. Stop looking at me like that. I was just kidding. First we spend a year crammed into Jordan's kinky can, and then I get my walk-in closet back here in terra firma. Do not forget your deodorant.

Jordan: We are a long way from packing our suitcases. What did you discover about oceanography courses?

Janna: I asked our Diffy Q prof because she is a graduate of our university and she said that she took oceanography from Professor Bowles. Apparently, he was the most popular lecturer on campus twenty years ago. I see that he still teaches through distance education, so I can try to entice him into giving us private lessons. Should I tell him about our plans?

Jordan: Let me google him. I see that he has been a Commander in the Navy Reserves. Unfortunately, there is a possibility that the US Navy considers submarines to be **their** sole reserve. I too have heard that Professor Bowles is a legendary lecturer but there is no need to bring the Navy into this venture if we can avoid it. We will have enough trouble staying out of their way while at sea.

Janna: Why not get somebody to approach the Navy for us? How about your uncle who is a famous trial lawyer?

Jordan: There is no point in bothering him because I know he will refuse. He says that he never asks a question unless he already knows the answer. Unless we already know the Navy's answer, he will not ask the question.

Janna: So, you are not planning to register this vessel, but you must have a name in mind.

Jordan: Il est évident, mademoiselle. Le nom est « Nautilus ».

(eel eh ay-veedont mah-de-mwah-zel. Le noh eh Notilus.)

Janna : I should have guessed, « 20,000 Leagues » and all that. What about the power plant?

Jordan: Every person's prime problem is power. Permit me to pass over that particular point pending production of my probability proofs, due presently.

Janna: Very funny. You know that I always do your probability proofs for you, no matter how many p's you can cram into a sentence. You skip Sadistics so often that the prof has created a special function to predict the probability of you appearing at any given class. I doubt if she will flunk you, though, given that the wing in which she teaches is named after your grandfather. I will finish your homework and call you so that we can meet in the library.

DH Hill Library, with Janna and Jordan at a table

Jordan: I have figured out that I will need to hire half-a-dozen engineers to help me build the Nautilus.

Janna: That is a healthy sign of realistic thinking. You are a brilliant designer but, let's face it, a klutz. You had trouble serving my mother's strawberry pie last week. My jeans are still stained. You even confessed after that incident that some teachers called you Klutzan instead of Jordan in public school. Anyway, how are your plans coming along? Are they still sub-standard?

Jordan: That was "sub-funny". Nowadays, the standard high-performance sub is a nuclear sub, so I have sent somebody with a concealed camera to the Navy's museum for the world's first nuclear submarine, ironically named the Nautilus.

Janna: I toured that sub with my parents a couple of years ago, in Groton Connecticut. They let us go everywhere except the old engine room, so I doubt if your spy will learn more than fancy plumbing. That engine room must still be somewhat radioactive, even though the fuel rods are long gone. As I recall, that Nautilus had a crew of 111 and a length of 319 feet, so that sounds like a bigger get-away car than we would need.

Jordan: Our first design rule will be to keep everything metric because we are going to incorporate automotive parts. Just about the only non-metric automotive part that you can buy these days is a speedometer. Consequently, measurements like 319 feet will simultaneously be listed in meters, specifically 97 meters.

Janna: Just a minute. There is no way that you are going to build a nuclear reactor in this country, no matter how small it might be. If we attempted that, we could both get a long trip up the river rather than out to sea. We would have to build a World-War-Two style of submarine, with a diesel engine for surface travel and batteries for brief submergence. In fact, the World-War-Two subs were not true submarines when compared to a nuclear vessel that may remain submerged across most of an ocean, as our Navy proved by taking their Nautilus under the Arctic ice cap in 1958.

Jordan: You are right. We will have to build a conventional submarine and get that to Haiti using diesel power.

Janna: Haiti is not my idea of a comfortable first stop. Are you going weird on me again?

Jordan: No. I have contacted some French Canadian engineers and they have agreed to build a small nuclear reactor for us in Haiti. Fortunately, the French Canadians could easily hide in Haiti because the official language there is French. Canadians are the only ones who have much experience building reactors that do not require enrichment of the uranium isotopes. A sustained nuclear reaction depends upon ^{235}U but this isotope never occurs by itself in natural rock. In nature, ^{235}U always is mixed with 138 times more of the isotope that does not produce enough neutrons to sustain a reaction, ^{238}U. The USA closely monitors the sale of equipment that can enrich the ratio of ^{235}U to ^{238}U, especially in places like Iran and North Korea. However, the French Canadians know how to get around this surveillance by building an unenriched reactor. They call it the CANDU reactor. Some MBA must have dreamed up that name.

Janna: Although the name probably came from an MBA, the design must involve smart engineering. I have an uncle who is a nuclear engineer at the local power plant and he tells me that 40% of our power comes from plutonium, toward the end of a fuel cycle. The seemingly useless ^{238}U that is mixed with ^{235}U progressively converts to plutonium during the life of the fuel rods and that plutonium then contributes power. I am surprised that the French Canadians would share their expertise with you. Do those engineers not have a sense of allegiance?

Jordan: They have allegiance to the extent that they will only accept payment in American dollars, not Canadian dollars, even though their money has French written all over it.

Janna: If you are going to have a nuclear engine assembled in Haiti, does that mean that you plan to replace the original diesel engine with your nuclear engine when we get there?

Jordan: No. I am designing the Nautilus so that the nuclear engine hangs onto the back of the preliminary diesel engine. We will not have the entire US Fleet ready to save us if something goes wrong, so we have to bring our own backup system. If we lose power underwater, we can manually activate a gas-releasing chemical reaction that will increase our buoyancy by driving ballast fluid through a one-way valve. Once we reach the surface, we can start our diesel engine. As you know, diesel engines cannot work underwater because they require atmospheric oxygen to combust the fuel.

Janna: You sound smart enough but I still think that you had better examine existing submarines as closely as possible before construction starts. On the same trip that my family took to the Nautilus Museum in Connecticut, we visited the Woods Hole Oceanographic Institution in southern Massachusetts. There we saw a much smaller submarine than the Nautilus suspended on the rear of a ship that was the size of a football field. The small suspended sub, the Alvin, is more like our size, with a length of just 7 meters (23 feet). Alvin can be operated by a single person but may carry three, thereby providing a couple of scientists with a tour of the deep ocean.

Jordan: Alvin cannot dive for more than ten hours at a time, depending upon its rate of power consumption, and its cruising speed is just half-a-mile-per-hour (0.8 kph). Alvin runs on just a chipmunk-powered battery, rather than the Brontosaurus-powered engine that we envision. On our proposed submarine, we will have rechargeable batteries that would run all electrical gadgets and would continue to supply power even if our main engine fails, but we could not rely on those batteries to get us very far. Alvin's batteries can keep its three-man crew alive underwater for only 72 hours, mostly because of limitations on air purification. Air purification is one of the prime environmental concerns on any sub, just as it is in manned spacecraft.

Janna: Yes. I remember Apollo 13. Those guys nearly died from the carbon dioxide of their own breath. Please tell me that you will not let that happen on our Nautilus.

Jordan: I would say anything to get someone to come along with me.

Janna: I bet you would, but I wish that you would not say that. How about saying, "I will test our sub in the water under all conceivable circumstances before going out to sea with it."

Jordan: I guess that I would have to take somebody else with me for all that testing. What would you tell my dad?

Janna: OK. Forget it. He would probably sue me for breach of contract. I will just cross my fingers, and maybe even cross my toes. Let me know when you have started construction.

…. A workshop with tools hanging on the wall. The actors are standing.

Jordan: How do you like it? The first thing that I had to do with this room was add cement blocks to the walls and six inches (15 cm) of insulation to the ceiling to dampen the hammering and drilling, to hide the noise from my parents.

Janna: How appropriate !! Your parents have often told me that they fear that you will end up in a padded cell. They would be surprised to learn that you are already there, and that you have padded it yourself ! What are all these pipes for?

Jordan: You should remember those from touring the Nautilus. We have to move fluids to power the electricity-generating turbines. Moreover, we will control much of the ship hydraulically, pushing fluids to open a valve or turn a rudder. We will have a redundant electric-motor-driven control system but tiny electric motors are less reliable than hydraulics, so we will only use that redundant system if we spring a leak in the hydraulics. Unlike the Alvin, we are not going to have a mother ship, so we need backup systems for everything.

Janna: I hope that you are not so engrossed in all the nuts and bolts that you have forgotten that we might get hungry out there.

Jordan: No problem. Admittedly, the diplomacy required to bring a submarine into somebody's port city is going to be beyond us in some parts of the world so I have arranged for CARE packages to be flown out to us.

Janna: CARE packages? I have read that Americans sent CARE packages to destitute Europeans following World War II.

Jordan: Let me tell you that we will indeed be destitute if we have to rely upon my fishing skills in the middle of the ocean where there are few fish anyway. Moreover, your nutrition classes must have emphasized a balanced diet. We have not yet developed the 2000-Calorie multi-food-group pill of Star Trek, so we will need somebody to drop us a bundle with a beacon every couple of weeks.

Janna: How will they find us? It is a big ocean, after all. One wave looks a lot like another.

Jordan: Satellites are the answer. In the 1967 movie, The Graduate, plastics were proposed to be the key to the future but now we rely on satellites, specifically GPS satellites. We should have no trouble guiding a drop plane to our location. Each dropped bundle will contain a GPS transmitter to facilitate finding it.

Janna: Hang on there. You must remember the notes that I took for you in our cost-estimation class. The project that you are describing is running into several million dollars. As I have confessed, your dad has promised me a small fortune if I get you to graduate but you are now talking about a big fortune. This is not like a pair of first-class tickets to Bangkok. Even your dad is not going to give you several million dollars as a graduation gift.

Jordan: I have found the money elsewhere.

Janna: Elsewhere? Do you have a subterranean subsidiary that tunnels into bank vaults?

Jordan: I went to see my dad's friend, Bill Bates. We can just bill Bates.

Janna: Bill and his billions? Do you think that his dollar bills are just going to pour out of his gates?

Jordan: No problem. Bill has instructed the Bill and Linda Bates Foundation to cover all our expenses. It is no loss to him because he either gives the money away through his foundation or the IRS takes it in taxes. He might as well have some fun with it. I convinced him that he comes out ahead with us because he actually can earn money by backing us.

Janna: How could he possibly earn money from us? Are we going to become the world's most expensive postal service?

Jordan: Let me give you a hint: National Geographic.

Janna: National Geographic? A documentary? National Geographic is paying Bates for the distribution rights? When will the filming start?

Jordan: Oh, about ten minutes ago, when you entered the room.

Janna: So, you have sold the filming rights for every minute of our year-long trip, and you expect me to be witty and wear makeup the whole time?

Jordan: I am sure that you know how to operate a light switch and can unplug a microphone.

Janna: Knowing you, I will not find all the microphones and there will be low-light cameras. I can only hope that Bates does not have an additional contract with a less-reputable distributor. I think that I had better negotiate for more money from your dad.

Jordan: Bates did say something about broadcasting us continuously once our sub reaches international waters, and we no longer have to be secretive.

Janna: Continuously? For a whole year? Like every sneeze, giggle, and whatever?

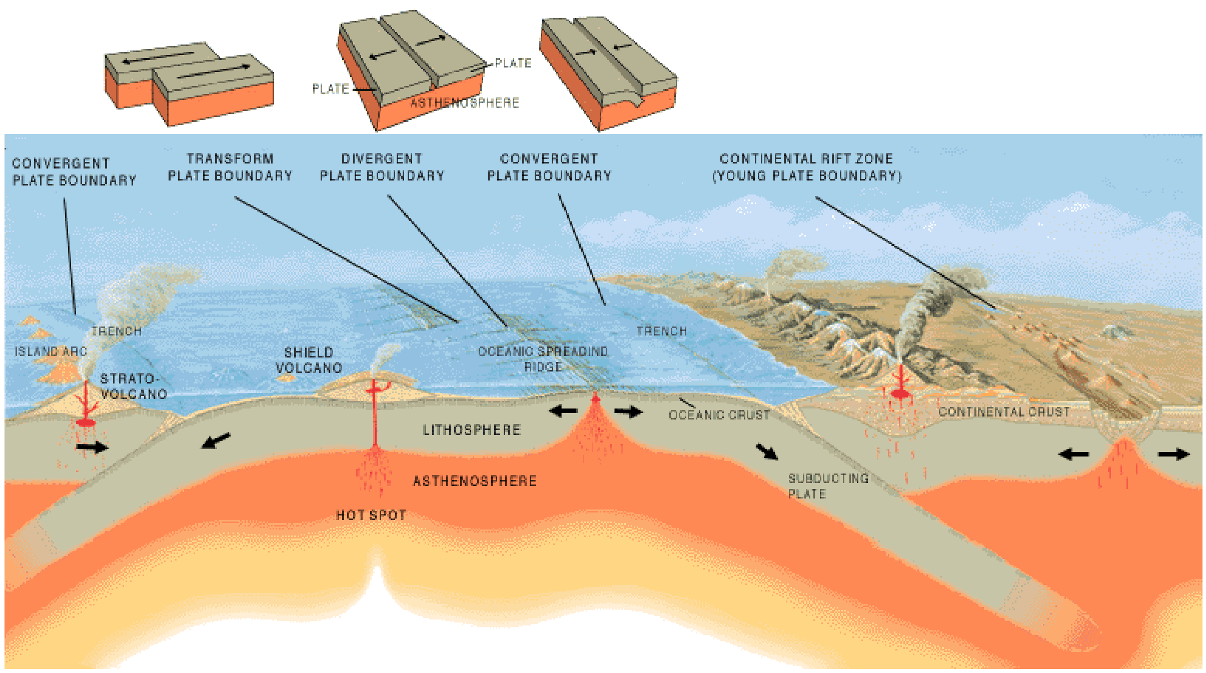
Jordan: This is a good way to make sure that you do not get angry with me, while being viewed by millions of people near the bottom of the ocean. You will have to chill, or else you would really chill, given that the water temperature is just barely above freezing all over the deep sea.

Janna: That wily Bates is probably going to make money on us, even if it costs him millions to fund our project. I do suspect, however, that I will go off your dad's payroll with that first broadcast, and my parents will learn that I have not actually enrolled for graduate work at the University of Outer Mongolia.

Jordan: Bates is not exactly known for money-losing ventures. Besides, he has promised me a lucrative job with him at the end of our televised year, and you can join me. You could enjoy a life like my mom's. Spending money is a full-time occupation for her and she barely makes a dent in the income. However, Bates is going to expect us to explain oceanography to those millions of viewers so we had better pay Professor Bowles to give us private lessons.

…. *new backdrop, with Prof. Bowles facing Jordan and Janna who are seated together.*

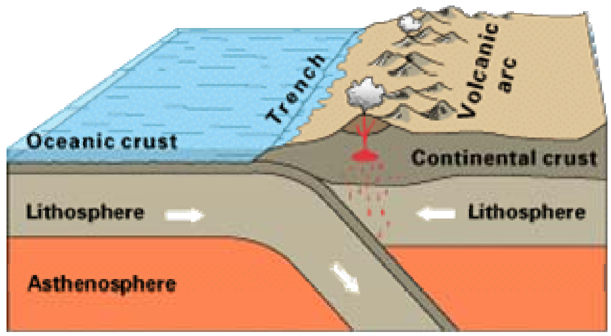
Prof. Bowles: Hello Jordan. I must admit that you are paying me so well that I have subcontracted for some other instructors to help me. I have had so many students complain about hidden bias in my lectures over the years that I will occasionally bring in Drs. Bubah, Fondah, and Anerkey to let you see overt bias. Dr. Bubah is a self-proclaimed redneck conservative. Dr. Fondah is a bleeding-heart liberal whereas Dr. Anerkey is a cynical liberal. Bubah's motto is, "Gonna build me a beeg seawater tank and grow whales for barbeque". Fondah's Web site says, "We should stop killing any plants or animals for food". What Fondah plans to eat, I do not know. Anerkey wears a prominant political button that reads, "Michael Moore for President". They will show up another day. Today, we will just review the morphology and movement of the seafloor, using the theory of Plate Tectonics. A German meteorologist, Alfred Wegener, started the precursor of Plate Tectonics a century ago. The modern Plate Tectonic model is largely based on seafloor data that has been laboriously collected by the US Navy since the days of Wegener. I must warn you that Professor Anerkey is likely to claim that the Navy has invented all this to confuse people because the Navy thinks that they should be the only ones who understand the seafloor. However, every oceanographic textbook on Earth presents the Plate Tectonic model so they cannot all be wrong. Here is a composite sketch for the Pacific.



Jordan: There once was a time when all the textbooks favored some model other than that of Wegener, so I am not convinced that unanimity guarantees accuracy.

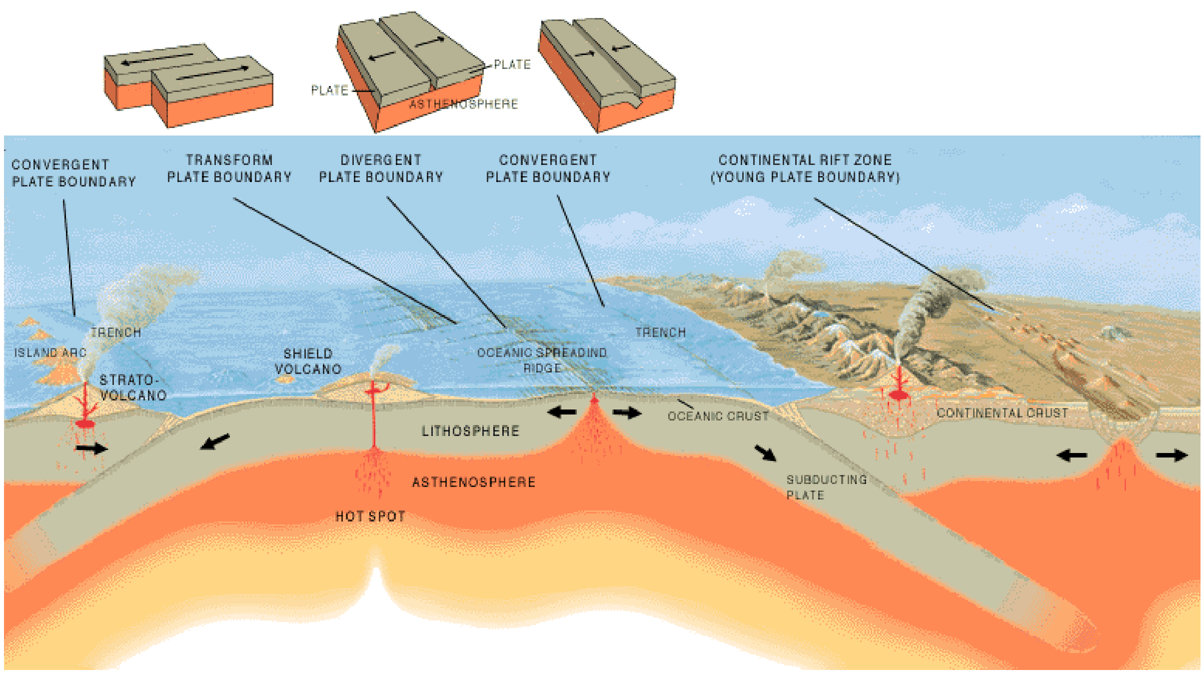
Janna: I suppose that all textbooks try to present the most popular concept so there will be little variation among textbooks at any given time.

Prof. Bowles: The theory of Plate Tectonics states that global seafloor spreading causes the continents to drift because the continents constitute parts of moving lithospheric plates, as we will see in a series of sketches from the US Geological Survey. We will return to this composite sketch repeatedly as we focus on specific aspects of Plate Tectonics. Although this sketch models the Pacific, both the Pacific and the Atlantic have a spreading ridge like that shown here. However, the perimeter of the Atlantic has few places where a lithospheric plate is descending into the Earth. As shown, a descending plate is called a subducting plate. Let us take a closer look at subduction.

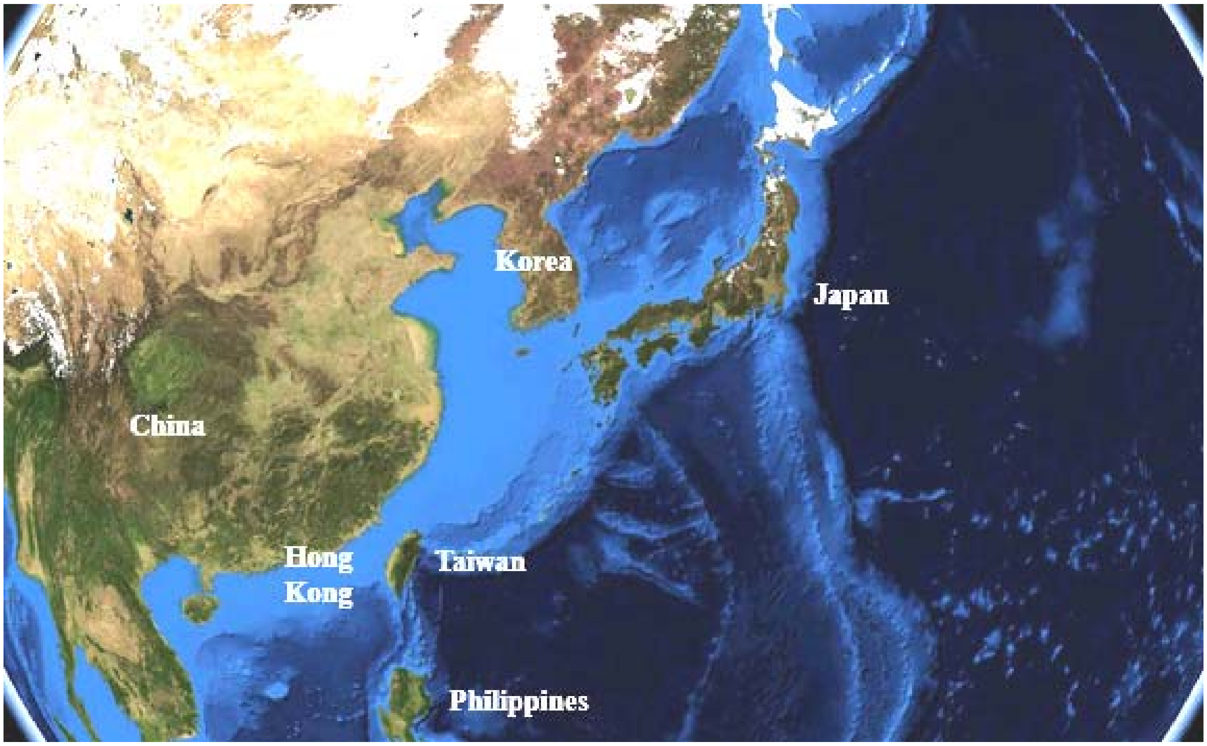


Oceanic-continental convergence

At the point where the plate starts to descend, the plate drags down the crust and produces a trench. If the trench does not collect much sediment, it may become quite deep, more than 3 miles (5 km) deep. Stratovolcanoes are sketched above the subducting slab. Each subducting slab becomes progressively hotter upon its descent. Eventually, it partially melts. The resulting magma rises to become stratovolcanoes like Mt. St. Helens. Indeed, stratovolcanoes like Mt. St. Helens may be found around virtually the entire rim of the Pacific, but there is a difference between the western and eastern rims of the Pacific. Let us go back to the composite sketch to see that difference.

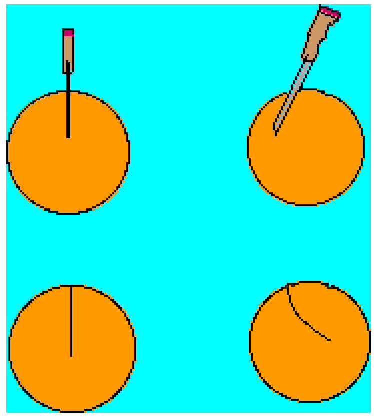


It is apparent that stratovolcanoes on the western side of the ocean form a series of arcuate islands like Japan and the Philippines. The tiny islands in southernmost Japan, stretching toward Taiwan, are particularly arcuate, as seen here.

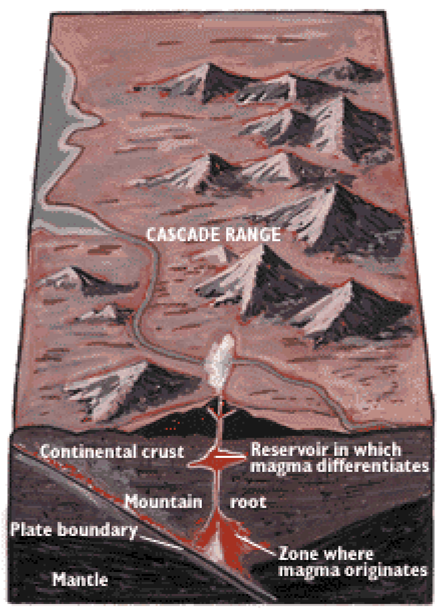


The northern Pacific also is bounded by a volcanic arc, the Aleutian islands of Alaska. The Aleutians are just one volcano after another.

All of these stratovolcanoes have formed due to partial melting of subducting lithosphere. The slab of lithosphere cuts down into the Earth. To understand why the chains of volcanic islands tend to be arcuate, one may think of a knife cutting down into an orange, as shown here. If the knife cuts straight down, the incision is straight. However, any other angle of cut produces an arcuate slice. Subducting slabs typically cut into the Earth at an angle of 45^o or less.



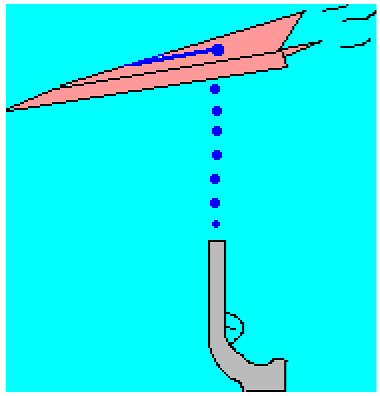
On the Pacific's eastern side, the stratovolcanoes sit on a continent, as in the Cascade Range of the Northwestern US. Here we see the Columbia River winding between Oregon and Washington State. All the illustrated mountains are volcanoes.



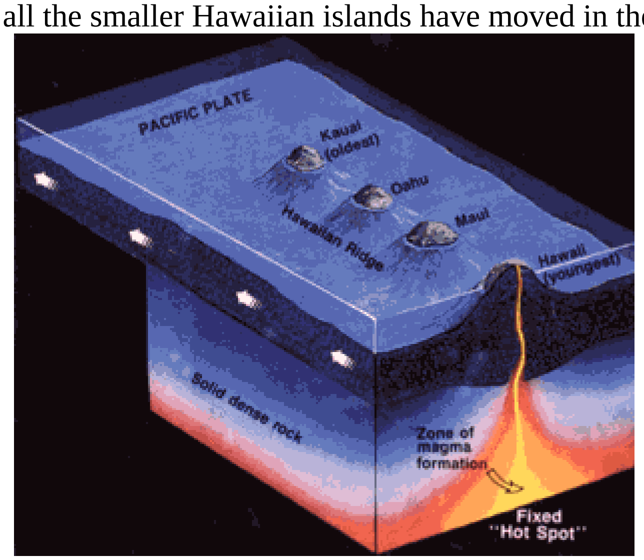
Janna: I drove from L.A. to Seattle last summer and the volcanoes of the Cascade Range were not as extensive as shown here in the U.S. Geological Survey sketch. They seemed more like widely-scattered pimples than a full-blown disease on Earth's skin.

Jordan: If one of those volcanoes had erupted during your roadtrip, it could have covered all of Oregon and Washington State with ash, making it seem more extensive.

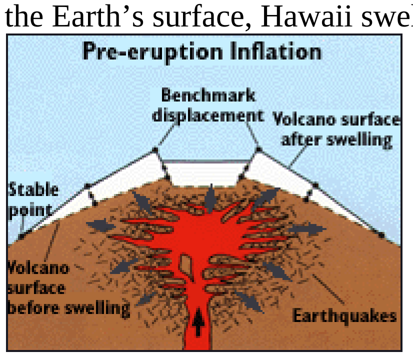
Prof. Bowles: Although the magma in stratovolcanoes arises from subducting slabs, the magma in Hawaiian-type volcanoes arises from a much deeper source, from deep within the mantle. Hawaii, Iceland, Samoa, Tahiti, and similar volcanoes are called shield volcanoes because they have gentle slopes, like a slightly curved shield. The mantle locations that generate the iron-rich, basaltic magma of shield volcanoes are called hot spots. Let us see what happens when the magma rises from a fixed hot spot to an overlying mobile lithospheric plate like that which includes the Hawaiian Islands. The trace of a water pistol on a paper airplane is analogous to the mantle's source region, shooting magma up to the Hawaiian Chain.



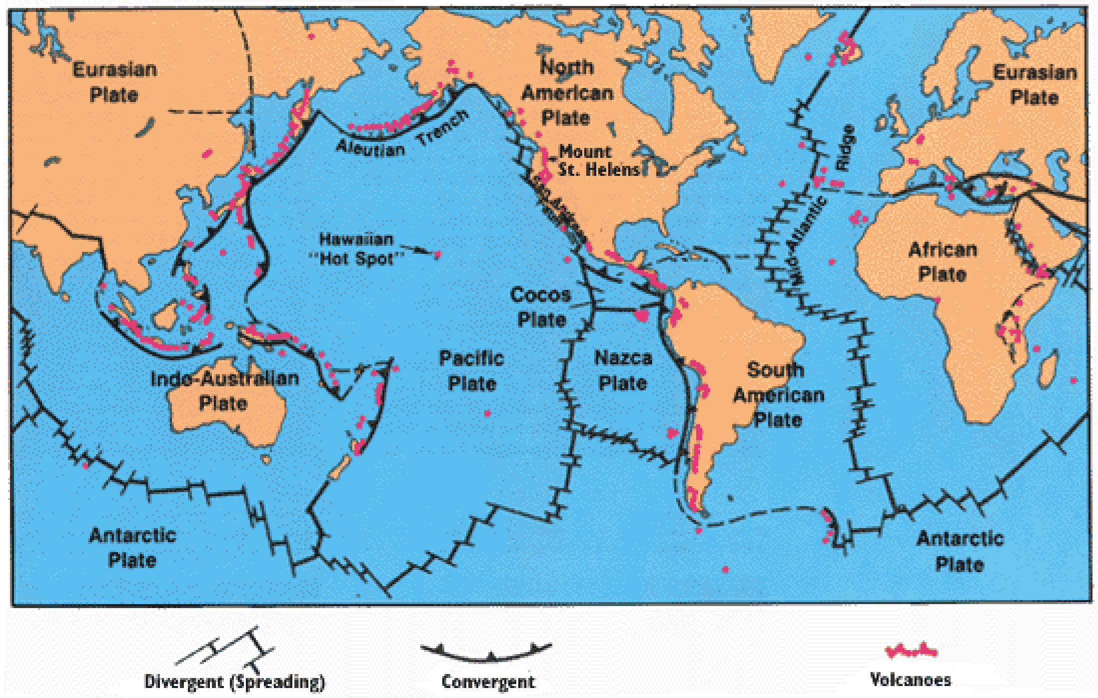
The moving lithospheric plate that includes the Hawaiian islands is not thick enough to extend down to the hot spot that is exporting magma to make those islands. One can see that the big island of Hawaii sits atop a hot spot but that the big island is moving off the magma pipe just as all the smaller Hawaiian islands have moved in the past.



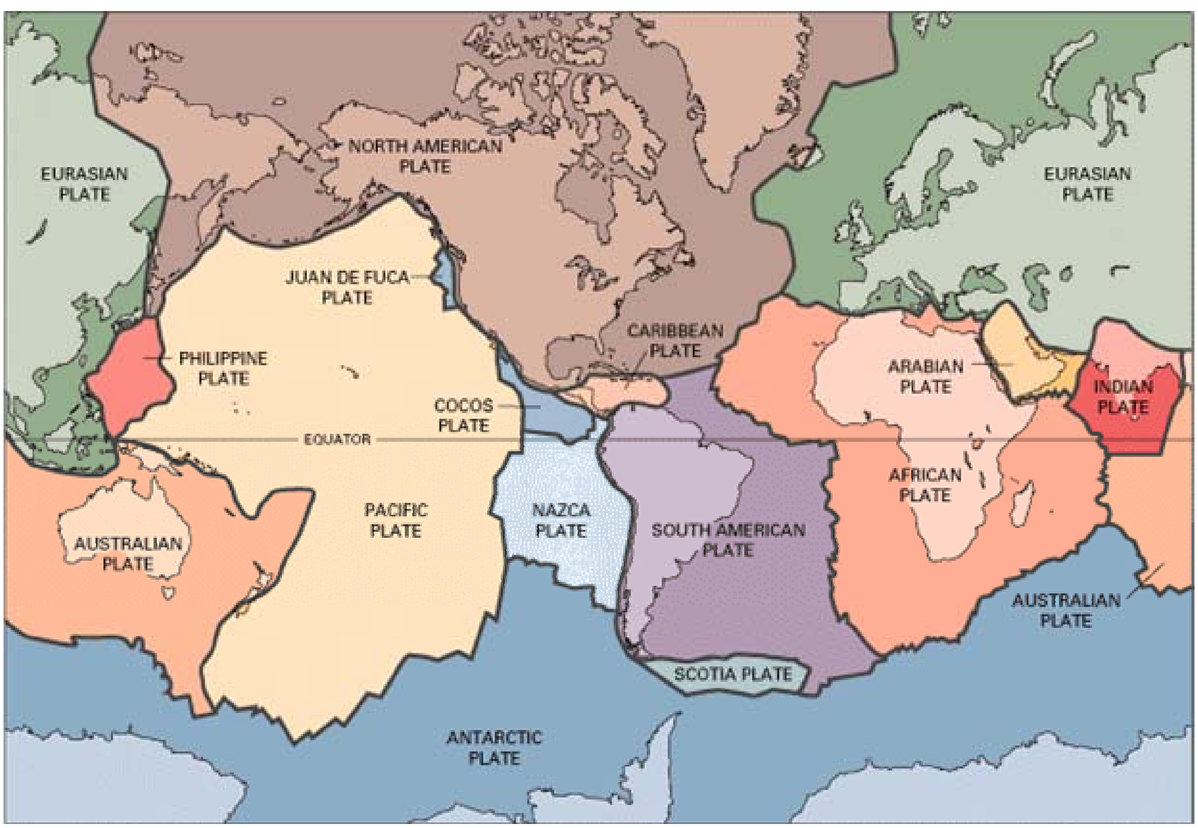
When the magma gets close to the Earth's surface, Hawaii swells slightly, like a balloon.



Hawaii is located near the center of the world's largest lithospheric plate, the Pacific Plate.



Perhaps this would be clearer if each plate were given a different color.



Unfortunately, both of these global-plate maps have severe distortions despite the fact that they can be found in any introductory oceanography or geology textbook. Although textbook maps are flat, we actually live on a spherical planet and it is impossible to flatten a spherical surface without distorting it.

Jordan: I have seen basketballs and soccer balls made from pieces of different shapes. I suppose that you could take each of those pieces and flatten them.

Janna: Yes, but each piece would wrinkle and there would be gaps between some pieces.

Prof. Bowles: The maps illustrated here use the popular Mercator projection to convert a spherical image to a flat image. The conversion starts by making a globe out of flexible rubber and then placing the globe snugly within a clear plastic cylinder, as shown here.

If air is pumped into the flexible globe, it will expand upward and downward against the walls of the cylinder but no expansion can occur around the equator. Given extreme pumping, the polar regions try to expand to the same circumference as the equator. Even though the poles are just unique points, they try to spread out to the equatorial dimension of nearly 25,000 miles (24,902 miles or 40,075 km).

Mercator maps of global plates never get very close to the poles because they would then start to look absurd. As it is, the Antarctic plate always looks huge on a Mercator map whereas it is really quite small. For example, the real area of Africa is more than twice that of Antarctica, but our map of colored plates makes Africa look smaller than just the coastal portion of Antarctica.

Jordan: Dr. Bowles, I think that I see a problem here. If you oceanographers cannot make a flat map of our spherical planet without distortions, then I suppose that nobody can make distortion-free blueprints of an oblong structure like a submarine. Am I right that blueprints are OK for flat walls in buildings but not for a curved object like a submarine?

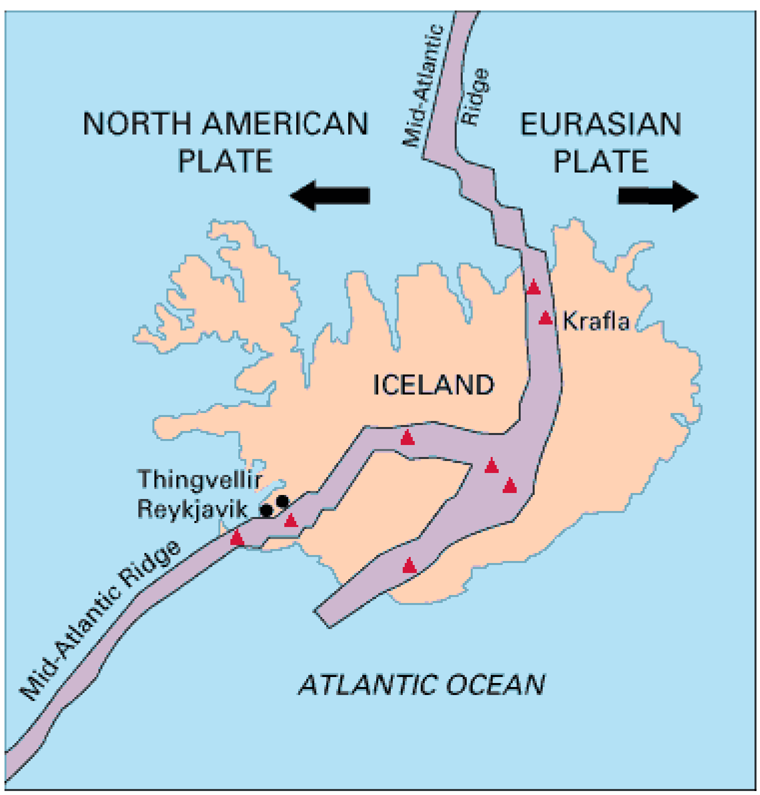
Prof. Bowles: Yes. Ideally, modern submarine plans are three-dimensional computer images. Why are you interested in submarine plans? I have heard of students building a yacht but never a submarine.

Janna: If we were the first students to build a long-range submarine, our lives would depend upon an exact fit and perfect seal between the submarine's components, so we certainly would not want any distortions.

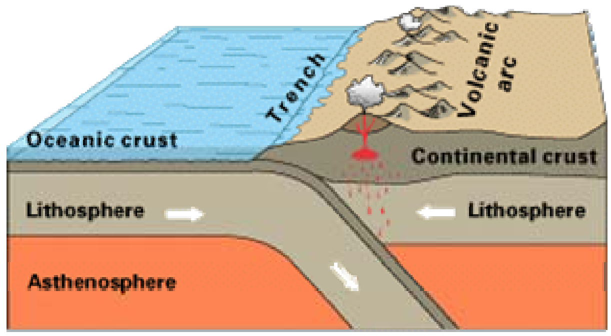
Jordan: Could you imagine a better way for students to test the theory of Plate Tectonics than tour the oceans in their own submarine?

Prof. Bowles: If you have that kind of money, I should raise my lecture fee. However, you guys are more entertaining than anything I could buy with the extra money so I will just stick around for the show. A divergent margin like the Mid-Atlantic Ridge tends to pull the crust apart, forming what is called a rift valley. Here we see one of the few places on Earth where a divergent margin crosses the land. This is a rift valley that runs through Iceland. The North American plate lies on one side of the valley and the European plate on the other. Footprints within the mud of the valley provide a scale.

Unless you are one of the 300,000 Icelanders, you do not live near a mid-oceanic ridge.



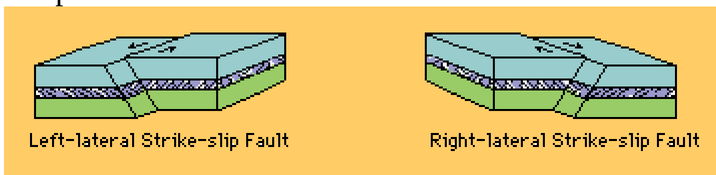
However, more than a billion people live near a subduction zone around the Pacific, so we should take another look at that region. Another name for a subduction zone is a zone of convergence. The example shown here involves a convergence between oceanic and continental lithosphere. Both types of lithosphere are moving over the asthenosphere. The asthenosphere means "weak sphere" because it contains a small proportion of magma, just enough to weaken the rock and allow it to deform. For the rigid lithosphere to move over it, the asthenosphere must suffer deformation.



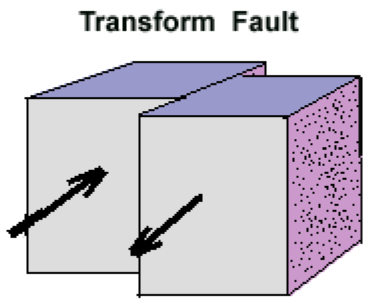
Oceanic-continental convergence

Jordan: The "astheno-" prefix must come from the Greek.
Janna: Yes, and that Greek word has become "ethics" in English.
Jordan: Cute. I cannot wait to tell our Engineering Ethics instructor that his subject matter is weak.
Prof. Bowles: Convergent margins are a type of active margin. Another type of active margin is a transform-fault margin. The world's most famous transform fault is the San Andreas, a fault that extends through most of California's coastal zone.

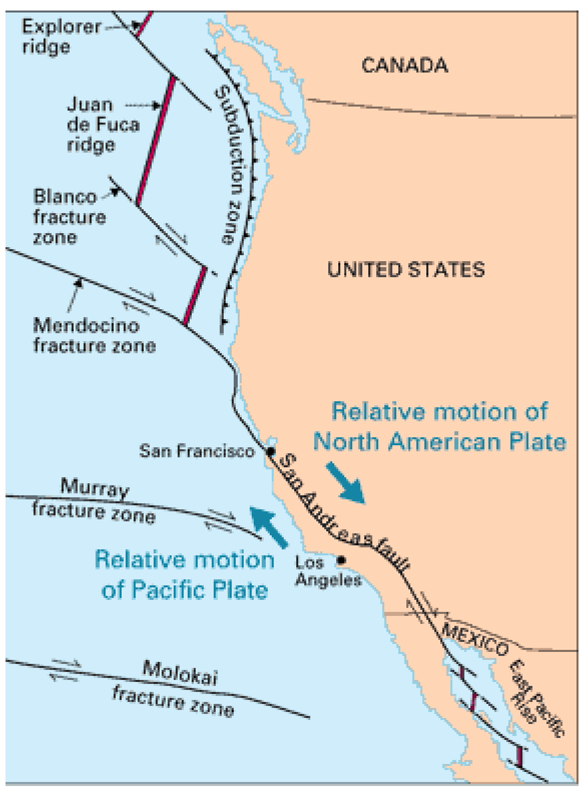
Transform faults involve a sideways motion. In a block diagram, one can see alternate types of transform faults, specifically right-lateral and left-lateral types. If you look across the fault plane, the other side is either moving to your right or to your left. With a right-lateral transform fault, the other side is moving to your right, no matter which way you choose to look across the fault plane.



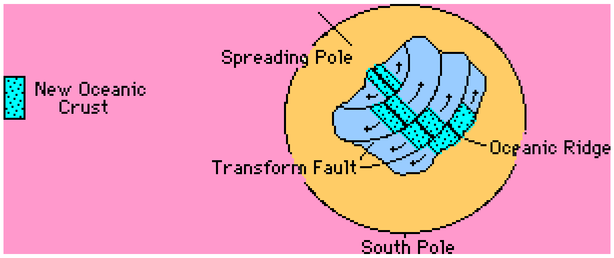
The San Andreas has a right-lateral motion, made clearer in this block diagram.



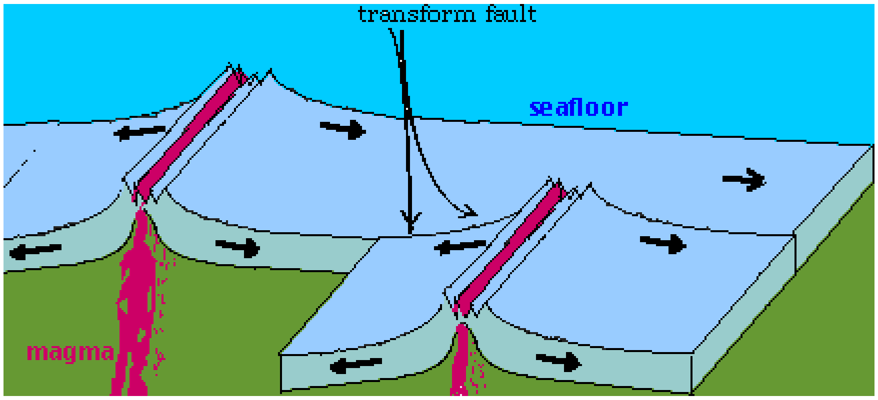
The San Andreas is just one of a series of transform faults that repeatedly offset the dominant divergent margin in the Pacific, the so-called East Pacific Rise.



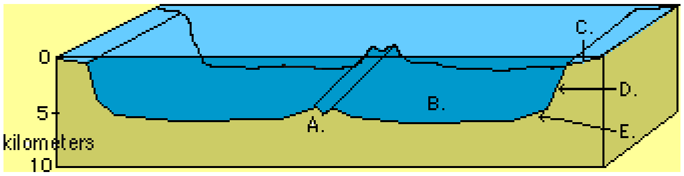
The occurrence of transform faults is not accidental. They are an essential feature of plate motion on a spherical planet. This is because each plate must have a pole of rotation, just as planet Earth has a pole of rotation, and the velocity of rotation must increase away from that pole. We just noted that the Earth's circumference is nearly 25,000 miles (40,000 km). Equatorial residents have to be traveling over a thousand miles an hour (1660 kph) to cover that distance in a day whereas polar residents are essentially stationary. Everybody between the equator and a pole is traveling some intermediary velocity. The velocity of a lithospheric plate typically reaches a maximum at the maximum distance from that plate's pole of rotation. However, lithospheric plates are composed of solid rock, so they must have transform faults to separate portions that are traveling at different velocities, as shown here.



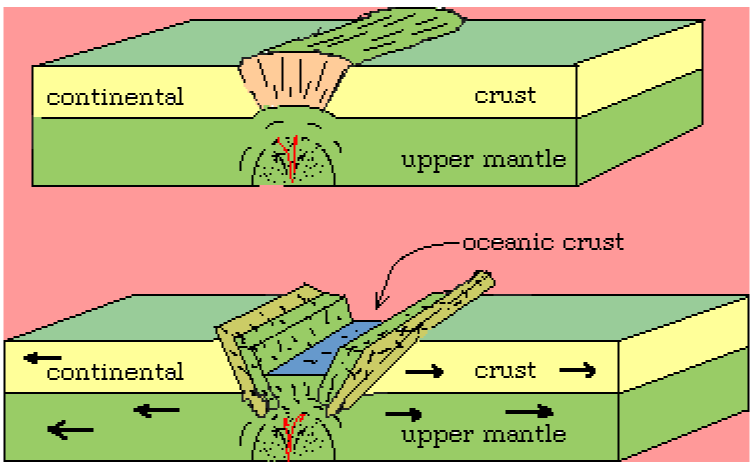
A divergent margin that is offset by a transform fault looks something like this.



Although Plate Tectonics is working overtime in the Pacific, its less vigorous activity in the Atlantic still merits our attention. Besides, that is where most of us live. The edge of the Atlantic generally lacks earthquakes or volcanoes, so it is called a passive margin. Volcanic activity does occur in the middle of the Atlantic, as seen in Iceland, so a cross-section across the ocean basin looks like the textbook sketch shown here.



Jordan: Although every textbook shows this simple cross-section for the Atlantic Basin, something tells me that we will find the seafloor topography to be much more complicated when we get out there with our submarine.
Janna: After finding the topography of the Pacific Northwest to differ from the textbook sketch, I am inclined to agree with you. However, textbooks are more interested in simplicity than accuracy, so I doubt if our observations will ever be published.
Prof. Bowles: A divergent margin extends along the middle of the Atlantic basin. It stands high because mantle magma rises here and solidifies to become seafloor basalt. As the oceanic lithosphere moves away from the spreading center in both directions, it cools and sinks to become the abyssal plain.
Heading seaward from the shore in a passive margin like the Atlantic, one usually finds shallow water extending far out to sea. One may anticipate a water depth less than 100 yards (m) for at least 30 miles (50 km). This platform is essentially flat and is called a continental shelf. The water depth suddenly increases at the shelf break and one passes to the continental slope. As the continental slope flattens out, one reaches the continental rise. This topography is a product of the Plate Tectonic origin of an ocean basin like the Atlantic. Let us look at Harry Hess' seminal explanation of seafloor spreading back in 1962.



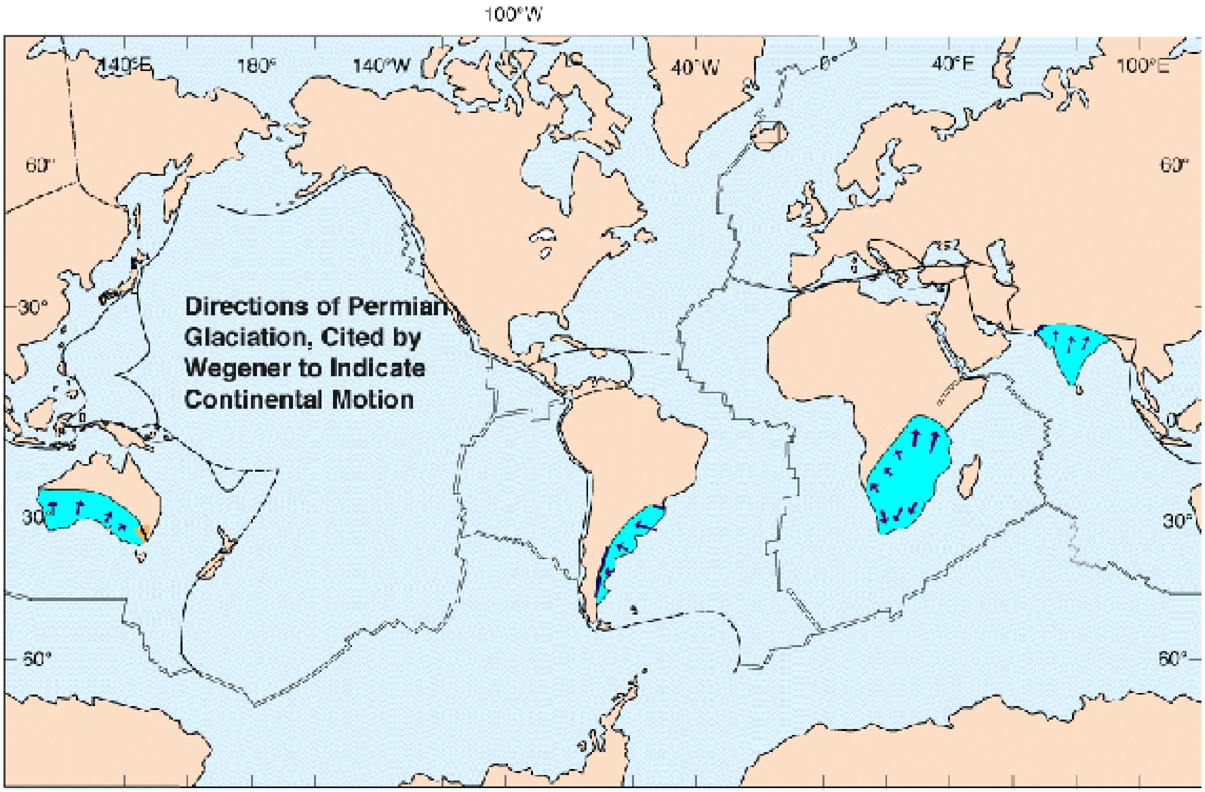
The irony of Hess' explanation is that a great depression like an ocean basin initially is an uplifted region because a rising mantle plume is needed to start a divergent margin. Once started, it may continue for hundreds of millions of years, as exemplified by the Atlantic.
It took a couple of years before Hess' concept became popular. By that time, many geologists were rereading an old publication by a German meteorologist, Alfred Wegener. In 1915, Wegener put down his pipe and wrote a paper entitled, "The Origin of Continents and Oceans".

Unlike the vast majority of other scientists, Wegener did not limit himself to just one branch of science but collected evidence from all the sciences. Here he explains his methodology, "Scientists still do not appear to understand sufficiently that all earth sciences must contribute evidence toward unveiling the state of our planet in earlier times, and that the truth of the matter can only be reached by combing all this evidence. . . It is only by combing the information furnished by all the earth sciences that we can hope to determine 'truth' here, that is to say, to find the picture that sets out all the known facts in the best arrangement and that therefore has the highest degree of probability. Further, we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw."

Jordan: I can see why Ph.D. stands for “Doctor of Philosophy”. Wegener is writing like the ancient Greeks here.

Janna: A century ago, in Wegener’s time, Ph.D. studies apparently were different than today. Wegener is implying here that students were expected to be multidisciplinary whereas modern graduate students become highly focused.

Dr. Bowles: Wegener’s own field of meteorology had been shaken a few decades earlier by the discovery that huge glaciers had repeatedly advanced and melted back throughout recent geologic history and that an earlier glacial time had existed before the dinosaurs appeared on Earth. Wegener knew that glaciers drag pebbles over exposed rock, leaving scratches that record their direction of motion, so he compared the ancient glacial directions to the modern configuration of continents. He found that the continents must have moved since the time of this ancient glaciation. For example, southern Africa must have been much closer to the South Pole to have been a source area for glaciers. Wegener also found that four nonmarine fossils had habitat ranges which extended across modern oceans. Hence, the modern oceans have opened since the time when these pre-dinosaurian animals and plants lived.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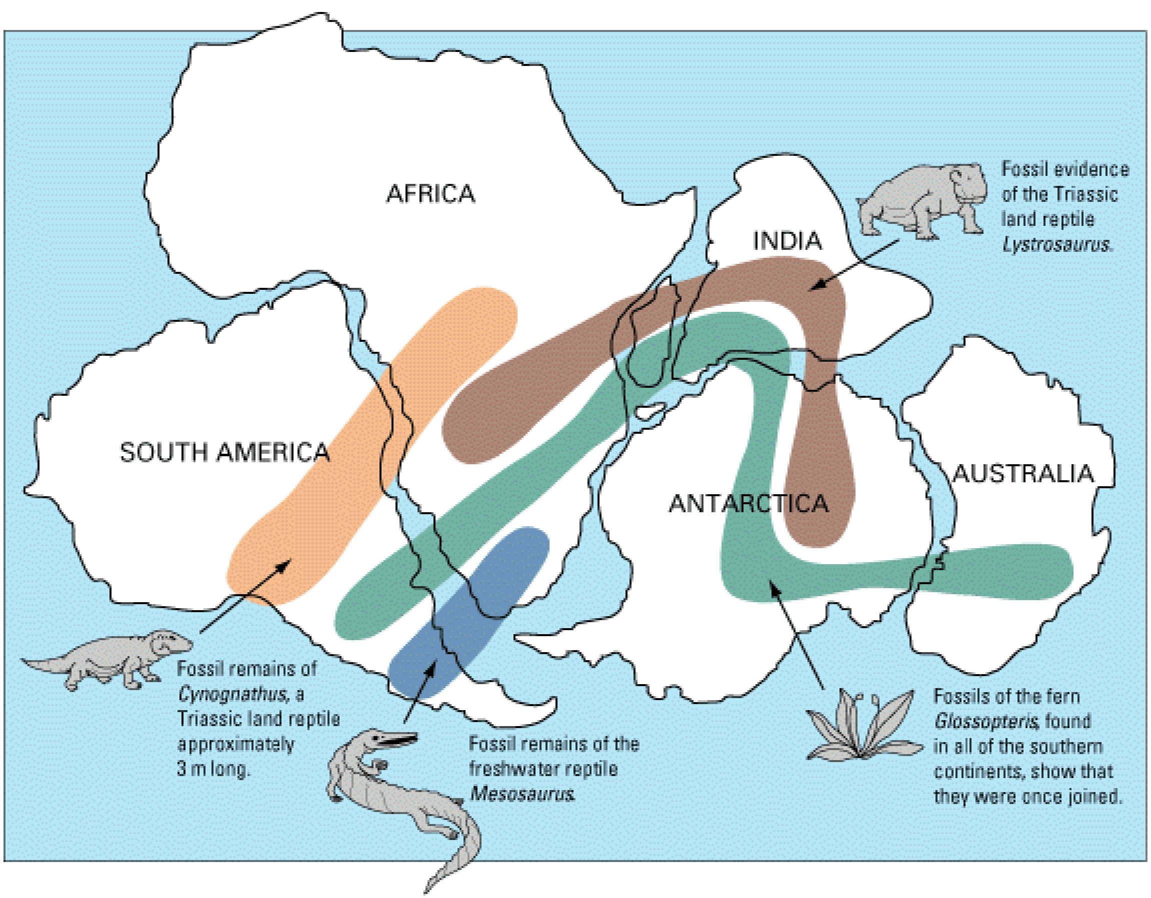
Directions of Permian Glaciation, Cited by Wegener to Indicate Continental Motion


AFRICA
INDIA
SOUTH AMERICA
ANTARCTICA
AUSTRALIA
Fossil evidence of the Triassic land reptile *Lystrosaurus.*
Fossil remains of *Cynognathus*, a Triassic land reptile approximately 3 m long.
Fossil remains of the freshwater reptile *Mesosaurus.*
Fossils of the fern *Glossopteris*, found in all of the southern continents, show that they were once joined.

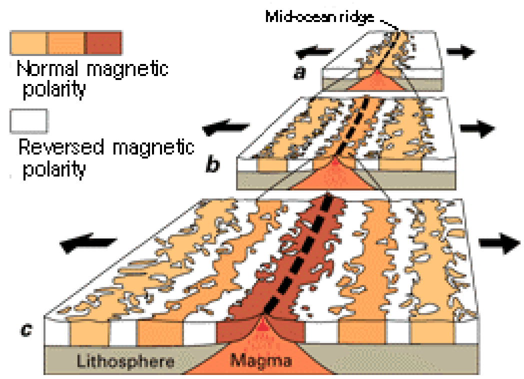
By studying paleontology, Wegener was not only following his own advice of collecting evidence from every relevant science, he was giving a nod to the reigning science of his day. A century ago, paleontology was vastly more popular than it is today because anyone could find a new fossil and name it after themselves, thereby getting their name into print forever. Paleontological societies existed in towns and cities all over the world, producing a wealth of published material. Wegener could confidently state that his four index fossils, Glossopteris, Mesosaurus, Lystrosaurus, and Cynognathus, had ranged through the sketched areas and that they could not have propagated across an ocean. The one animal that could swim, Mesosaurus, was restricted to fresh water.

Jordan: Now I know why I have studied engineering instead of paleontology. I cannot handle all those syllables in name-after-name, even if the names all end in the letter, s.

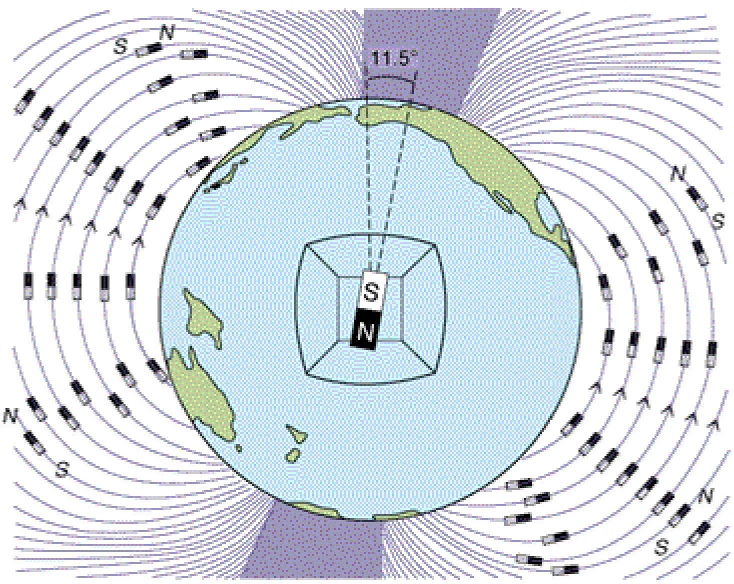
Janna: Actually, you would have been a good paleontologist because you are so driven that you would have found the world's single remaining *T. rex* fossil, even if you had to scour the globe to do so.

Prof. Bowles: Wegener's concepts achieved some acceptance in parts of his native Europe but America was openly hostile to drifting continents until the early 1960's. Wegener did not have a viable mechanism for moving continents. However, Harry Hess of Princeton provided that mechanism in 1962 when he proposed seafloor spreading. Hess had commanded an attack transport ship in the Pacific during World War II and had collected thousands of miles of depth soundings, thereby discovering the East Pacific Rise.

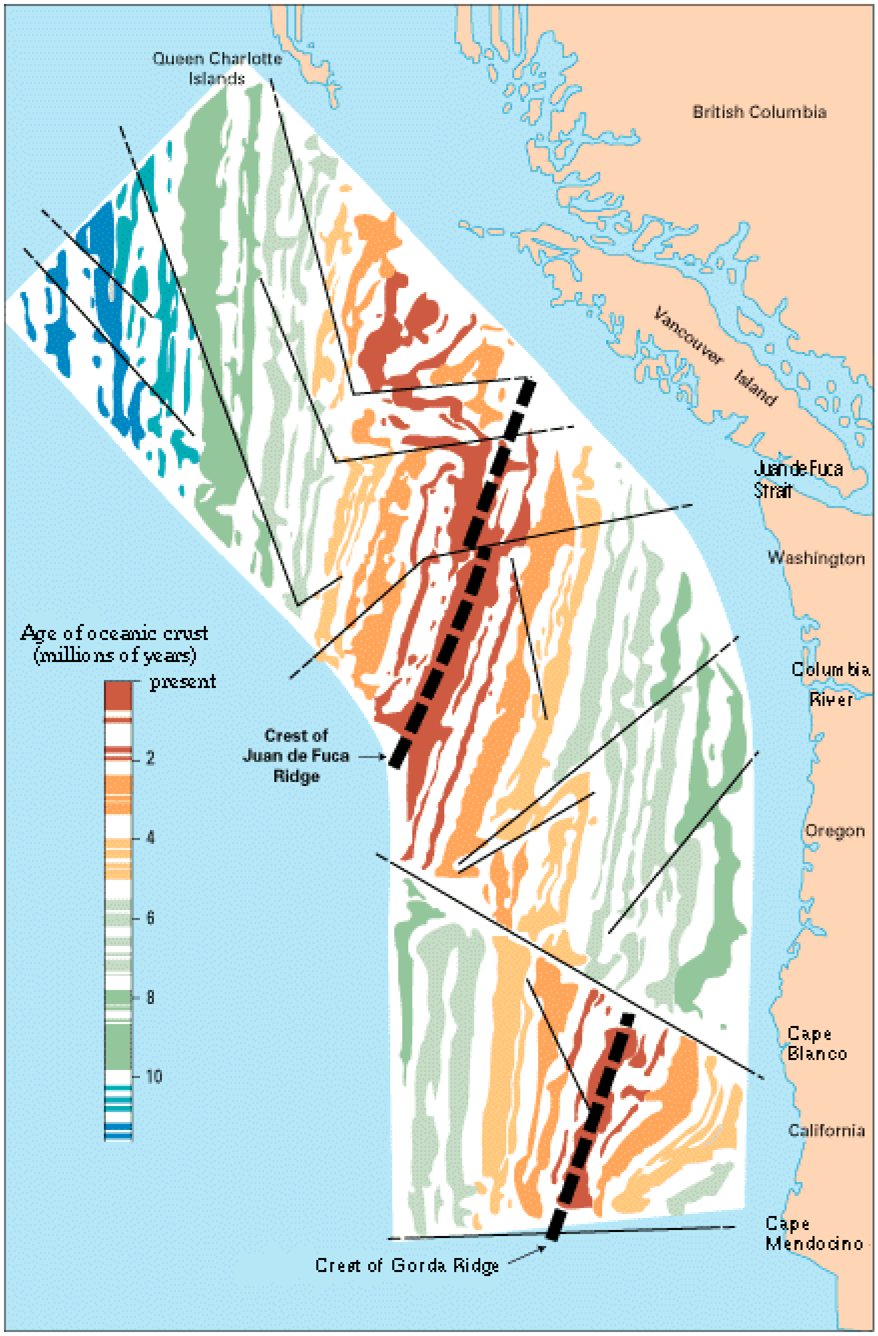
Hess' model was quickly shown to be consistent with seafloor magnetic data. Peculiar magnetic stripes had been recently mapped in the seafloor off the Northwestern US.



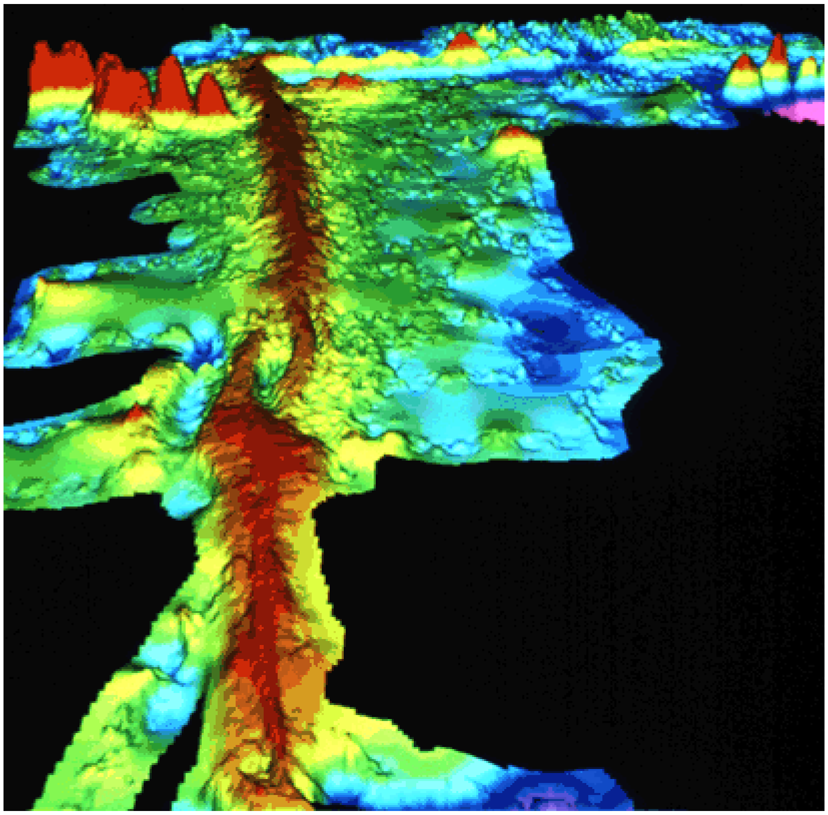
These stripes became interpreted to represent an alternation in Earth's magnetic polarity, with the magnetic north pole flipping with respect to the magnetic south pole.



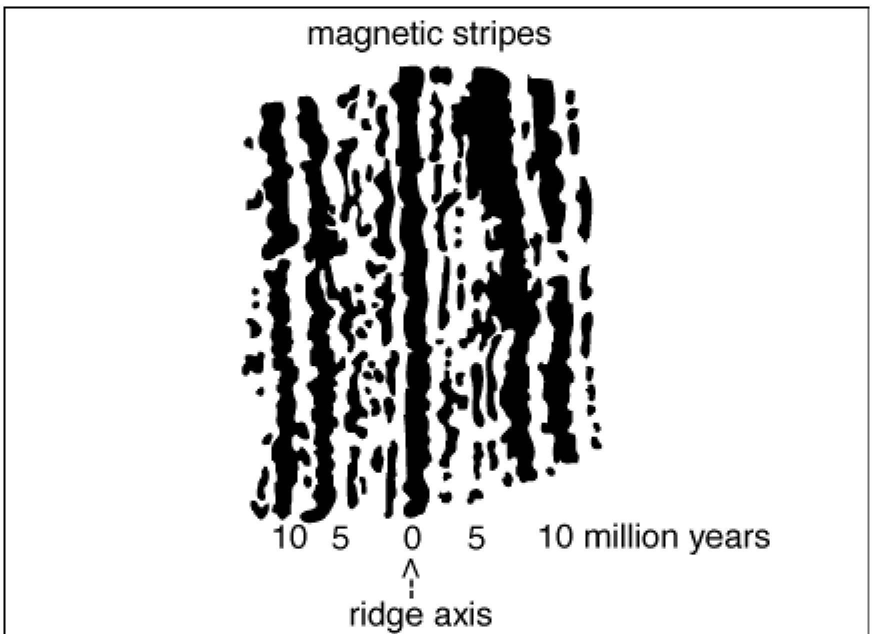
Within Hess' model, magma rises along a mid-oceanic ridge and solidifies to become oceanic crust. Here is the raw data that provided early confirmation for Hess' model. The ridge is marked by bold dashes. The age of the oceanic crust increases away from the ridge, as shown by the legend. A left-lateral transform fault has offset the ridge off Cape Blanco.



The Northwestern US is geologically active, so there are several faults that disrupt the magnetic stripes. Most textbooks therefore publish the simpler stripes that occur south of Iceland. Let us first examine a computer image based on a composite of topographic data for the area south of Iceland.



You may recall that the Mid-Atlantic Ridge crosses Iceland north-south, so the stripes shown here straddle that ridge with a north-south orientation.



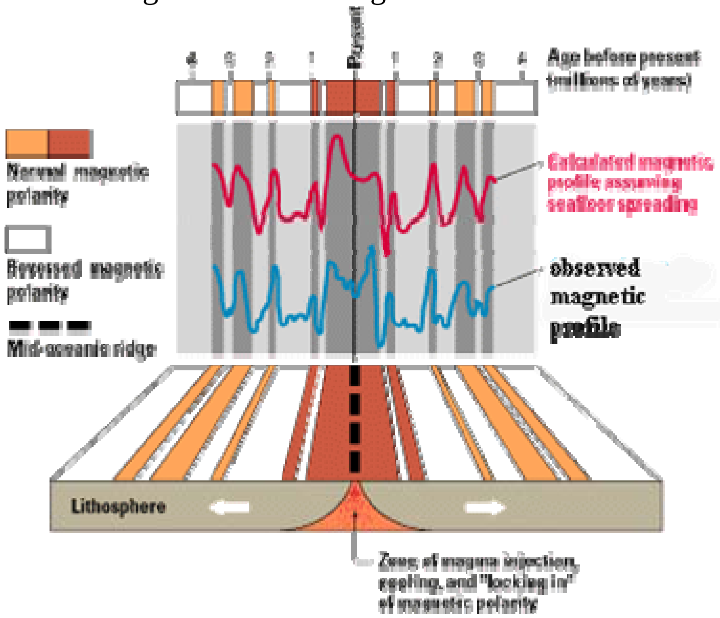
Pattern created by magnetic stripes along the Mid-Atlantic Ridge south of Iceland.

Jordan: This sketch does look convincing but I worry about artifacts in data collection. Plate Tectonics hinges on these stripes, so I think we should head to this area south of Iceland.

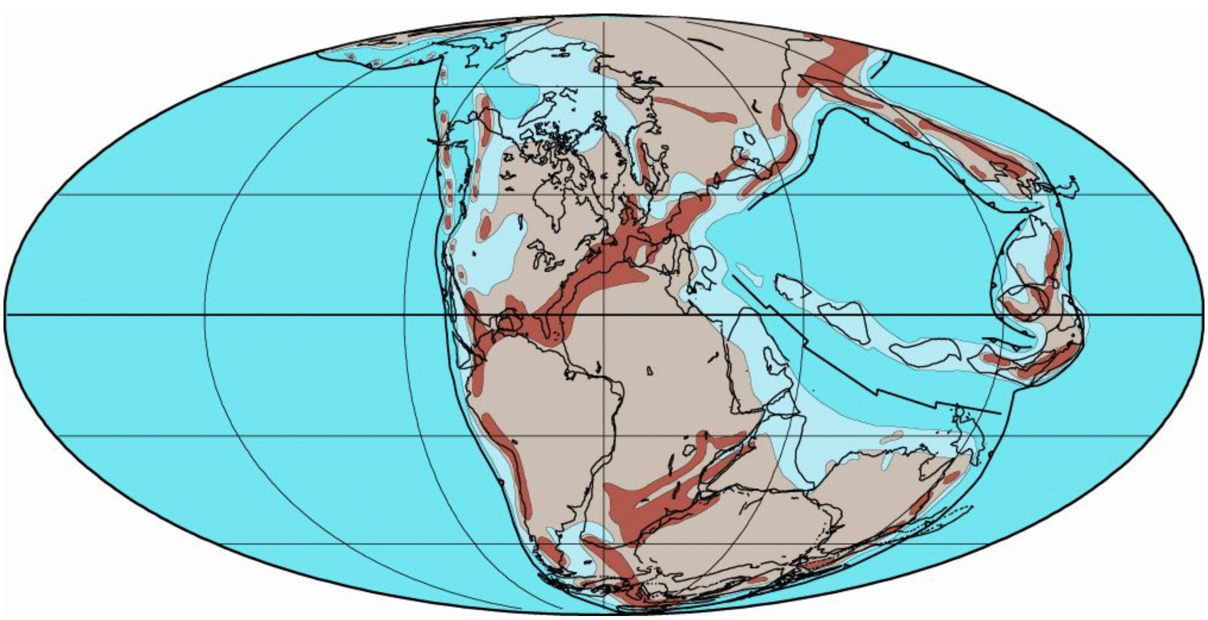
Janna: Does this mean that we will have a magnetometer on board?

Jordan: You always see beachcombers with a magnetometer, so we should take one too.

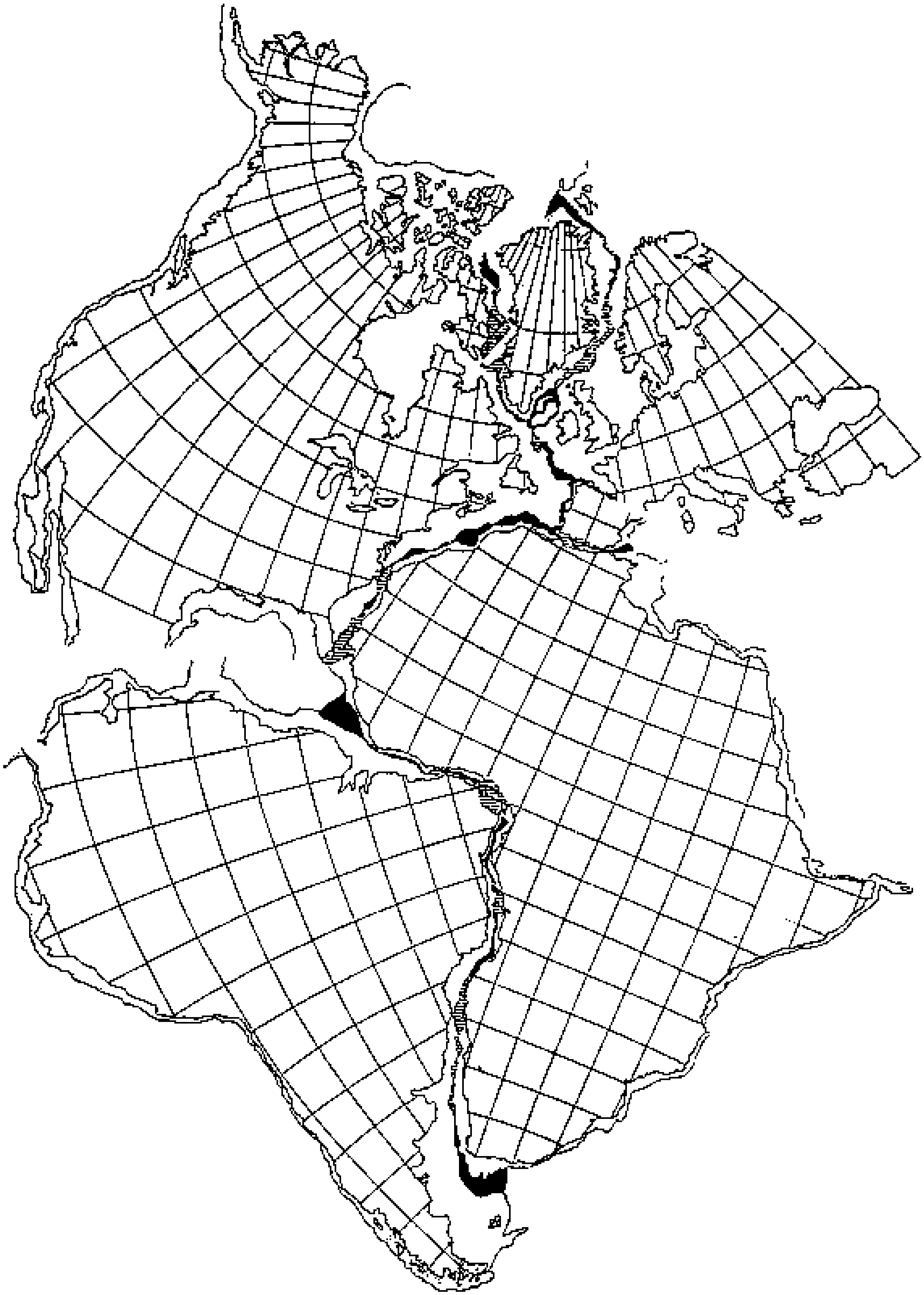
Prof. Bowles: Let us review how the stripes are made. Magma rises and congeals to become basalt. Magnetite is the most magnetic common mineral in the basalt. Upon cooling, magnetite acquires the Earth's magnetic field and retains that initial imprint, even after Earth's field flips. Although the stripes look neat in the following image, the original data is not. Mother Nature garbles her messages and we have to do a lot of translation.



Of course, none of this magnetic data was available to Wegener. To him and his predecessors, the most obvious evidence in favor of mobile continents was the matching outline of adjacent continents, as shown here.



The fit across the Atlantic was noted with production of the first accurate map, in the 1600's.



Here is an expanded view of that amazing match, including North America. So, are you two guys convinced about Plate Tectonics? Have I convinced you to build a less expensive combination of car-plus-home than a submarine?

Jordan: And be like the other six billion people on Earth?

Janna: Jordan is definitely unique and she is determined to prove that fact by traveling underwater, going glub-glub in her submerged homely car.

Prof. Bowles: Of the twenty thousand students who have taken introductory oceanography from me, I must admit that you are the first to try building a submarine. I hope that my lectures do not tempt you to do anything foolish. Submarines are just as dangerous as aircraft. At least your sub will not have the added danger of being nuclear, like the one where I served while a junior officer.

Jordan: Of course not, sir.

Janna: We are really enjoying your presentations and look forward to seeing some of those oceanographic features first-hand as we circumnavigate the world.

Prof. Bowles: Circumnavigate the world? Your submarine would have to cost several million dollars.

Jordan: I do not want to offend anyone in the teaching profession but there are other professions which bring in substantially more money.

Prof. Bowles: You can say that again. About all that we professors have to look forward to is the possibility that somebody might endow a University professorship in our name. That would cost about as much as your submarine.

Janna: We would be honored to help endow a chair in your name, Professor Bowles. We have found a rich sponsor for our submarine project and that sponsor may well endow your chair if you occasionally help us identify what we see with our submarine. Have you switched to a computer-based telephone system at home?

Prof. Bowles: Indeed I have, so I can make free phone calls through my wireless computer system. However, it looks as if it will be a long time before you launch your sub. In the meantime, you might want to learn more oceanography. How far along have we gotten in the lectures?

Janna: We had just finished looking at the matching outlines of North America, South America, and Africa.

Prof. Bowles: Yes; those interlocking outlines were first noted in 1620 by the English philosopher, Francis Bacon. Bacon's early work on continental separation was more successful than his subsequent experiment using snow as a preservative for meat. Handling too much snow gave him pneumonia and that killed him.

Janna: Living in a submarine is a good way to avoid snowfall.

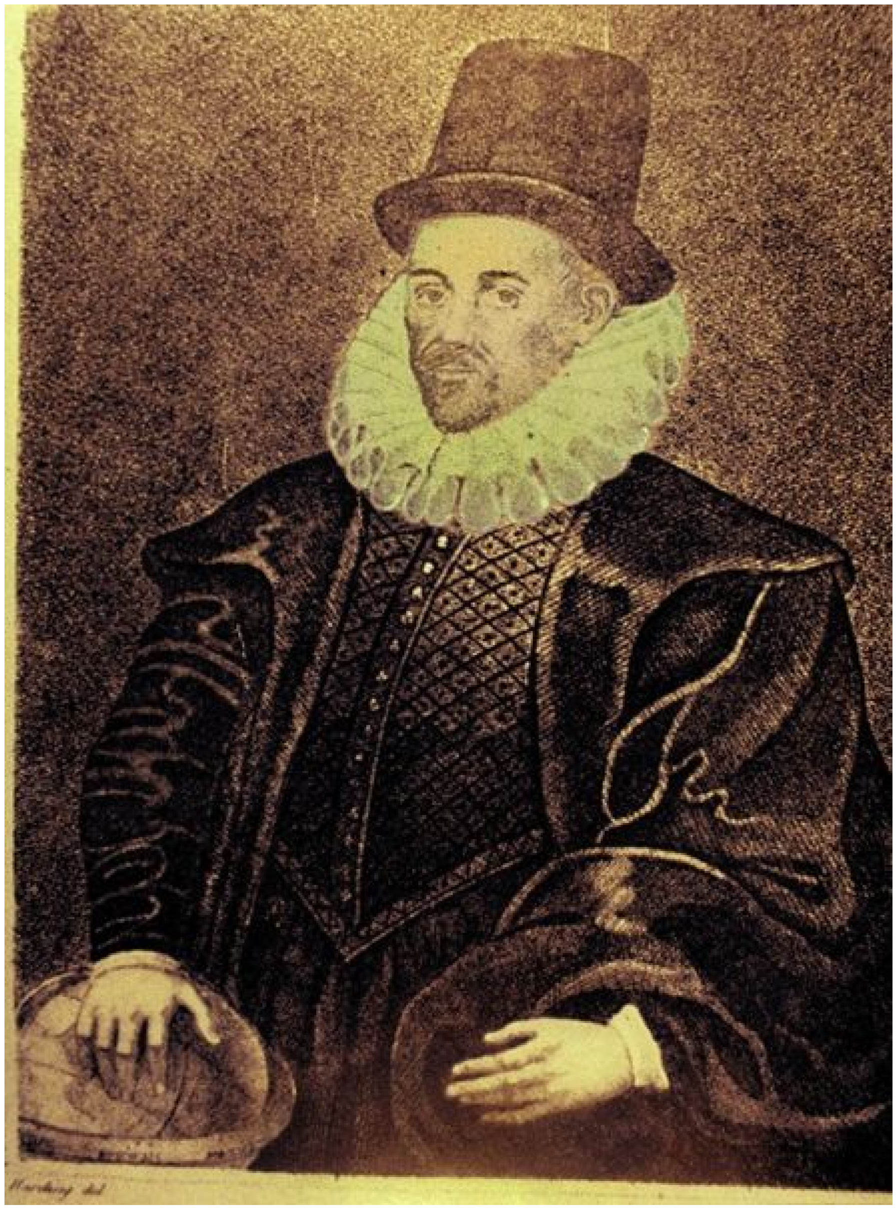
Prof. Bowles: A submarine may be a "no snow" zone but in that cramped space it can never be a "no show" zone.

Jordan: Janna and I have been roommates in college so this is going to be like one long TV night, watching Gray's Anatomy.

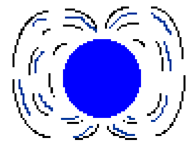
Prof. Bowles: You are going for a full year? Trust me. The TV show will not keep your attention that long. You may call me at any time, but do remember that I am Dr. Bowles, not Dr. Phil.

Janna: Thanks for being so cooperative. It means a lot to us that you would take some interest in our project.

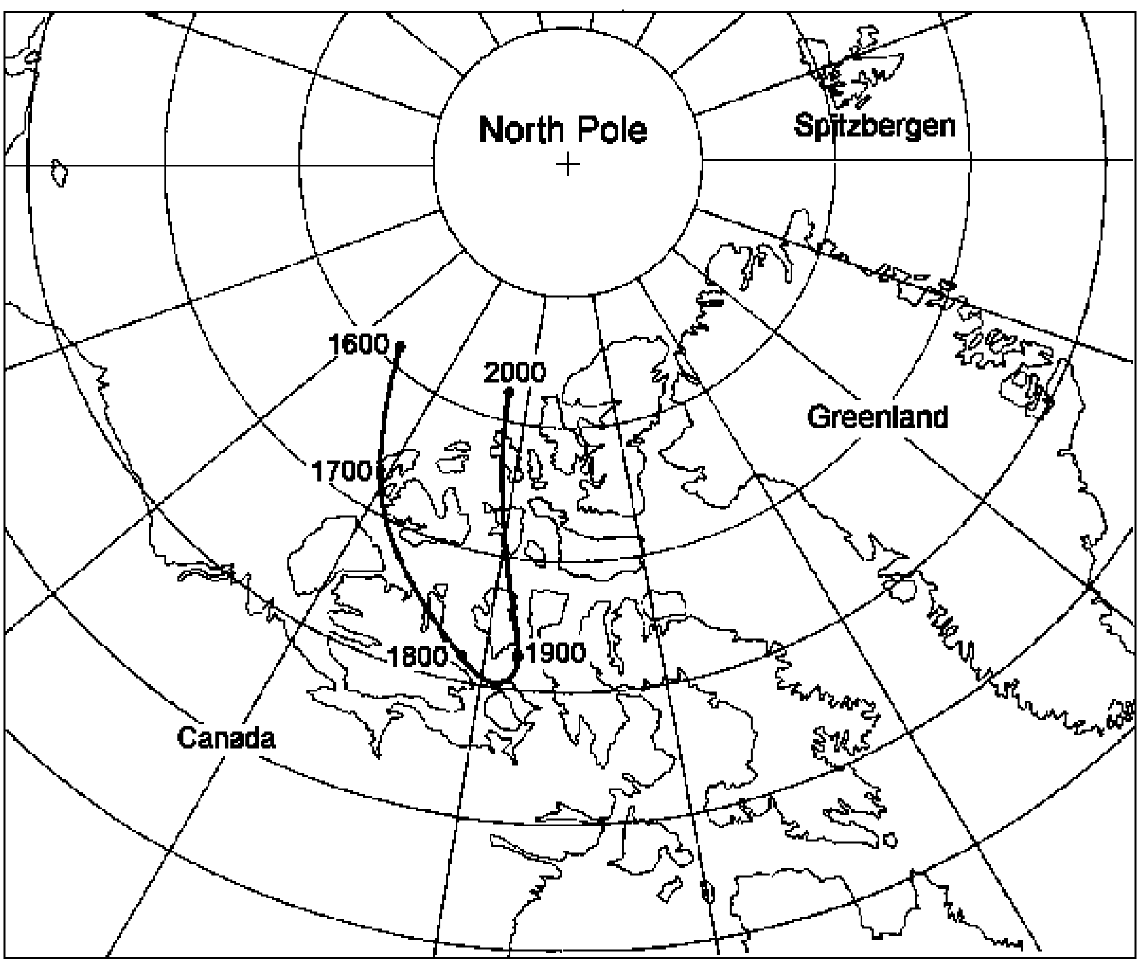
Prof. Bowles: Are you kidding? You guys are fun. You should be on TV.
Jordan: Yes. Somebody has already thought of that.
Prof. Bowles: Given that magnetic data is the prime modern evidence for Plate Tectonics, let's consider the Earth's magnetic field. We will start with Sir William Gilbert, a contemporary of Francis Bacon and physician for Queen Elizabeth the First.



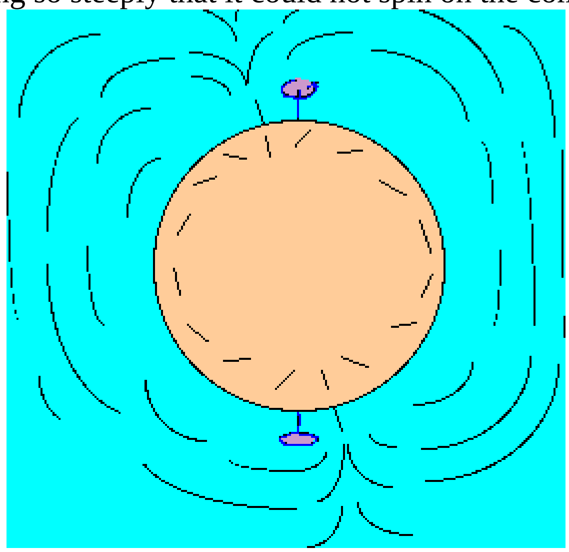
Sir William Gilbert was the first to understand that the Earth's magnetic field resembles the field of a bar magnet, so the Earth's magnetic poles may be located by finding where the magnetic field is perpendicular with respect to the Earth's surface, as shown here.



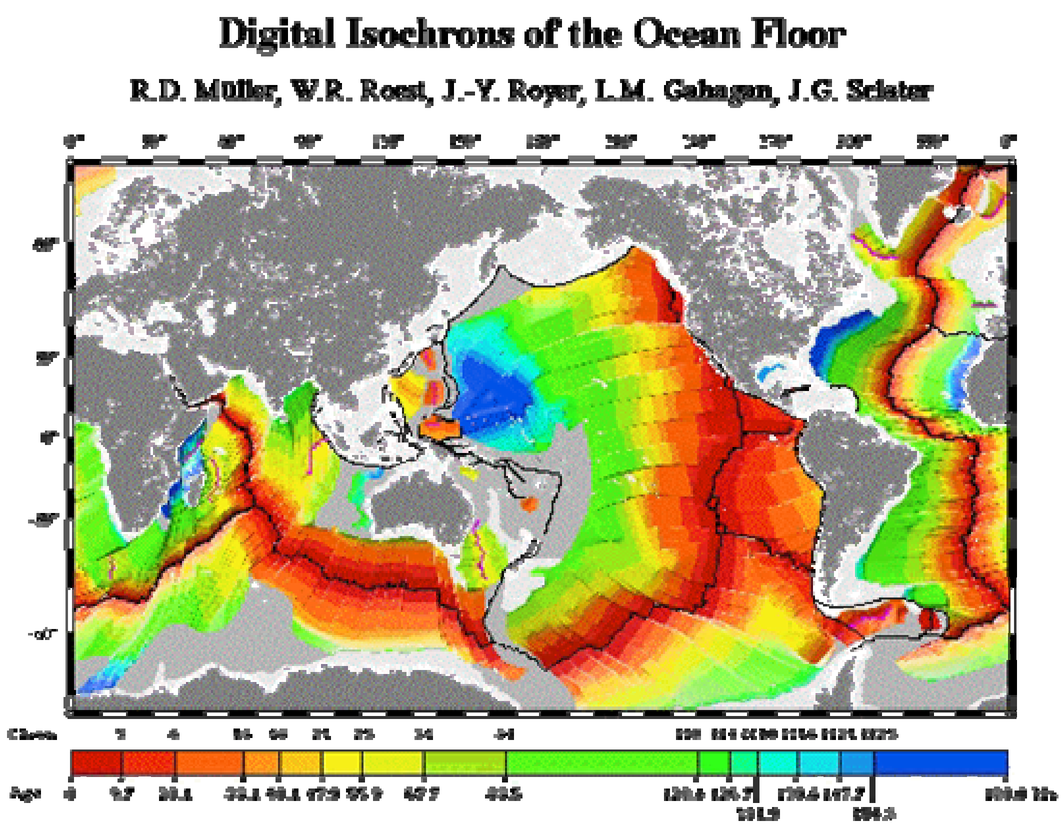
Our magnetic poles do not coincide with our poles of planetary rotation but they do dance around those poles of rotation, as became evident in the century following Gilbert and Elizabeth I. The magnetic compass was the mainstay of marine navigation from the time of its invention by the Chinese around 1090 A.D. until the GPS satellite system became operational in 1994. Nonetheless, continual movement of the north magnetic pole has complicated navigation. Here is the path since 1600, compliments of the University of Tromso in Norway. As you can see, the pole has increased its velocity of migration through the past century, now traveling at 7 mph (11 kph). Some scientists fear that this increase might herald a flipping of the poles. Although the flipping is handy for tracking Plate Tectonics, the Earth's magnetic field would have to turn off, at least briefly, during this transition and that would allow harmful radiation from Outer Space to reach us here on the Earth's surface. Consequently, nobody wants the magnetic field to flip any time soon.



Given the offset of Earth's magnetic field from its pole of rotation, a proper sketch of Earth's field differs from the tiny drawing shown above, and is better represented by the following sketch. Just within the Earth's surface, one can see a series of bars that record the inclination of a compass needle at that latitude. Only at the equator is the compass needle flat, parallel to the Earth's surface. Near either pole, a compass cannot work because its needle would be dipping so steeply that it could not spin on the compass' pivot point.



Besides the magnetic data, we have data on sediment ages that corresponds to plate motion. As expected, the age of oceanic crust increases progressively away from the mid-oceanic ridges. In the chart here, an "isochron" is a fancy way of saying an age range, given that "iso" is a Greek prefix meaning "the same" and chron refers to time, as in those expensive watches that are called chronometers when they are really just watches.

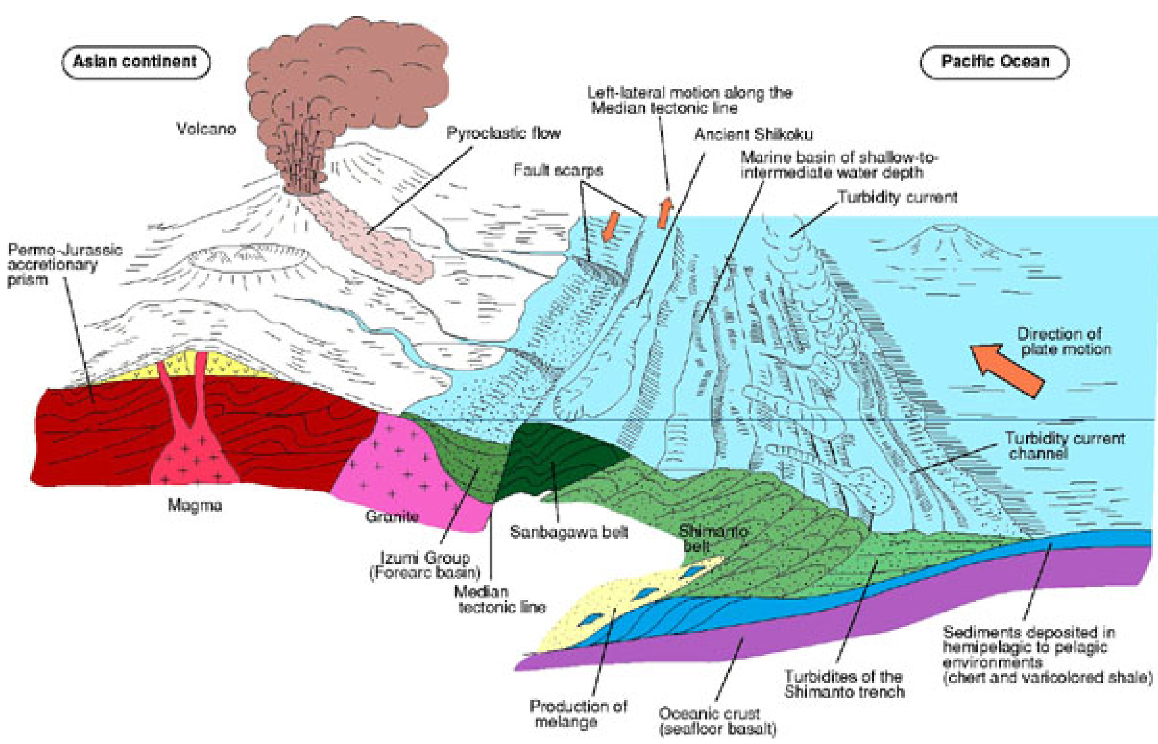


Jordan: Hey, my dad's Rolex Chronometer set him back about $5000. Fortunately, he only had to work a couple of days to pay for that watch.

Janna: It only took my dad one day to pay for his watch, but it is a Timex.

Prof. Bowles: The farthest distance that the seafloor spreads away from any divergent margin occurs in the Pacific, across the entire width of the Pacific Ocean from Baja California to the Philippines. Consequently, it is not surprising that the world's oldest oceanic crust, 180 million years old, occurs off the Philippines. In contrast, most continental rocks are much older than 180 million years, as old as 4000 million years in northern Canada. The continents probably represent the remnants of ancient subductions during which some low-density rock was scraped off and accumulated to form masses that are too light-weight to be subducted.

Here is a more complicated view of subduction, based on the historic subduction of the Pacific Plate under Japan. Unlike most simple sketches of subduction, the Pacific Plate is colliding at a shallow angle and this is creating a left-lateral transform fault close to shore. Distinct rock bodies are sliding along that fault. Submarine landslides are partially filling the trench from the landward side and a seamount is headed into the trench from the oceanward side. The lower-density rocks at the top of this seamount are likely to become scraped off and accumulate with all the highly-deformed sedimentary rocks along the continental side of the trench. This accretion of lower-density material onto the continent is an example of how the continents initially grew, long ago. The accretion process should have been more vigorous on the early Earth because Plate Tectonics is driven by convection in the mantle. Higher temperatures in a more radioactive lower mantle would have induced faster convection upward toward the Earth's surface.



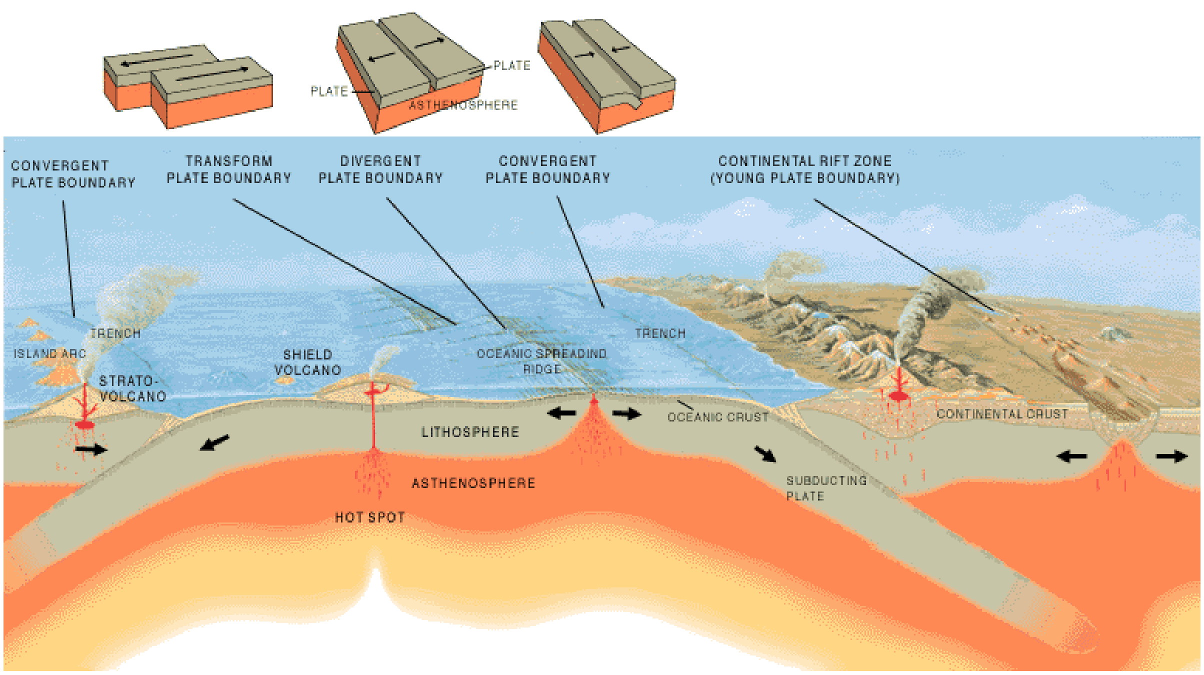
Jordan: Wow !! Look at all the detail in this Japanese image. When we get to Japan, we will have lots to see. In the meantime, we have all this jargon to learn. Right now, I can only decipher about half of the terms on this sketch. Of course, some of those words are just Japanese place names that have no special meaning. They are simply used to distinguish one rock body from another. However, "Permo-Jurassic" must be an international term that refers to a time span, given that dinosaurs roamed during the Jurassic, and it was during the Permian that the continents were all amalgamated, as deduced by Wegener.

Prof. Bowles: The complex plate-tectonic activity that we see here around Japan is all attributed to mantle convection. Everyone is familiar with the convection of soup on top of a stove. Here is some boiling water convecting on top of a Bunsen burner.

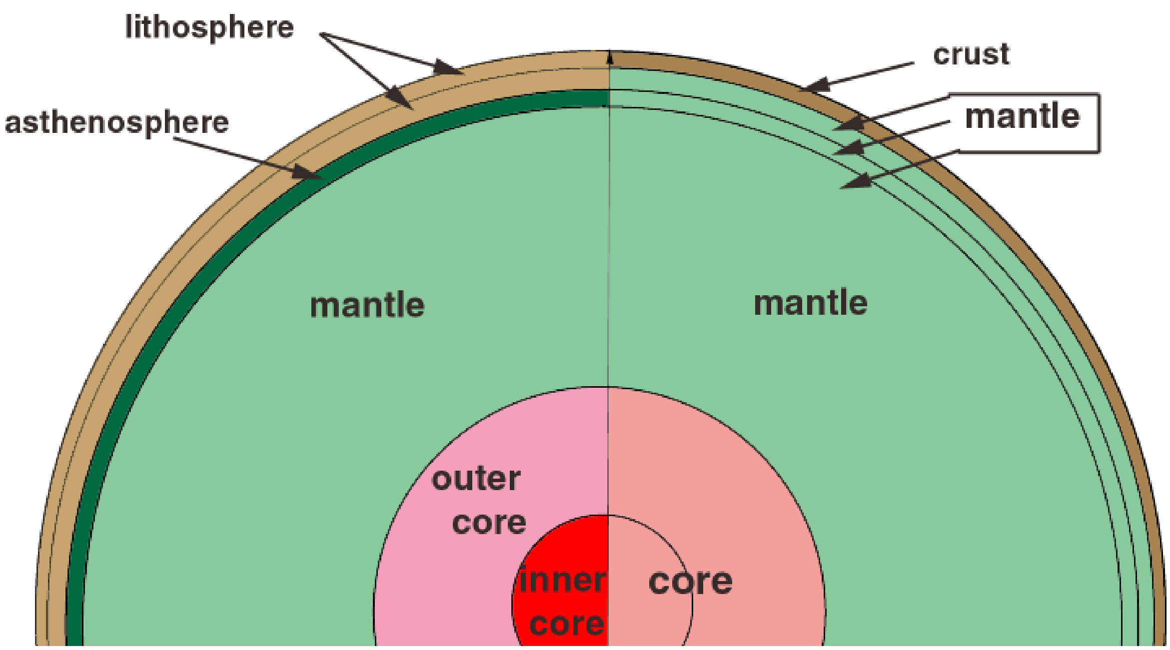
Janna: I think that I can hear Jordan's stomach convecting.

Jordan: Yes. It is. I guess that we should break soon for some chow.

Prof. Bowles: Okay. We will close this discussion of Plate Tectonics by looking at the volcanic rocks which it produces. We have differentiated between stratovolcanoes that accumulate above subducting slabs and shield volcanoes that accumulate well within an ocean basin.



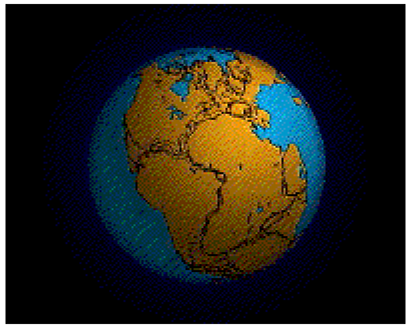
Stratovolcanoes are made of andesite whereas shield volcanoes are made of basalt. These names imply different chemical and mineralogical compositions. Andesite contains more of the SiO_2 component and more alkali elements such as sodium and potassium. Basalt contains more iron and more of the alkaline-earth elements such as calcium and magnesium. Both rock types are largely composed of a mineral called feldspar, but the composition of that feldspar reflects the elemental preferences that we just noted, namely, potassium in the feldspar of andesite and calcium in the feldspar of basalt. Quartz, the dominant mineral on nearly all US beaches, is typically absent from both andesite and basalt. Basalt is consistently darker than andesite because it contains a higher proportion of so-called ferromagnesians. These are iron-magnesium-rich minerals. Let us look at the ultimate source of these volcanic rocks. That is partial melting within the Earth's mantle. As you can see, the mantle constitutes the bulk of the Earth. It is largely composed of ferromagnesians rather than feldspar, unlike the crust.



The mantle is always hot because the Earth remains hot from its initially violent beginning and because of ongoing radioactive decay. Divergence at a spreading ridge pulls apart the oceanic lithosphere, producing a rift valley. This valley decreases the mass on the underlying mantle. Any mineral other than ice tends to melt if the pressure decreases. However, most of the ferromagnesians in the mantle have such a high melting point that they remain solid even under a rift valley. Only 15% to 25% of the mantle rock melts, and this magma rises to become basalt along the mid-oceanic ridge. The first minerals to crystallize in this basalt are some very-high-temperature minerals.

When sea-floor spreading carries this basalt down a subduction zone, it becomes heated. The high-temperature minerals resist melting, so the magma that rises to make stratovolcanoes differs compositionally from the basalt that partially melted to produce that magma. The new magma is andesitic in composition.

I will end my introductory overview at this point and pick up on seafloor features next time. My "parting shot" is a view of Pangea. On Wikipedia, this is an animation that shows how the continents have moved to their present locations through the past 300 million years.



Jordan: I am still not sure about this business of moving continents. It all seems too cute to me. With our submarine, we are going to have a rare opportunity to check on Plate Tectonics first-hand.

Janna: I hope that you will not be too disappointed when you find that the seafloor conforms nicely to the Plate Tectonic Model.

Chapter 2: ***A Deep-Thinking Duo Scans Seafloor Features***

… Janna and Jordan are seated together, facing an empty chair that awaits Dr. Bowles.

Janna: I don't understand you, Jordan. You rarely go to the classes in which you are enrolled but here you are in a review session for which you are **not** enrolled.

Jordan: Professor Bowles is cool, and cool is where I want to be.

Janna: Look, Jordan, I am going to lose **my** cool if you do not go down the hall to your class on Data Structures. How could I know that you scheduled today's session with Dr. Bowles to conflict with Data Structures?

Jordan: Data Structures. Ugh !! Not cool !! You got a good grade last semester and I have all your notes, so how can I go wrong?

Janna: By not going to class.

Prof. Bowles (*walking in)*: Hello Jordan. Did I hear that you are supposed to be in class?

Janna: Yes. Jordan should be leaving for her Data Structures class down the hall.

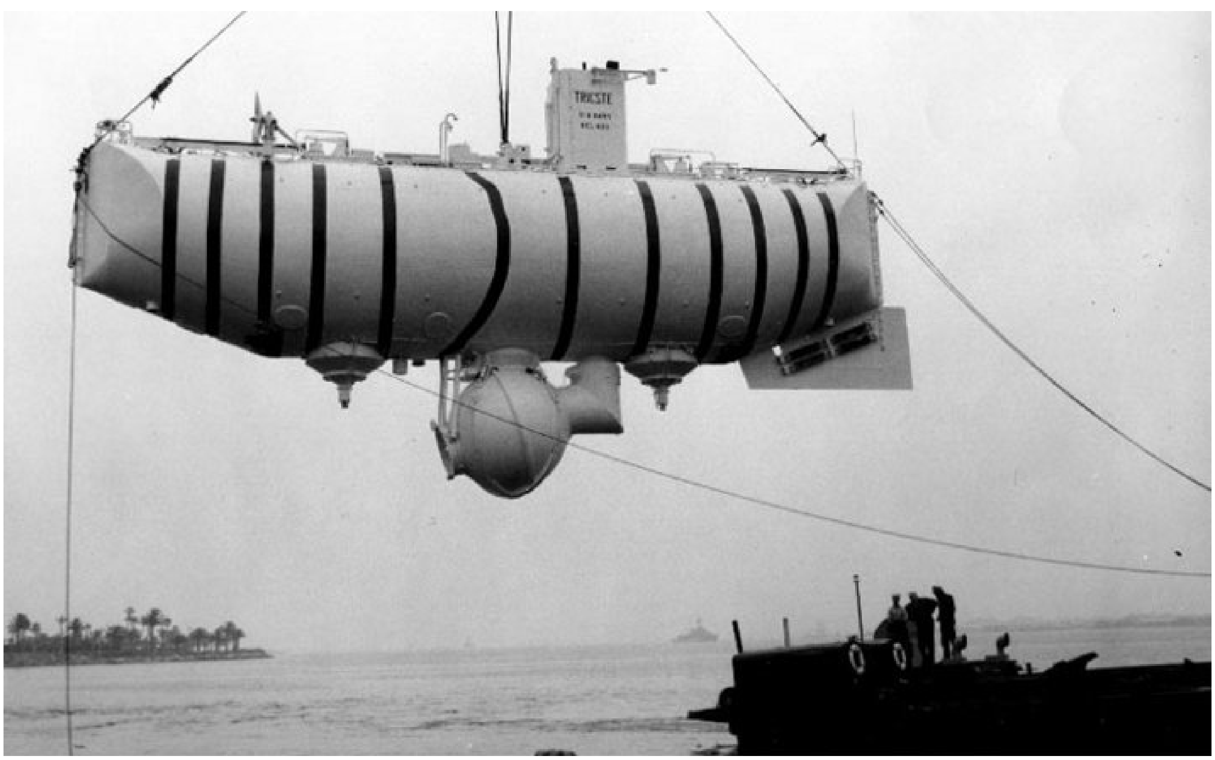
Jordan: I am sure that the prof is **not** expecting me.

Prof. Bowles: Data structures? I took that class back in the days of punched cards and it drove me onto a nuclear submarine. It was up there with Automata Theory for automatically failing students. If you need an escape, you are welcome to return. Besides, you need to keep an eye on Janna, given all the sharks that infest this building.

Jordan: Thanks. I will head off for attendance-taking and come back.

… Jordan leaves Janna with Dr. Bowles.

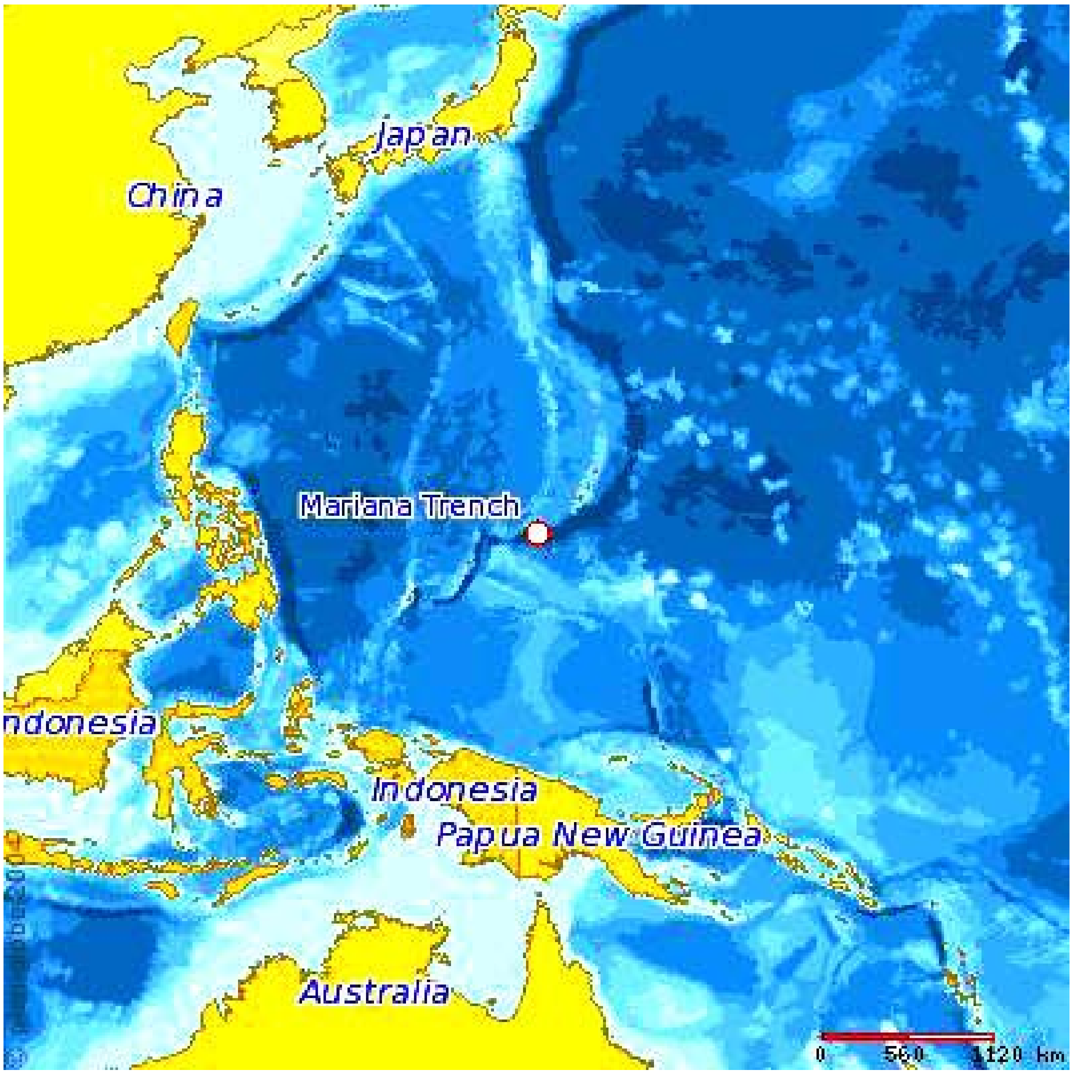
Prof. Bowles: OK. Let's continue. Now that we understand the Plate Tectonic processes that have produced the overall topography of the seafloor, we can focus on specific features that we would see if traveling in a submarine. The Swiss-built bathyscape, Trieste, reached the deepest depth in 1960. Here is the Trieste being lifted out of the water.



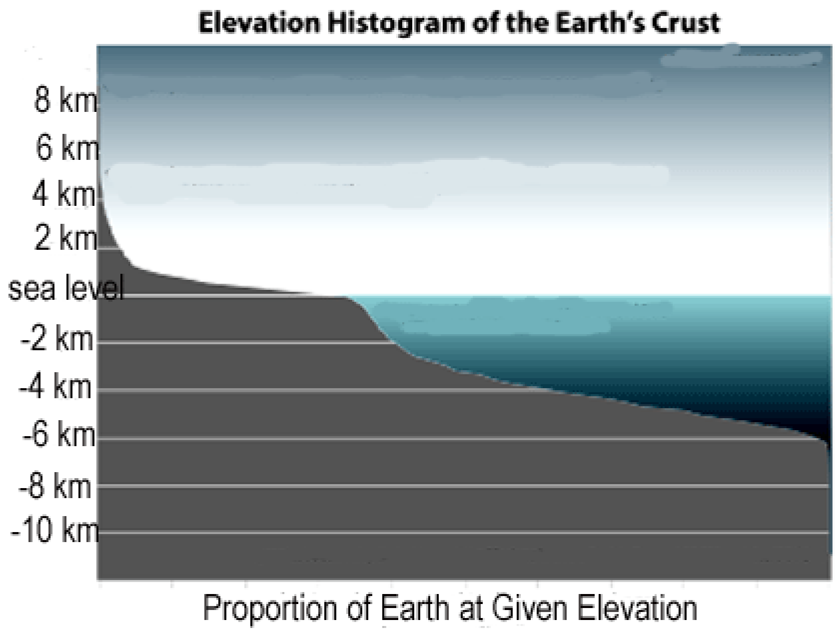
Unfortunately, the Trieste is no longer serviceable and no modern submarine can achieve this feat. The deepest point in the ocean is the Challenger Deep, at 11 km (6.9 miles) deep. The Challenger Deep occurs near the southern end of the Mariana Trench, east of the Philippines. This trench lies so far from land that little sediment is entering it. The Japanese have a near-shore trench that would be as deep as the Mariana Trench if it were not receiving so much sediment from the southern Japanese islands.

Strangely enough, the deepest point on Earth does not lie very far from one of the Mariana Islands. If you were to ask people to guess the location of the deepest point in the Pacific, most would say that it lies far from any exposed land.

Note that the Mariana Trench exhibits an arcuate shape north of the Challenger Deep. In our discussion of Plate Tectonics, this shape was attributed to the cutting of a lithospheric slab into the Earth, like a knife cutting an orange. In this case, the Pacific Plate is subducting westward under the Mariana Islands.



Let us take an overview of elevations on Earth, from a low of -11 km (-6.8 miles) in the Mariana Trench to a high at Everest of +9 km (+5.6 miles). This makes a total relief of 20 km (12.4 miles). Ironically, our tiny Moon has an even greater total relief, 30 km (19 miles) because it lacks water to wash sediment into its impact craters. Unlike other planetary surfaces, Earth has a sharp distinction between high-standing continents and deep ocean basins, as revealed by the step function in this chart of global elevations. On Venus, for example, this curve of elevations is nearly a straight line. The lack of a step function on Venus is evidence against Plate Tectonics on that planet. On Earth, only oceanic lithosphere is dense enough to be subducted and the lateral transition from oceanic lithosphere to continental lithosphere is abrupt, coincidental with the sharp break in the step function.



Oops ! My cell phone is vibrating so I should take a minute to answer it. I am expecting word about a proposal from my program manager at the National Science Foundation.

Janna: (*watching Jordan sneak back into her seat*) So, Jordan, did you sign the attendance sheet in Data Structures?

Jordan: Sign? On paper? I doubt if that professor knows what paper is. We all have clickers to register attendance. I will have to give you mine on the days I plan to skip.

Janna: I found out who you should hire to build our submarine, the guys who successfully built the deepest-diving submarine ever assembled. You will never guess.

Jordan: Since I have to guess, it must be some small, high-elevation country far from the ocean. How about Nepal?

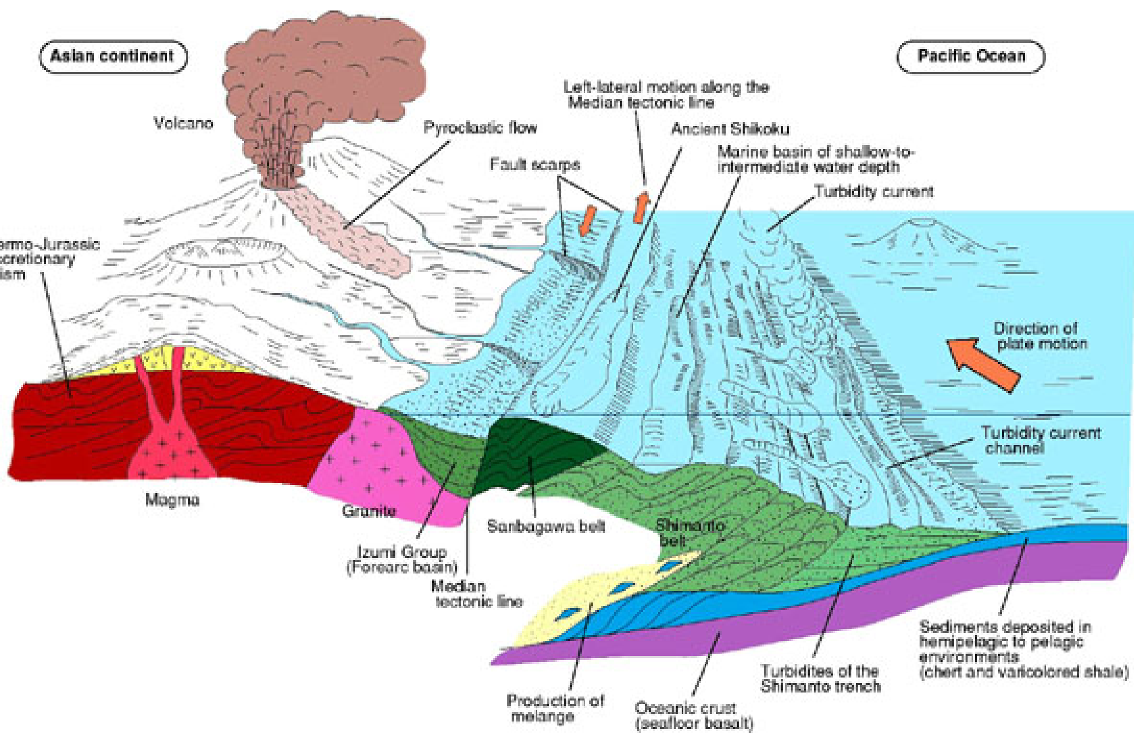
Janna: Nepal? The country that has Mount Everest but lacks wrenches? I must say that your criteria were good but, as usual, you went too far. The deepest-diving sub was built in Switzerland. I think that you should turn the construction over to the Swiss or else it will be our sixtieth-class-reunion trip rather than our post-graduation romp. After you completed the basic computer model for our sub last week, you seem to have lost your zeal for the project. Nuts and bolts are just not your thing. Besides, Bates must already be hiding some of his money in an unnumbered Swiss bank account, so it would be easy for him to pay your construction engineers.

Prof. Bowles: Sorry about that. It was not my program manager, after all. You guys must realize that we faculty live and die at the whim of NSF managers. If I do not pick up my phone, she is just as likely to call the next person on her list and give them the quarter-million dollars that is up for grabs. As much as I dislike interrupting our discussion, my dismissal for failing to bring in grant money would also disrupt your education, so I would ask that you understand why we faculty sometimes shortchange you.

Janna: No problem. We all live in the same system and try to deal with its inconsistencies and pitfalls on a daily basis. We appreciate your insight.

Jordan: Janna tells me that Swiss engineers built the world's deepest-diving submarine. Do you know any Swiss engineers who would build a submarine for me?

Prof. Bowles: You would not want to rely on the submarine builders that I know because they also make Swiss cheese. Going back to our lecture on seafloor features, we may lift ourselves out of the Challenger Deep and look at the eastern side of the trench. There the Pacific plate is carrying some unsuspecting sediment down the throat of the trench where it becomes squeezed and crumpled. The Mariana Trench lies just south of Japan, so the cross-section that we saw in the last chapter applies here too. The seafloor features on the incoming lithospheric slab are simple compared to those above the subduction zone, west of the trench, where intense deformation is occurring.



As we saw in our elevation histogram, the average depth of the oceans is vastly greater than the average elevation of the continents, specifically almost five times greater. The oceans average 3.8 km (2.4 miles) deep whereas the continents average 0.8 km (half-a-mile) high. There are many cities that lie far from the ocean but are not far above sea-level. For example, Cairo Illinois is only 96 m (311 feet) above sea-level but lies about 760 km (470 miles) from the sea. This ratio of distance/elevation is nearly 8000. This is essentially dead flat. Nonetheless, the Mississippi River somehow travels down this meager slope of

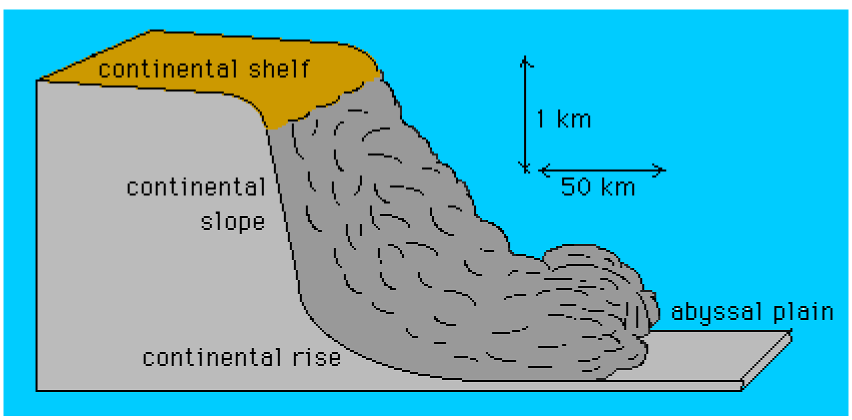
1:8000 to get from Cairo Illinois to the Gulf of Mexico. In the previous chapter, we mentioned that abyssal plains are the flattest areas on the seafloor. However, even the flattest abyssal plain rarely exhibits a slope less than this over distances on the order of 1000 km.

Now that we have had a good look at the abyssal plain on the seaward side of the trench, we may turn around and look at the more interesting landward side. If we could look far enough, we would see a stratovolcano rising above the sea, about 100 to 400 km (60 to 250 miles) landward of the trench. The factor-of-four variation in distance from the trench depends on the angle of subduction and the corresponding heating of the downgoing lithospheric plate. When the plate gets deep enough, it partially melts to feed magma to the overlying volcano. However, the volcano lies far from the trench and there will be plenty to see in our imaginary submarine as we glide away from the trench in a landward direction. Both sedimentation and erosion should be evident.

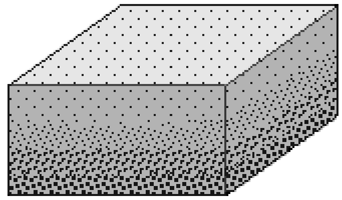
Janna: Our real submarine will be like a helicopter and you must know that helicopters are dangerous. They may run into obstructions such as cliffs. Visibility around a sub would be much worse than around a helicopter, so our sub would be even more dangerous. We could not even see a submarine landslide heading our way.

Jordan: Excuse me, Dr. Bowles. Just how frequent are these landslides?

Prof. Bowles: Of course, they are not really landslides since they occur in the ocean. We call them turbidity currents and they typically recur on time scales of several decades to centuries. Given a steep continental slope or steep submarine volcano, a turbidity current may rapidly carry voluminous sediment down to a continental rise, as shown here.



The effect of being caught in a submarine landslide would be much like being caught in a terrestrial landslide or snow avalanche. Initially, you get hit by the fast-moving particles that would dent your submarine and finally you could become buried. Downslope velocities of these turbidity currents reach 90 kph (56 miles per hour). This is an impressive speed, given all the friction imposed by the surrounding water. The resulting sediment layers are called turbidites and they exhibit characteristic sedimentary structures. The most characteristic of these is an upward gradation in grain size because the coarse particles settle first, followed by progressive fining-upward of particle size, as seen in this sketch.

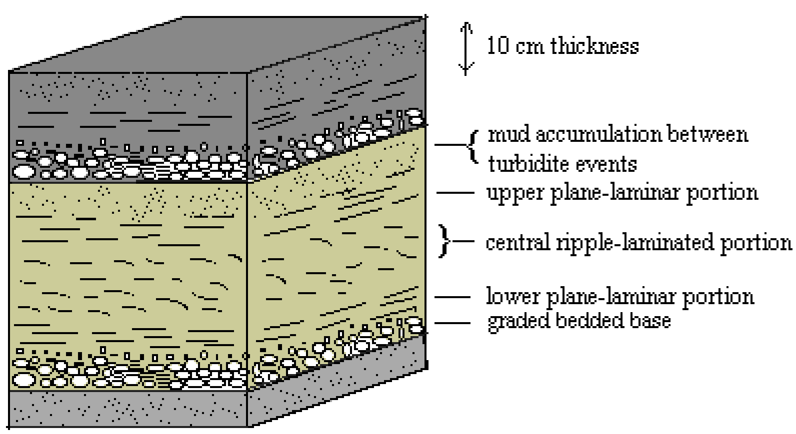


Janna: If our submarine gets caught in one of those turbidity currents, then we are going to become just a large particle at the bottom of some turbidite bed. Nobody will ever find us.

Jordan: Maybe not, but think of all the mystery novels that will be written about us. We would then be the Amelia Earharts of the sea. Amelia became the subject of America's most expensive marine search when her plane ran out of gas in the southwestern Pacific in 1937. Five years earlier, President Hoover had escorted her around the White House because she was the world's most famous lady aviator.

Janna: I do not want to become a world-famous lady submariner by being the first who is buried within a turbidite. Besides, they have never found Amelia's plane, despite several sophisticated recent surveys. Perhaps it has become buried within a turbidite. How does a turbidity current produce a turbidite anyway?

Prof. Bowles: As the turbidity current slows, it can deposit sheets of sand, with each sheet having moved like a playing card, independent of other sheets. With further slowing, rippled sand is deposited, but the ripples typically become deformed due to minor downslope motion (creep) within the accumulated sediment. With further slowing, fine-grained sand accumulates in flat laminae that resemble the underlying playing-card layers, but these upper laminae form from slowly-settling sand rather than rapidly-sliding sand layers. During the long time span between turbidite events, background mud accumulates extremely slowly, through centuries to millennia. In contrast, all the sandy layers underlying the mud may accumulate within a few hours. Although typically just a few percent of the thickness of a turbidite, the mud usually represents more than 99% of the elapsed time. Here we see a complete turbidite sandwiched between the tops and bottoms of other turbidites. The number of stacked turbidites in a continental-rise sequence may reach several thousand.



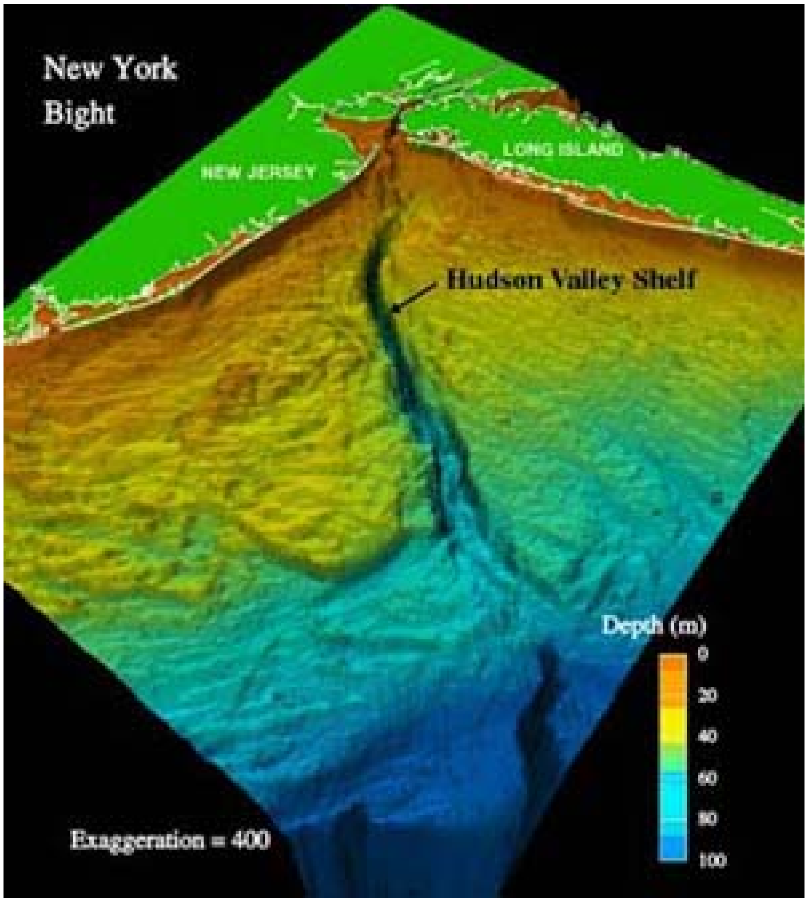
Turbidity currents commonly are triggered by earthquakes. Here is a monotonous sequence of scores of turbidite beds from southern Italy. Note that the thickness varies considerably from one turbidite to the next. This is related to the distance from the source of the corresponding turbidity current and the volume of material which moved in that event.

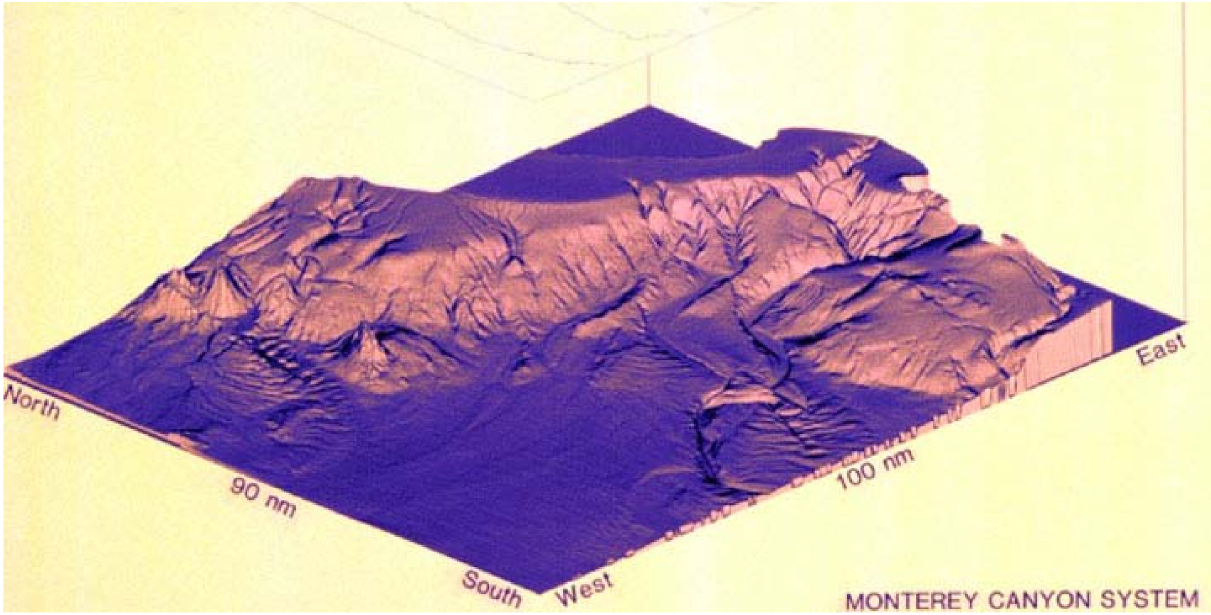
Janna: Italian turbidites may be monotonous but none of those Italian hunks on the daytime soaps are monotonous. Why not abandon all this submarine nonsense and go study bedding in Italy?

Jordan: Along with tour groups from every high school in America? That is not how Amelia Earhart merited a ticker-tape parade in New York City.

Janna: OK, but I hope that we drop the turbidity topic because it still scares me.

Prof. Bowles: Moving laterally along a continental rise and slope, we will eventually encounter a submarine canyon. This would be like encountering the Grand Canyon while driving over the tableland of Northern Arizona. In fact, submarine canyons are normally measured in units of Grand Canyons. Here is the Hudson Canyon off New York’s Hudson River and the Monterey Canyon off central California, each roughly a “Grand Canyon” in size.





Submarine canyons feed sediment from the continental shelf down the continental slope, to the flatter continental rise. Within the rise, one may find distributary channels for this sediment, just as the Mississippi river has distributary channels where it crosses the flat rim of the Gulf of Mexico.

Given that submarine canyons are typically comparable to the Grand Canyon, it is appropriate to view the Grand Canyon to conjure up a mental image of these canyons. The Grand Canyon has obviously been eroded by the Colorado River, which we see here.

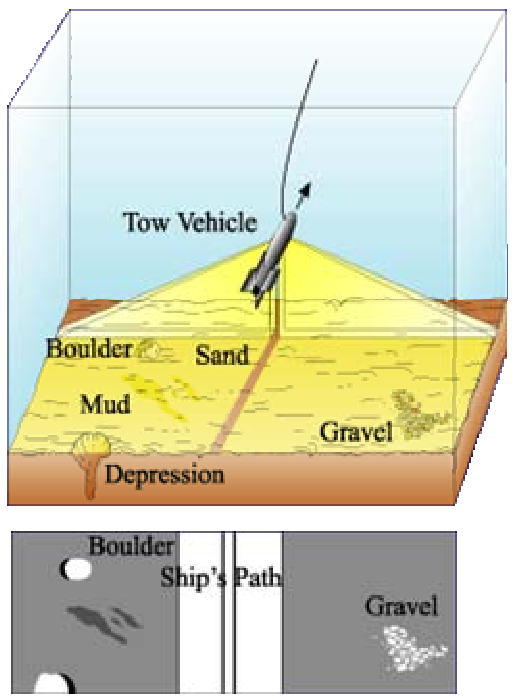
Janna (*to Jordan*)**:** Hiking the Grand Canyon took me a couple of months of training. I expect that we will also have to train before maneuvering our sub into a submarine canyon.

Prof. Bowles: The original explanation of submarine canyons was that they too had been eroded by river-related processes, given the river-mouth location of such canyons as the Hudson of New York. However, the discovery of canyons far from major rivers, e.g., the Monterey Canyon of California, has opened an intense debate that is not entirely resolved. Even river advocates realize that the erosive power of river flow is presently inadequate to produce such enormous canyons but they note that some rivers reached the shelf break during the height of the glaciations, when sea-level was about 110 m (yards) lower and much of the continental shelves were exposed. Sea-level lowering resulted from the glaciers holding so much water.

River advocates suggest that some direct erosion may have occurred when the rivers reached the shelf break and that erosion may be continuing during the present time of high sea-levels due to the transport of river sediment to the deep sea by turbidity currents. Alternatively, the submarine canyons may be the surface expression of deep-seated fractures in Earth's crust, along which strong earthquakes occasionally occur. In this sense, submarine canyons would be related to the fractures (rift valleys) along which some of the world's biggest rivers flow, including the Amazon and Mississippi rivers.

Jordan: Dr. Bowles, how could one see features like that from a submarine? I know that sunlight does not penetrate very deeply into the ocean and that artificial light also becomes attenuated in just a short distance, so how could one see a submarine distributary channel?

Dr. Bowles: Well, Jordan, we may talk about underwater sensing devices in a subsequent chapter but I will simply mention here a side-scan sonar. This is a towed vehicle that emits fan-shaped pulses of sound, usually in the range of 100 to 500 kHz, and analyzes the intensity of the reflected sound. Both topography and reflectivity of seafloor features may be deduced from the acoustic reflections. Here is a sketch of a side-scan sonar, showing both the device and its analysis of the illustrated seafloor. Note that the area immediately under the towed vehicle cannot be resolved.

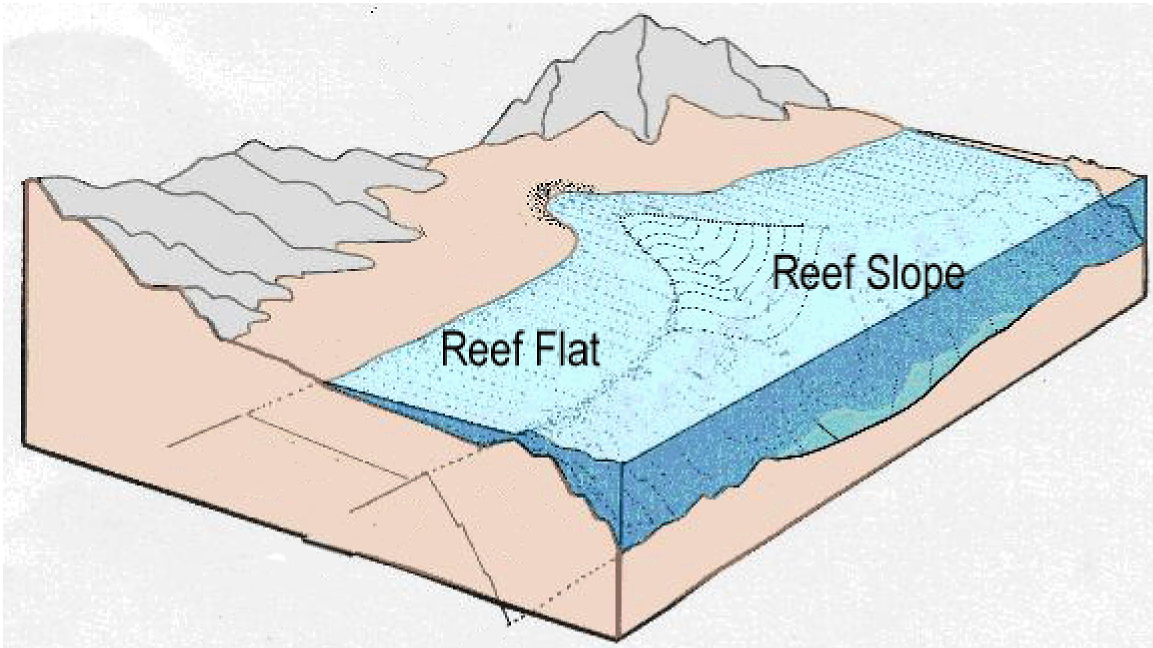


Jordan: I suppose that a side-scan sonar is not just good for tourism but also can find dangerous scarps, shipwrecks, communication cables, and left-over mines from the wars.

Prof. Bowles: Yes. You would rather have an external device like this run into trouble than your submarine. We should go back to deep-sea features and consider isolated islands, including atolls. I will bring in Drs. Fondah and Bubah to entertain you with their overtly biased views of islands. I think that we should all stand back and let them duke it out.

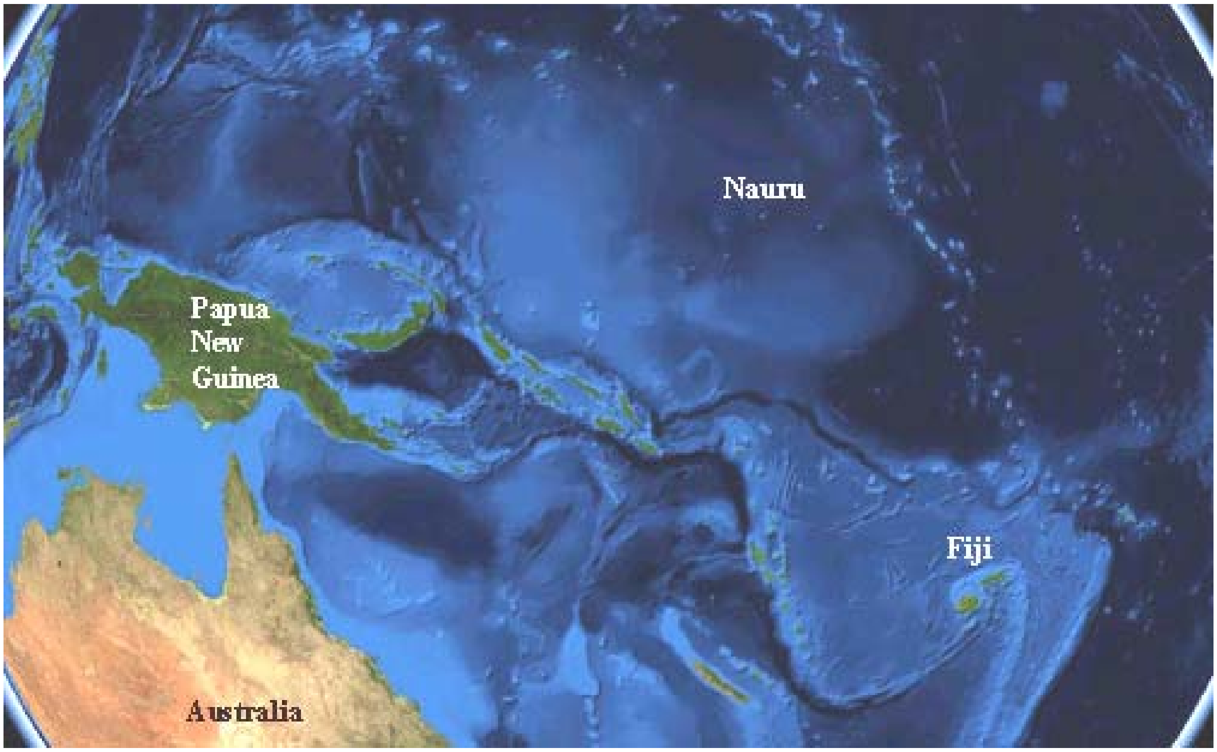
…*Jordan, Janna, & Dr. Bowles stand up and give their chairs to Drs. Fondah & Bubah.*

Dr. Fondah: Atolls represent harmony between Earth's constructive and destructive forces. One of the great geniuses of all time, Charles Darwin, deduced that atolls are submerged volcanoes. The volcanoes had grown because voluminous magma kept rising to the same point on the seafloor. However, magma influx eventually ceased and the destructive forces of erosion and sinking became dominant. The subsiding volcano had a fringing reef and the coral in this reef grew upward just as the volcano itself was eroding and sinking under its own weight. Persistent upward growth of this reef metaphorically represents the tendency for all of life to reach heaven-ward. Here is a fringing reef.

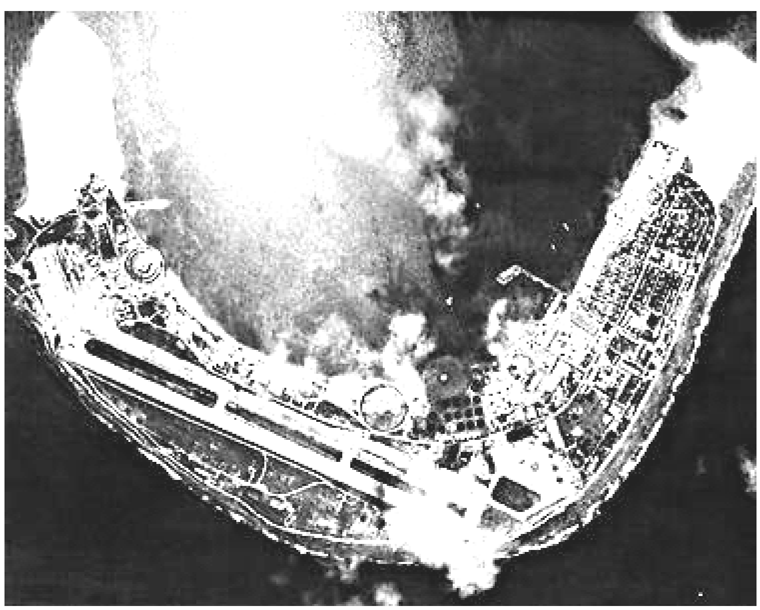


Life's growth tendency always faces some type of competition. In the case of reef coral, it is hurricanes. Hurricanes are called typhoons in the western Pacific and cyclones around India. Whatever name one chooses to give them, hurricanes can break off near-surface coral over vast areas, threatening permanent destruction of a reef system. If the former volcano sinks too deeply, a hurricane can break down its fringing reef to such a great depth that the reef cannot successfully grow back to the near-surface zone where there is enough sunlight and nutrients to feed it. Reef coral requires light because it relies upon photosynthesis by an alga living within it, zooxanthella. Zooxanthella provides up to 90% of its host coral's energy requirements in exchange for shelter and a constant supply of carbon dioxide. However, this magnificent symbiotic relationship ends if a hurricane cuts the reef down so deeply that it cannot grow back. Here is a species of *Acropora*, a famous reef-building genus of coral. I cannot image what Dr. Bubah thinks of these beautiful corals, or should I say Dr. Blah-Blah.

Dr. Bubah: Coral-rimmed tropical islands are typically worthless except for darkening your tan. Even the Japanese could not be bothered to take Hawaii after destroying most of our defenses. They immediately headed to Indonesia to acquire the vast petroleum reserves of that extensive archipelago. Admittedly, a few islands did prove to be important in World War II, such as Nauru and Kwajalein. Phosphate-rich Nauru lies northeast of Australia and has an area smaller than my ranch in Texas, just 21 km^2 (8.1 $miles^2$). We had to dislodge the Japanese from both these islands in World War II. Here we are bombing Nauru.



Kwajalein was of more strategic importance in World War II because the Japanese were using it as an airbase. Kwajalein is one of the world's largest atolls, with a lagoon of 2174 km^2 (839 $miles^2$) enclosed by just 16.4 km^2 (6.3 $miles^2$) of land. As seen here, the airbase at the southern tip of the atoll is barely accommodated by the available land.



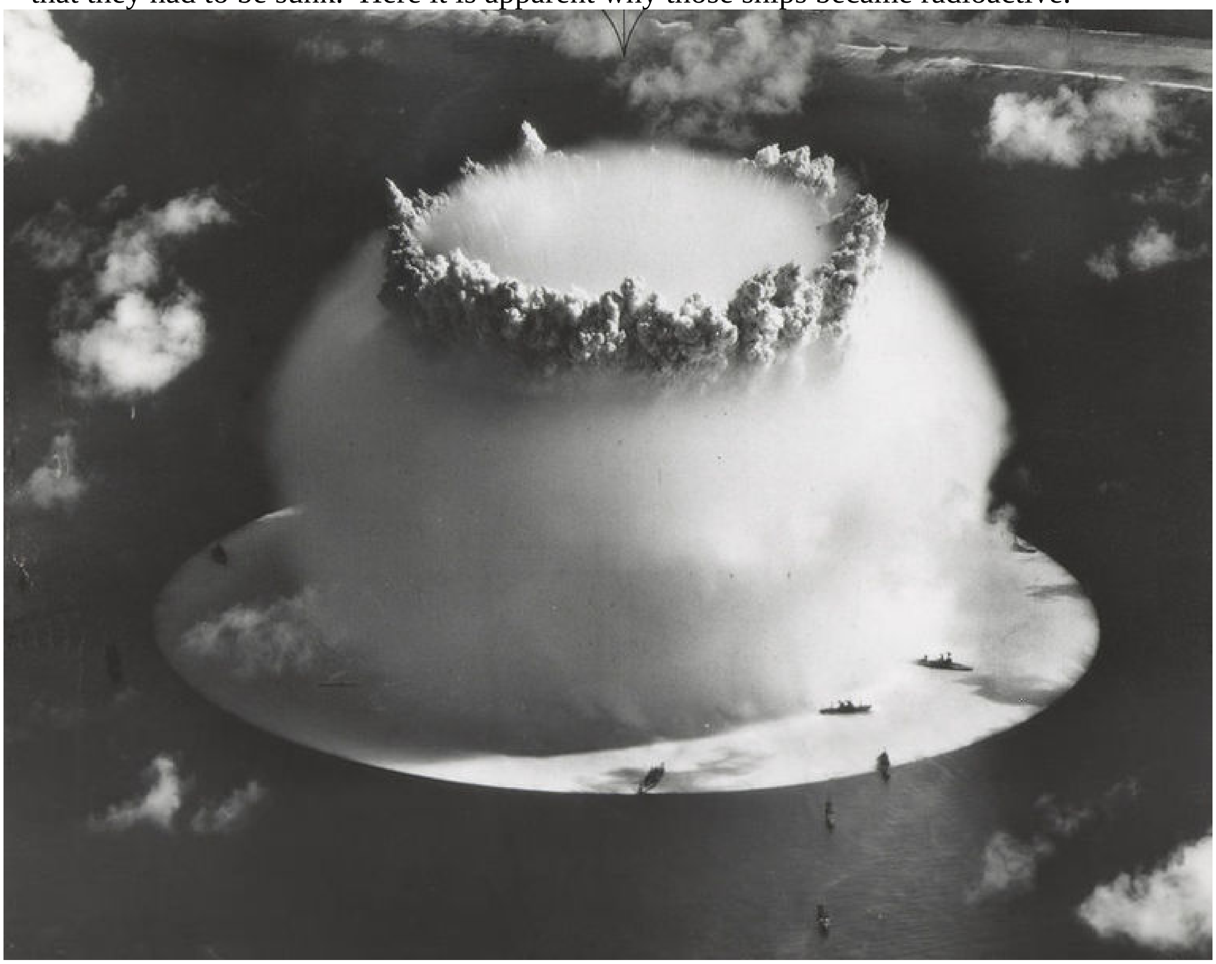
Kwajalein lies 2400 miles (3900 km) southwest of Honolulu. Americans visiting Kwajalein in early February of 1944 did not bring the usual tourist gear that one takes to a tropical island. Instead, as shown here, they had to carry flame throwers. Exposed reef rock like that covering this atoll typically is full of caves. If not for the flame throwers, the atoll would have been easy to defend. As it was, the Japanese lost 97% of their men whereas America lost less than 1%. American losses would have been higher if the Japanese had not concentrated their defense around beaches that could readily be shelled by our ships. However, the Japanese learned from this mistake and took better advantage of marine geology in subsequent encounters. Six months later, we faced little resistance while landing on the Mariana Islands (near the famous Mariana Trench). However, the Japanese counter-attacked at night from their inland caves. It got to be a hot time in the old town.

Janna: I bet that there are live mines still positioned at various water depths around some of the Pacific islands.

Jordan: Mine fields that have not been cleared should be shown on government maps. We will need to scan hundreds of maps and take digital copies with us.

Dr. Bubah: Let us go back to Naura. Despite the bombing photo here, Nauru was just a sideshow in World War II. Nauru's claim to fame is that it has provided more phosphate for fertilizer than any other small island on Earth. There are two runners-up, Banaba and Makatea. Although these voluminous phosphate deposits have been attributed to bird feces (guano), this hypothesis is not supported by the huge difference between these three islands and the thousands of other islands scattered across the Pacific Ocean. Scattered guano is a common occurrence on many of these islands, but in trivial quantities.

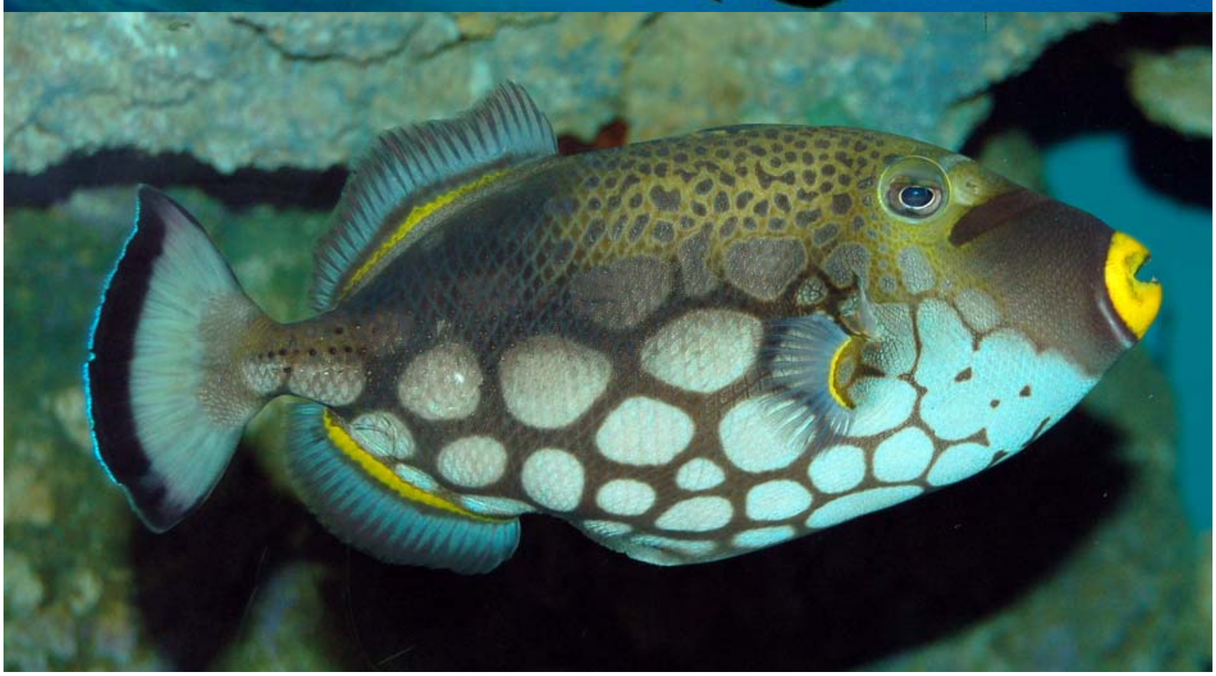
Although limestone islands were unpopular with the American military in World War II, the military soon found a good use for them once we needed a place to test nuclear weapons. A year after the world's first atomic bomb experiment, in New Mexico, a couple of bombs were detonated on Bikini atoll. The New Mexico and Bikini bombs all used plutonium, unlike the uranium bomb dropped on Hiroshima. Unfortunately, many of the ships used to monitor the Bikini explosions became so contaminated that they had to be destroyed. Eight years later, in 1954, a thermonuclear bomb was exploded in the northwestern corner of Bikini Atoll. This fusion bomb had about a thousand times more power than any of the previous plutonium bombs. Once again, several monitor ships became so contaminated that they had to be sunk. Here it is apparent why those ships became radioactive.



Dr. Fondah: (…*raising her hands in disbelief*) Let me see if I understand your point of view. After showing you that mid-oceanic islands are the homes of some of the world's most beautiful creatures, all you can think to do with these islands is to obliterate them with nuclear bombs! Have you not seen any of those movies where radiation induces mutations that create a monster? Which planet do you plan to inhabit after you destroy this one? At last check, NASA has not yet been able to find another planet with the liquid water that we need to support life, let alone figure out how to get us there.

Dr. Bubah: Are you trying to tell me that all those fish are pretty? What about the boxfish? Those ugly spineless creatures have fused platelets all over their body instead of a skeleton. Our bombs did the world a favor by frying ugly animals like these boxfish. Would you want one of these staring back at you from your dinnerplate?

Dr. Fondah: Meanwhile, you were also cremating beautiful fish like this Royal gramma, French angelfish, Circular spade, and clownfish, all shown here.



Dr. Bubah: Yup, the very definition of "small fry". (*Exit Bubah; enter Julie, Emily, Laura)*

Julie: We could hear that bulbous Bubah half-way down the hallway and decided to come to your rescue, Dr. Fondah. Have you managed to keep any tropical islands out of bilious Bubah's radioactive hands?

Dr. Fondah: I should have known better than to discuss my beautiful islands with bubonic Bubah. Could you guys review some marine habitats while I try to recover my composure?

Emily: Sure. We all got to visit Australia's Great Barrier Reef last year so let's start there.

Laura: Australia's Great Barrier Reef sits on a broad continental shelf in northeastern Australia. It's the world's most extensive reef, stretching 2600 km (1600 miles).

Julie: This is the most extensive animal colony on Earth, if one discounts the man-made structures along Interstate-95. From Maine to Miami, I-95 runs for 3100 km or 1900 miles. A similar but smaller reef lies along the Kimberley district of northwestern Australia.

Emily: Cyclical development of barrier reefs is related to cyclical fluctuation of sea-level. Global sea-level has been primarily controlled by the cyclical growth and melting of huge glaciers in Canada and Scandinavia. The world has been colder than it is today through most of the past couple million years. The two most-recent times when it has been as warm as it is now occurred 75-to-125 thousand years ago and 200 thousand years ago.

Laura: There were huge glaciers as recently as 20,000 years ago, 20 ka. The corresponding glacial growth lowered global sea-level by 120 m (130 yards). Before that low-stand at 20 ka, one has to go back to the 75-to-125 thousand-year span to find a time when sea-level was as high as it is today. In that time span, the barrier reefs apparently resembled modern reefs. However, nearly all of that coral died from exposure due to the subsequent lowering of sea-level related to the growth of glaciers, from 75,000 to 20,000 years ago.

Julie: When sea-level reached its nadir 20,000 years ago, the coastal plain extended out to the location of the previous (and modern) barrier reefs. Hills of dead coral sat on the coastal plain, and partially submerged hills of the old reef rock rose from the continental slope near the shelf break, rimmed by fringing reefs. As the Canadian-Scandinavian glaciers started to melt, sea-level correspondingly rose until all the old hills became inundated around 6000 years ago.

Emily: This inundation produced the modern barrier reef. Sea-level has not risen much for the past 6000 years and the reef has remained fairly stable, despite suffering from occasional diseases. Although some people worry that a global rise in sea-level will cover half of Florida, the history of sea-level change reveals that it is more likely to go down.

Laura: Fortunately, we live in a time of high sea-level, so we could take a glass-bottomed boat on Australia's continental shelf and see beautiful coral and brightly colored fish. I am really looking forward to returning to that Great Barrier Reef off Queensland.

Julie: Me too. I have also explored the possibility of visiting the smaller reef off Australia's Kimberley district but I dumped that idea when I discovered that Kimberley is so boring.

Dr. Fondah: I must have been the one that warned you about Kimberley. Have you guys gotten anywhere with my assignment of creating a virtual submarine tour?

Emily: I'm having trouble envisioning the submarine. For example, are we supposed to look out a porthole as in the days of Jules Verne or should we have externally mounted video cameras? If we have external cameras, they could get knocked off as we maneuver around obstacles like the submerged hills of reef-rock off Queensland.

Dr. Fondah: Your virtual submarine should have lots of low-light video cameras and you should carry several spares in case of accident. What other electronic devices should you have?

Laura: My mother claims that I am "locationally challenged", loco for short, so my prime device would be a GPS system, a global positioning satellite system. To determine location, I would have a transmitter that talks to a GPS-equipped buoy somewhere above the submarine. The buoy would use GPS to determine its own location and sound waves to deduce my location relative to it.

Dr. Fondah: Very good. The time lapse between producing sound and hearing its echo corresponds to the distance that the sound waves have to travel. We know that the speed of sound in seawater is 1.5 km/s (3355 mph). Of course, you would not depend upon an echo but would generate a returning sound that resembles an echo.

Julie: I remember your lecture about side-scan sonar so I would be sure to drag that device beneath my submarine to survey seafloor topography.

Emily: Dr. Bubah has offered to provide me with a side-scan sonar if I ever actually build a small submarine. However, I overhead one of his grad students confess that Bubah hides some additional sensors within all his sonars. These sensors are specific-ion electrodes that detect dissolved metals. He must be looking for a hydrothermal vent that emits metals which accumulate on the seafloor.

Laura: Dr. Fondah, in class you mentioned a hydrothermal deposit off Washington State that is worth more than nine billion dollars. You said that it contains lots of gold, silver, lead, zinc, and copper. Bubah probably just considers us to be his Three Musketeers of marine exploration, ready to work without any salary.

Emily: If I ever use one of Bubah's side-scan sonars, I would tap into his signal from the specific-ion electrodes.

Julie: Good idea. I would also arrange for a delay in transmission of my echo to the GPS buoy so that only I would know the correspondence between my actual and apparent locations. I would just watch for Bubah's crew to show up and then calculate the location of the actual metal deposit from the spot where they started to sample. That way, I would not even have to analyze the metal-solute data carefully. I could calculate the true location from a combination of my sub's log and the time differential that I built into the echo. Bubah would eventually figure out what I had done and he have to negotiate with me.

Laura: What if he makes you an offer that you cannot refuse?

Julie: Signorina Gerardi, surely your uncle Malvolio could help me deal with Bubah.

Laura: Malvolio? Malvolio is a bit malicious and his name does mean "bad wishes", but he is best known for spouting one-liners, like "Some are born great; some achieve greatness, and some have greatness thrust upon them".

Emily: That should work. Just show up with Malvolio repeating his world-famous line over-and-over again and you are bound to behold one beserk Bubah.

Laura: Then I would have all the hydrothermal gold to myself and be rich forever !!

Julie: I would not mind being rich myself. I have always liked Michael Caine's view of wealth. He rose from poverty to become one of Britain's highest paid actors. He said that those who keep saying, "Money cannot buy you happiness", are actually spreading propaganda for the rich. New-found wealth made him a lot happier.

Dr. Fondah: Any other electronic devices on your virtual submarine?

Laura: Uncle Malvolio has suggested a laser gun.

Emily: A laser gun? Are you trying to become an attack submarine for some third-world country that has a gross domestic product smaller than Bangor Maine?

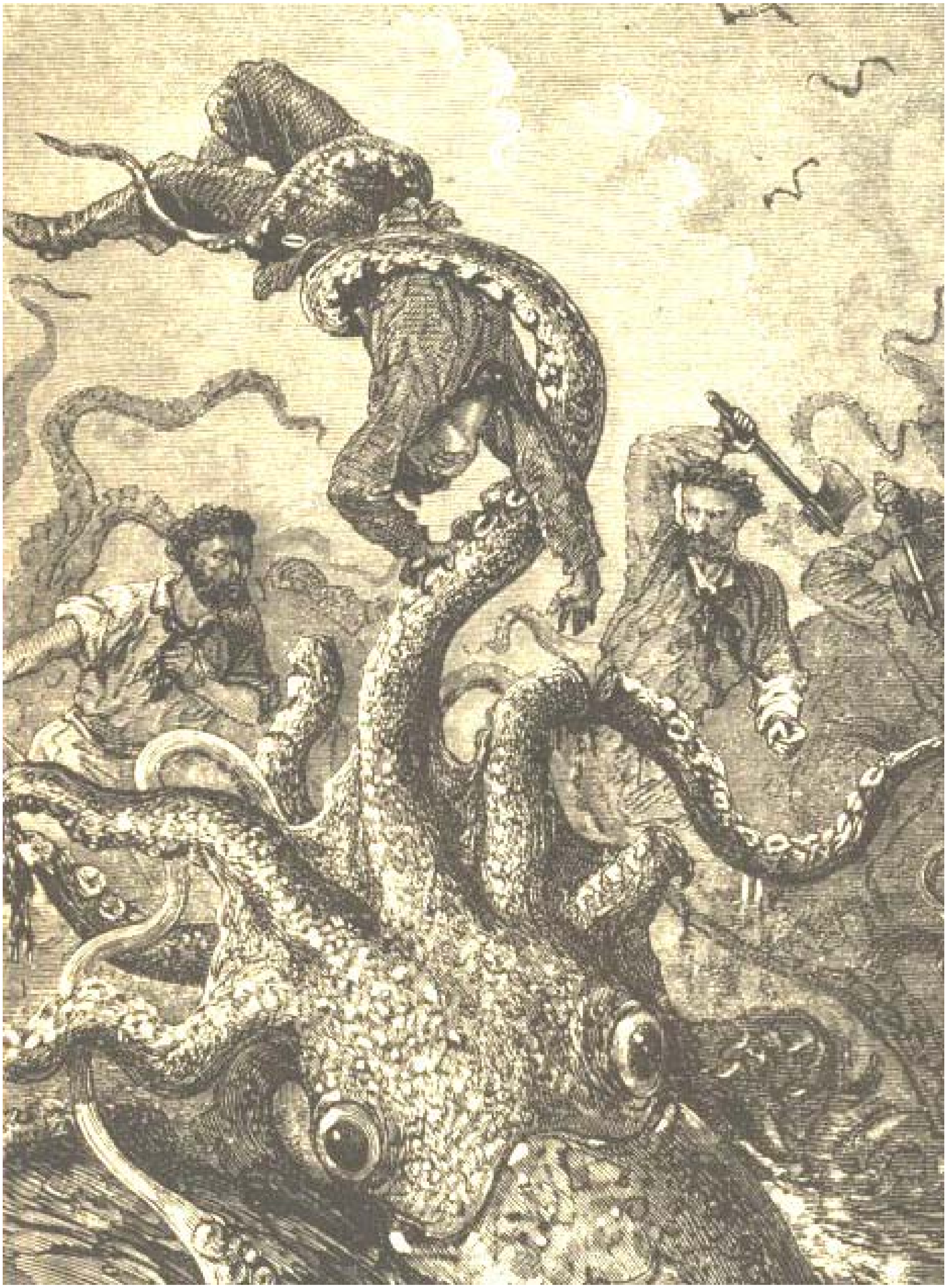
Julie: Are you anticipating monsters like the one in Jules Verne's "20,000 Leagues under the Sea" ? Jules Verne himself does not appear to be very frightened.

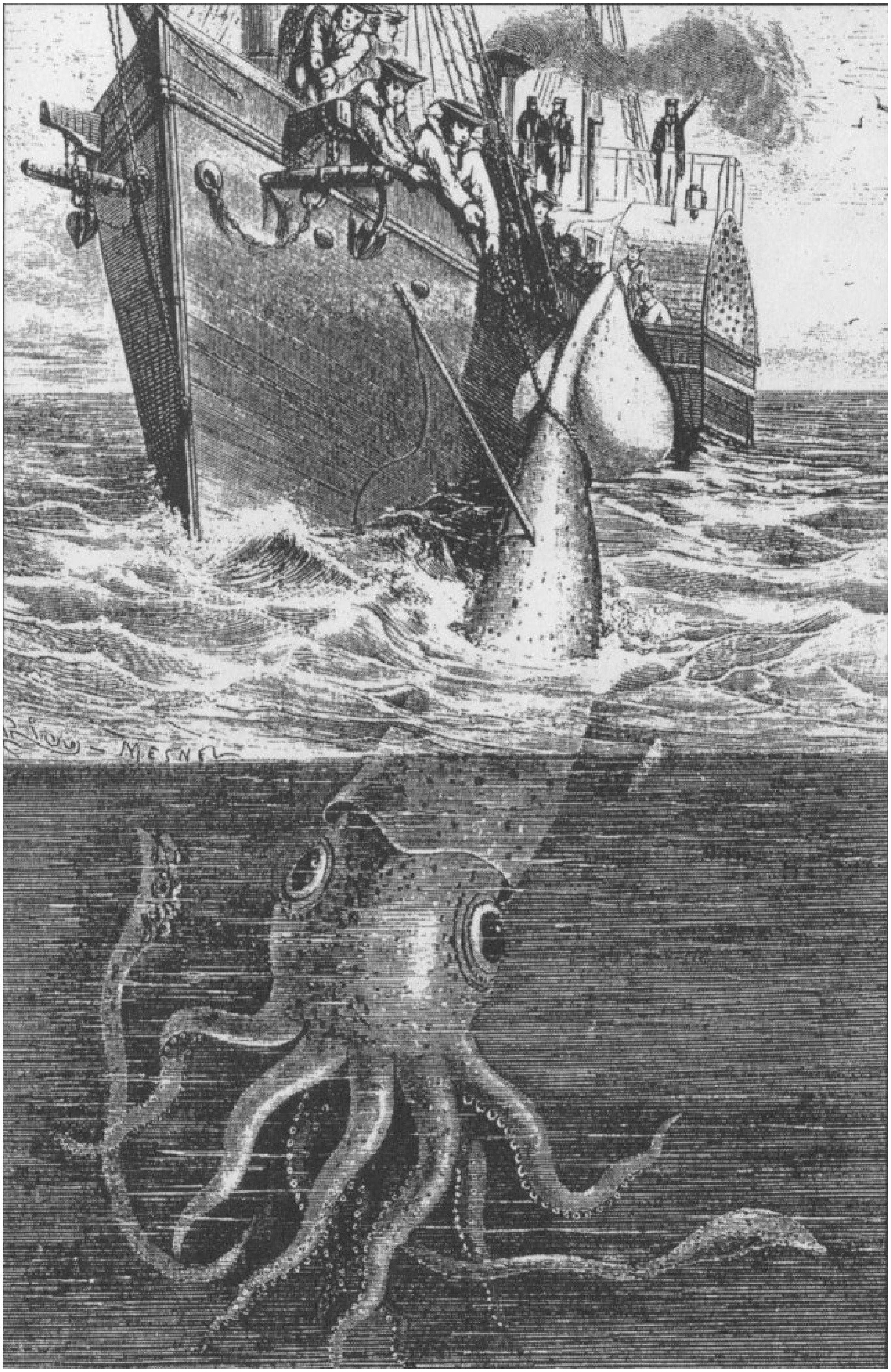
Laura: One of Verne's prep-school teachers went on to design the first submarine in the US Navy, the USS Alligator. It sank in a storm off Cape Hatteras, North Carolina.

Emily: It was being towed and they cut the rope.

Julie: Either that, or an even bigger alligator ate it.

Dr. Fondah: Jules Verne did not terrorize his readers with images of alligators. He presented the unexpected but realistic threat posed by a giant squid.





Laura: Surely these images are as imaginary as the creatures in comic-book movies. Was Verne experimenting with laudanum like his contemporary, President Lincoln?

Emily: While you were gazing at bizarre modern drawings in the English translation of "20,000 Leagues", I read the original French edition and it showed an authentic giant squid battling under-armed sailors. Jules Verne's account was based on an encounter nine years earlier by the French Navy. That encounter is also show here, along with the original sketch from Verne's book.

Julie: Malvolio's laser gun has got to beat an axe, I suppose. How big can a giant squid become?

Dr. Fondah: The giant squid reaches at least 13 m (43 feet). A squid that is a meter (yard) bigger than this lives near Antarctica and is called the colossal squid. Claims of twenty-meter-long (66-foot) squids have not yet been verified but may well be true.

Laura: Uncle **M** tells me that if we ever encounter such an animal and haul it to shore before it decays, we can collect a fat reward. Australia recently paid $100,000 for a specimen. If we could not sell it to a research museum, we would have a whole lot of calamari on our hands.

Emily: I have seen a video of Japanese fishermen trying to haul in a giant squid, using an octopus as bait. Here is a frame from that video. I bet that the video was a money-maker too.

Dr. Fondah: (*cell phone vibrating*) Hello Jordan. I'm fine, still here in the classroom with some of my students. So, you guys have been with Dr. Bowles all this time, helping him research osmotic desalination. I suppose that you will need to know how to make a good cup of coffee from seawater, but be careful with Bowles. He is always trying to talk students into extra projects. Oh, oh, so he has already talked you into filming a documentary about your favorite heroes of oceanography. That should be OK. His class could use a distraction before he subjects them to his medieval trial by water, the thermodynamics of seawater chemistry. It makes me shiver just to say the words. I bet that he is going to use you to keep his students enrolled until the course-drop deadline passes. Then he will slowly submerge them, bound and gagged, in his medieval water torture. Good luck with filming oceanographic history.

Julie: So Jordan and Janna are making a video. I wonder if they would cast a part for me.

Emily: You could be Artemesia, the most valiant lady in the history of naval warfare.

Laura: Yes, but the Greeks defeated the Persian Artemesia twenty-five hundred years ago.

Emily: I want to play Cleopatra, the most famous woman of all time.

Laura: She did great until she lost a major sea battle and then the Romans hunted her down like a dog.

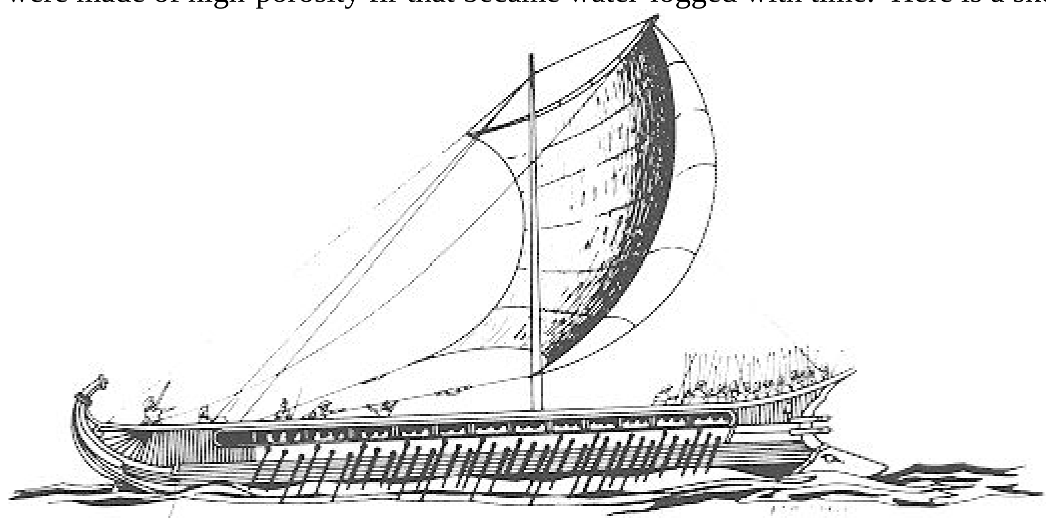
Emily: I give up. Maybe I could just be married to a naval hero and listen to his tales of glory rather than experience them. Dr. Bowles has mentioned that his grandmother's sister married a British Lord who was a captain during World War Two. I should adopt her motto, "Marry a rich man. You will soon learn how to love him." Their son did well, becoming the manager of Barclay's Bank on Oxford Street in central London.

Julie: The son did better than the father. The British Lord did not outlive the war. His World War Two mission was to supply American weapons to our Russian allies through Archangel. Archangel sits in a bay of the Arctic Ocean near Finland. Most American supplies to Russia were carried by English ships. However, the Germans managed to sink a large proportion of those English ships as they approached frigid Archangel. Guess how…

Emily, Laura, and Dr. Fondah (in unison) Submarines !!

Chapter 3: "How Seafarers Have Fared through Time" or "History-Making Hunks Have Had Hulls"

Janna: What shall we call this? I'm thinking: "How Seafarers Have Fared through Time".
Jordan: That's a wreck. How about "History-Making Hunks Have Had Hulls"?
Janna: If we circumnavigate the world in our own submarine, we too will be making history. In the meantime, we can alternate between these two titles and let Dr. Bowles decide. I hope that he will like the way we present the history of oceanography within the context of naval and cultural history. It looks like our cameraman is ready, so take it away Jordan.
Jordan: Advancement of mankind out of the Stone Age partly depended upon ships because ships are vastly more efficient than land transportation.
Janna: The Mediterranean Sea provided the early Western civilizations with easy access to all the resources that they needed to develop sophisticated lifestyles, once the Greeks and Phoenecians learned how to build ships that would take them all the way to England. In contrast, there is no central, ice-free sea within the Americas, so trade was more limited. Consequently, Columbus discovered a native population that was still in the Stone Age.
Jordan: Besides building trading vessels, the ancients constructed big warships to protect their merchant marine fleet. Marine research has been done by those with the dominant navy so we will start by reviewing the history of warships and naval battles. The most common marine warship among the Greeks, Egyptians, and Romans was a trireme, so-called because there were three rows of oarsmen stacked on successive levels. The crew numbered 200 and could lift the ship onto the shore. These boats needed to be dry-docked routinely because they were made of high-porosity fir that became water-logged with time. Here is a sketch.



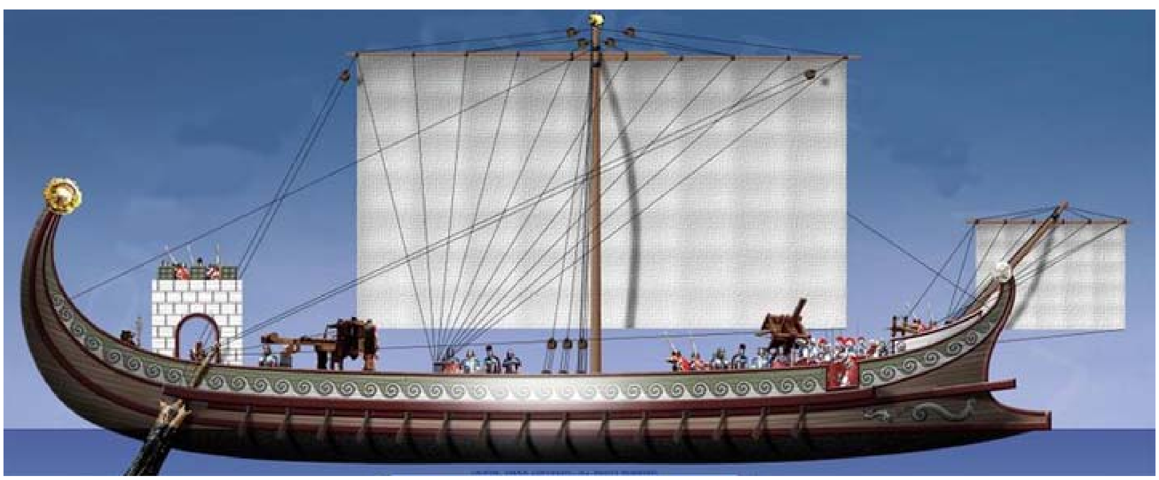
Janna: I see that the original Marines are grouped at the front, ready to board any ship that gets rammed with the forward-extending protrusion. I wonder how we can be sure of all this detail, given that none of these triremes ever became preserved. These ships were built with wooden pegs rather than nails, so all parts of the ship floated. Nothing ever sank to the bottom where it could become preserved like the Titanic.
Jordan: Besides written descriptions, the Greeks left carved images of triremes at the Acropolis of Athens. Unlike other civilizations, the Greeks manned their ships with fellow Greeks rather than with slaves. They have reconstructed a trireme and sail it proudly.

Jordan: Some historians believe that a naval battle in 480 B.C. decided the course of Western Civilization. A large Middle Eastern force attacked Greece with three times more ships than the Greeks could muster. If those Persians had won, they could have controlled all of Europe. However, the Greeks used false messengers, knowledge of local winds, and powerful rams on their triremes to win the battle.

Janna: The famous quotation from the Persian king, Xerxes, was that "My men have become women, and my women men." His best naval commander that day turned out to be a woman, Artemisia, who rammed nine Greek triremes. Many of Xerxes' Persians died because they did not know how to swim.

Jordan: The Greeks went on to rule the Western world until the Romans conquered them. A Greek who was the King of Egypt around 200 B.C., Ptolemy IV, wanted to impress the locals by building a ship that exceeded the length of a football field, including its endzones. This monstrous rowboat required a crew of 7400 and proved to be impractical. Nonetheless, Ptolemy succeeded in impressing his Egyptian subjects.

Janna: When Cleopatra and Mark Antony fought for control of the Roman Empire in 31 B.C., each of their couple hundred ships required a crew of 470, about twice that of a trireme. However, malaria had decimated their ranks and made the big ships difficult to maneuver, compared to the liburnian ships of Julius Caesar's adopted son, shown here.



Jordan: Cleopatra remains one of the most famous women of all time. In the 300 years of Greek rule of Egypt, she was the first of Ptolemy's descendents to learn the Egyptian language. Her love-child with Julius Caesar could have become the Roman Emperor if Caesar's adopted son, Octavian, had not assassinated him.

Janna: Those were wild times, both on and off the water. While being Cleopatra's lover, Julius Caesar had slaughtered a quarter of the Europeans living north of Italy, the Gauls. Some of those northerners, the Vandals, sacked Rome in 455 A.D. but had little interest in maritime exploration. They were farmers when not vandalizing beautiful cities. Consequently, the Mediterranean was open to the Muslims for several centuries. Given their desert roots, the Muslims preferred to hire Venetians to be their merchant marine.

Janna: In 1571, the Venetians and their Christian allies finally confronted the Muslims of the Ottoman Empire in the last great naval battle fought by rowed vessels. They fought at Lepanto on the western coast of Greece. It was an intimate affair, with the ships coming so close that it resembled a land battle more than a sea battle. There were nearly three times as many soldiers as sailors on those ships.

Jordan: Those ships were not like triremes. A small galley of that era is shown here. It seems that they used more cloth in their flags than in the oarsmen's clothing.

Janna: With improvements in cannons, the distances between opposing forces kept increasing proportionately until Horatio Nelson surprised the French and Spanish at Trafalgar by sailing right through their line of ships, blasting cannons all the way. The French and Spanish lost nearly all their ships while the British lost none. Napoleon lost his navy on that day in 1805.

Jordan: Through the next century, England dominated the global ocean and thereby acquired global political power that was vastly disproportionate to its population or land area. The area of England is almost identical to that of North Carolina. Its population through that century tripled from ten to thirty million but never exceeded 2% of the world population. It was the British Navy that allowed 2% to control 98%.

Janna: The century following the defeat of Napoleon has been called *Pax Britannica* because the British Navy practiced gunboat diplomacy. If the prospect of a local war threatened to disrupt lucrative marine trade, the British Navy would sail a gunboat within sight of the offending coastal city and threaten to open fire. Besides enhancing trade, the British used their naval superiority to establish an international postal service.

Jordan: Just as *Pax Britannica* started with the Battle of Trafalgar, the naval battle lost by Cleopatra and Mark Antony ushered in *Pax Romana*. This was a century-and-a-half of unprecedented peace secured by the Roman navy.

Janna: The only serious uprising during *Pax Romana* came from Queen Boudica of eastern England in 61 A.D. She took London but ultimately lost 150,000 English to less than a thousand Roman casualties. Despite his great military victory, the Roman commander was recalled because he had inspired the uprising by allowing his men to take liberties with the daughters of Queen Boudica. The Romans did not recognize Boudica as queen because Roman law, unlike English law, did not allow women to rule.

Jordan: The English playwright, Congreve, has the most famous description of what happens when men do not respect women, "Heaven has no rage like love to hatred turned / Nor hell a fury like a woman scorned."

Janna: After Boudica, the Romans were more careful not to be scornful and routinely recalled generals if they did not get along well with the local population.

Jordan: The Roman Empire, shown here, relied heavily on the navy. The navy could deliver tens of thousands of soldiers anywhere throughout the Mediterranean without fear of losing men to foreign powers at sea. The Empire was only limited by the distance inland that those soldiers could maintain their supply lines.

Janna: Today we live in *Pax Americana*, over half a century of relative peace since the day a few dive bombers destroyed the Japanese fleet near Midway.

Jordan: The era of colossal warships is past. It is now too easy to eliminate a large warship that costs a couple billion dollars with a sophisticated missile that costs just a couple million. The range of warplanes is now so great that one does not need to transport them on an aircraft carrier until they are close to their target.

Janna: Although big surface warships have become obsolete, navies will always have submarines.   Submarines are not so vulnerable to missile attack but are themselves good launch pads for missiles. The prime threat to a submarine is another submarine. (*an aside to Jordan)*.. So we will have to play romantic music or something to show that we are harmless.

Jordan: Now that we have briefly reviewed the history of warships and naval power, it is time to focus on the world's first major maritime research expedition, the British Challenger Expedition. By 1872, *Pax Britannica* had the English believing that they owned all the oceans. However, they were not sure what it was that they owned, so they outfitted a research vessel for global exploration, the HMS Challenger.

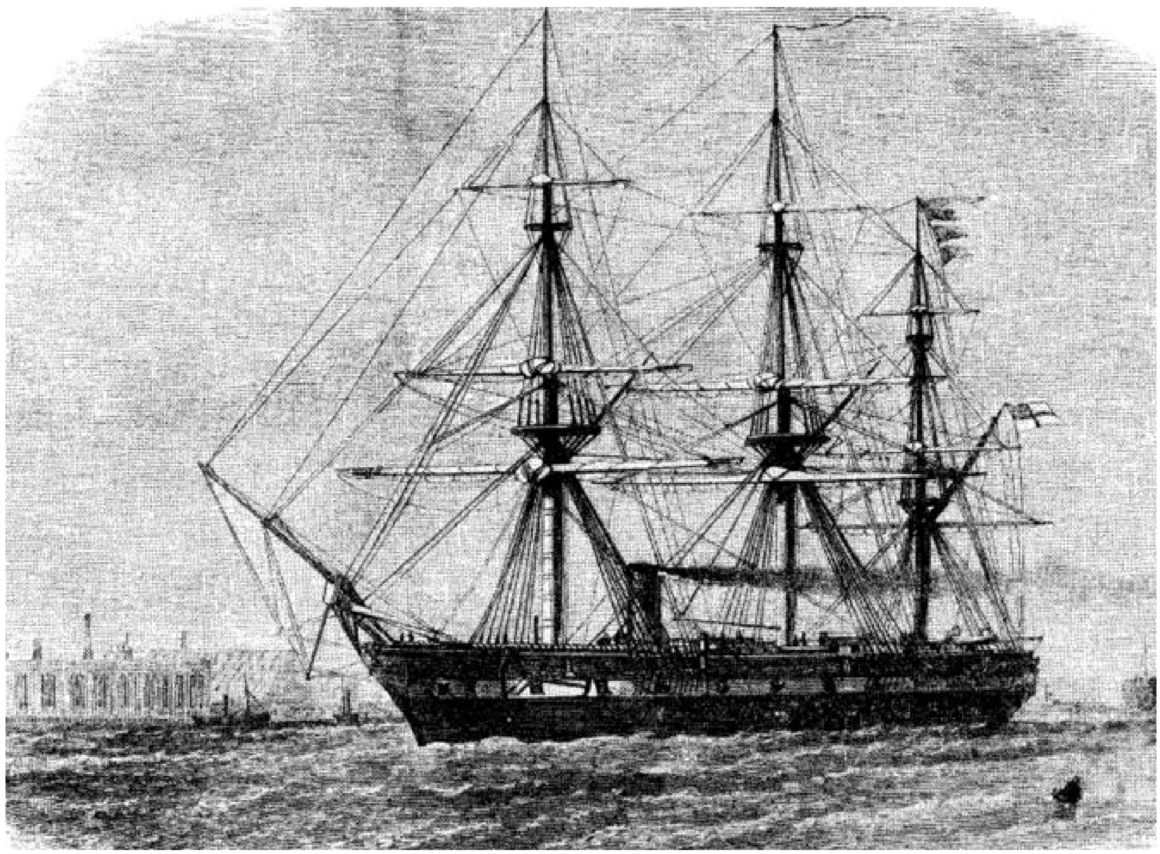
Janna: The history of the Challenger helps justify our inclusion of warships in this review of oceanography because the Challenger was itself a warship before it became a research vessel.

Jordan: The Challenger was part of the British-French force that attacked Vera Cruz, Mexico in 1862 while the US was preoccupied with its Civil War. Built in 1858, the Challenger had a 1200 horse-power steam engine in addition to its many sails. As a warship, it carried 17 guns but only two of those were left during its refitting for research.

Janna: The Challenger expedition is generally regarded as the most successful scientific expedition of all time, not just the most successful oceanographic expedition. When the expedition started, most oceanographers doubted if there was any life in the deep ocean because of the intense pressure, cold temperature, and lack of light. Moreover, they thought that a lack of deep currents would keep the temperature uniform.

Jordan: The predictions of the arm-chair oceanographers were all proved wrong during the three years of data collection and two decades of data analysis.

Janna: The Challenger carried 181 miles (290 km) of hemp for depth-sounding and dredging. Besides the daily ration of rum for every sailor, there was plenty of alcohol for preserving animals caught in a dredge or trawl. The expedition identified about 4000 previously-unknown species and traveled the equivalent distance of three times around the world. There were nearly 500 deep-sea depth soundings, thanks to their steam engine's ability to lift the lead weight and miles of rope needed to reach the bottom.



Jordan: The animals caught in deep-sea trawls and dredges proved to be closely related to animals that were already known from shallower depths. This disappointed some scientists who expected the deep animals to be the equivalent of fossil animals, not other living animals.

Janna: Another surprise for some scientists was that the tiny fragments on the deep seafloor, the so-called ooze, were parts of plants and animals that had originally lived at the surface of the ocean before settling to the bottom upon death. They had expected that the deep-sea sediment would consist of fragments of deep-sea animals. However, the sunlit surface of the ocean is vastly more productive than the deeper portions, so its debris overwhelms that of deeper contributors.

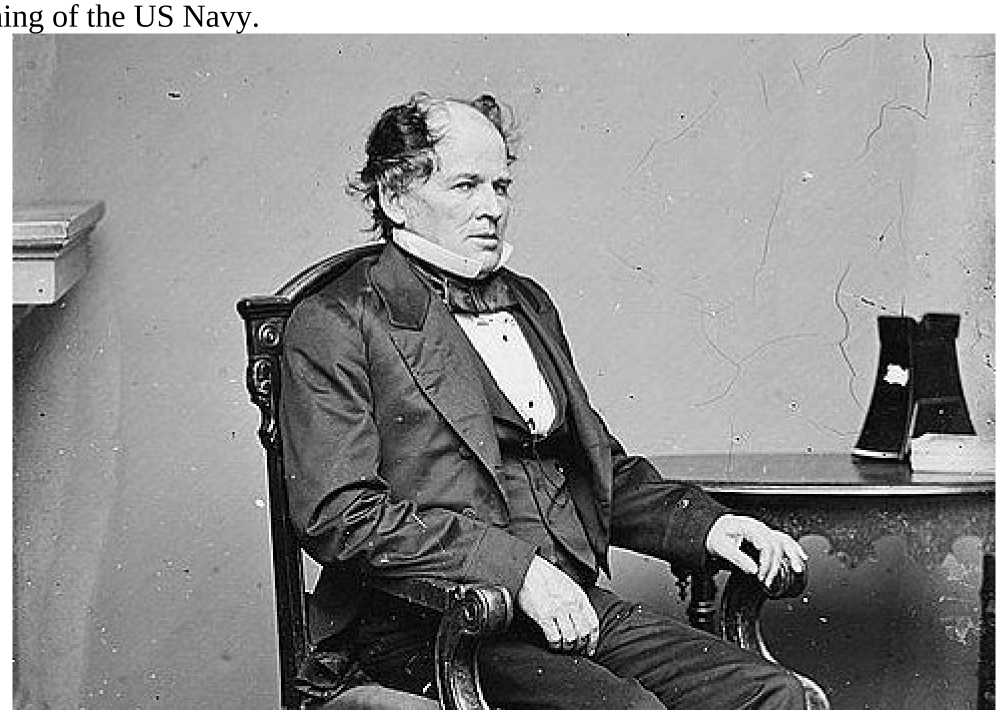
Jordan: Microscopes and chemical laboratories on the Challenger were under the command of chief scientist Thomson. However, Thomson died of exhaustion during the tedious post-cruise editing and it was left for his assistant, John Murray, to complete the 50-volume set twenty-four years after the Challenger had embarked.

Janna: Murray went on to become the most famous oceanographer of his day. In fact, he invented the term, oceanography. He teamed up with the Norwegians to launch an even more ambitious research cruise than that of the Challenger. The resulting book in 1912 became the prime text for oceanography. Here is Sir John Murray. Like all famous scientists, Sir John had his detractors. An octopus that is named after him, *Cirrothauma* murrayi, lives deeper than a mile (1.6 km) and cannot recognize objects. A lack of objectivity has characterized some other highly-productive scientists.

Jordan: Although Murray was entirely funded by the British, he was born in the Americas (in Canada) and was the first world-class oceanographer from what some British call “the other side of the puddle”.

Janna: Ironically, the first full-time oceanographer in the United States had a similar-sounding name, Maury. Maury’s grandfather was an educator who had three students that went on to become presidents: Thomas Jefferson, James Madison, and James Monroe.

Jordan: In 1842, Maury became the first superintendent of the US Naval Observatory and undertook a synthesis of captain’s logs that had accumulated without analysis since the beginning of the US Navy.



Janna: In a sense, Maury made his observatory the successor to the library in Egypt that had been established by a student of Aristotle. Every ship entering Egypt had to provide all documents to be copied for the library. The Egyptian library thereby became the best in the world.

Jordan: Maury certainly assembled the best record of currents and winds around the Americas. However, he became an advocate of the Northwest Passage, the hypothetical passageway between the Atlantic and Pacific north of Canada. Many American adventurers disappeared trying to find such a passage. Their bravery went unsung because "dead men don't tell tales".

Janna: Having been born in Virginia, Maury fought for the Confederates during the Civil War. He invented an electric torpedo that worked like a modern contact mine. This torpedo sank more US shipping than all other Confederate devices combined.

Jordan: After the war, Maury taught at the Virginia Military Institute and helped to found what has become the world's largest general scientific society, the American Association for the Advancement of Science. In fact, it is a good bet that Dr. Bowles is a member of that society.

Janna: A contemporary of Maury was Charles Darwin. In the same year that Maury initiated the US Naval Observatory, Darwin published his explanation of coralline atolls in the Pacific. Darwin deduced that volcanic islands had subsided while the corals fringing them were growing upward. Atolls had become the remnants of coral reefs, surrounding a subsided volcano. Beneath the atoll and its enclosed lagoon lay the unseen volcano. This flash of insight foreshadowed Darwin's genius in his "Origin of Species".

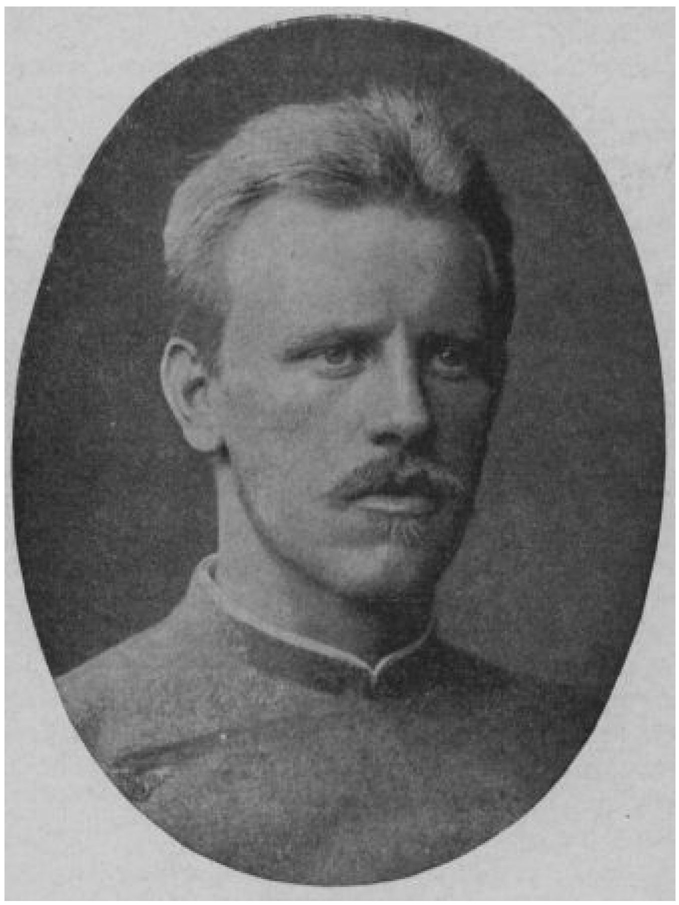
Jordan: Darwin's early autobiography, "Voyage of the Beagle" has been posted to the Web and makes for great reading. Several of these early oceanographers published similar accounts of their sea-faring adventures and thereby established oceanography as one of the world's most popular academic pursuits. Everyone wanted to become another Darwin and sample the fruits of foreign fields as he did.

Janna: I suppose that the equivalent adventure today would be in a submarine. I wonder if Dr. Bowles knows anyone brave enough to try that.

Jordan: Moving right along, we get to the Norwegians, Nansen and Sverdrup, who took a round-hulled ship into the Arctic in 1893 and allowed it to be frozen into the ice and drift along for four years, trying to reach the North Pole. Given the shape of the hull, the ship rose as the ice compressed against it.

Janna: This pair of cold-blooded oceanographers had become friends five years earlier by skiing across Greenland. I would call that the ultimate in cross-country skiing.

Jordan: When they got within about 600 km (400 miles) of the North Pole with their boat, Nansen decided that drifting with the ice would get them no closer, so he set out on foot, leaving the ship to Sverdrup. He only got a third of the way when he had to turn back, but he could not make it to the ship, so he tried to reach a charted island. Unfortunately, the island did not exist, so he wandered the Arctic until he luckily ran into a British expedition. He had survived on walrus blubber and polar-bear meat. When he finally got home, Nansen wisely decided that he should spend more time lecturing and less time wandering.

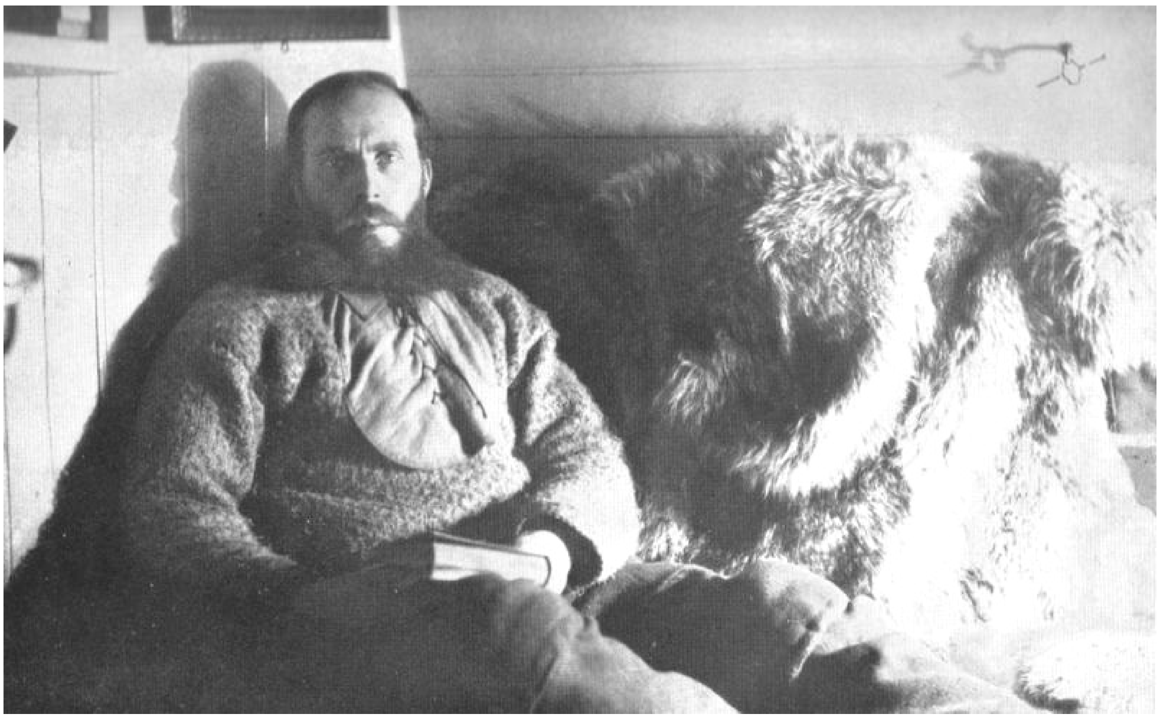


Janna: Nonetheless, Nansen was to leave his mark on oceanography in many ways. He invented the first practical bottle for sampling water from any depth in the water column. He also pioneered the study of sea-ice formation and thermal conductivity. Most importantly, he demonstrated that there is no continental landmass under the Arctic, contrary to the popular opinion in his day.

Jordan: Nansen had started his academic career as a zoologist and had discovered the neural network that animals use for communication. Following his oceanographic work in the

Arctic, he went on to politics and became the Norwegian ambassador in London. He was awarded the Nobel Peace Prize in 1922.

Janna: Meanwhile, Sverdrup continued roaming around the Arctic, and eventually discovered the group of islands that bear his name north of mainland Canada. He claimed these for Norway and returned home to a jubilant reception. However, Canada and the US were not keen on having a European power on their doorstep so they pressured Norway until it abandoned its claim to the islands in 1930. In 1931, Canada purchased Sverdrup's original charts for $67,000. Here is Sverdrup on his initial voyage with Nansen.



Jordan: If you are going to drift around the Arctic for four years locked in ice, I am sure that a good book and a warm fur blanket would be welcome company.

Janna: As impressive as the exploits of Nansen and Sverdrup were, Iceland was discovered long before by a more impressive Greek, Pytheas, way back in the time of Alexander the Great. Starting in southern France, he circumnavigated Britain and established the names, Britain and Germany. He managed to navigate using the North Star and approached the Arctic Circle, thereby discovering pack ice, aurora and ultimately the midnight sun.

Jordan: From *Pax Romana* to *Pax Britannica*, we skipped the Vikings and Columbus. Although not very peaceful times, the era from 900 to 1800 A.D. produced some great explorers. Perhaps the most impressive were the Vikings who established colonies in the Americas five hundred years before Columbus.

Janna: The Vikings took open boats through the rough and frigid North Atlantic, island-hopping from Iceland and Greenland into Newfoundland, Canada. Erik the Red started by colonizing Greenland in 985 A.D. This was a time of global warming, a global trend that warmed the hearts of Vikings.

Jordan: One of the new colonists missed Greenland by sailing too far south and ended up in Newfoundland. When Erik the Red heard about that land, he colonized it too. However, global warming turned to global cooling and the colonists suffered crop failure. Although they ultimately disappeared, the colonies lasted about 450 years, almost until the time Columbus landed.

Janna: Columbus was a high-powered salesman who toured royal palaces in Europe with his scheme of acquiring riches from the Orient by sailing westward. He first approached the Portuguese because they were the best sailors of that era. However, in the midst of the negotiations, a Portuguese explorer returned from the first trip to the Orient around the southern tip of Africa.

Jordan: The Portuguese concluded that they did not need Columbus and his scheme of heading across the Atlantic. Moreover, the Portuguese were smart enough to realize that the world was nearly twice as big as Columbus was estimating it to be. He and his crew would starve before reaching Japan if they headed westward.

Janna: Columbus approached Henry the Seventh of Britain but the British were as reserved as ever and it took them so long to agree that Columbus had already found a partner in Spain.

Jordan: Columbus has born in Italy and secured half of the needed resources from his Italian countrymen. Even though the Spanish oceanographers knew as well as the Portuguese that the world was about twice the size estimated by Columbus, the Spanish king overruled them. He knew that this was a fairly cheap bet, compared to the potential winnings.

Janna: The Spanish king's whim proved to be better than the collective knowledge of his scientific experts. The experts were right, but Columbus happened to run into something on his impossibly long voyage to Japan. He ran into America.

Jordan: As suggested by this painting, Columbus soon got his fingers into too many pies and the Spanish monarchy arrested him eight years after his famous first voyage.

Janna: Columbus had demanded that he be the governor of all newly-discovered lands but the monarchy reneged on that part of their contract. When Columbus announced that he opposed their decision, the monarchy effectively replied, "So you oppose us. You and whose army?"

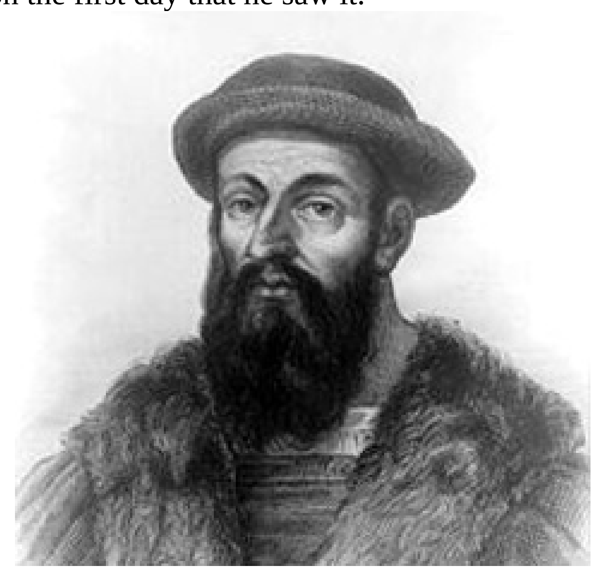
Jordan: Considering his pivotal role in global marine exploration, Columbus was not much of a navigator. He kept a false log to show his crewmen and another ship's log that he considered to be accurate. It turned out that his invented log was closer to reality than his official ship's log.

Janna: Despite being a poor politician and a worse seaman, Columbus set off the world's greatest land rush. Emigration to the Americas remains a worldwide dream for billions of people.

Jordan: So far, we have ignored the world's most extensive ocean, the Pacific. The Pacific has about half of Earth's ocean surface whereas the Atlantic has just a quarter. The Indian Ocean has nearly all of the remaining quarter. Getting across the vast distances of the Pacific has represented a bigger challenge than getting across any other ocean.

Janna: The first sailors to cross all of the major oceans, the Pacific, Indian, and Atlantic were those with Magellan. Of the original crew of 270, only 18 survived the three-year voyage that ended in 1522. Magellan was not one of those who successfully circumnavigated the world, given that he foolishly tried to take on 1500 Filipinos with just 50 men.

Jordan: Before succumbing to that imprudence, Magellan had discovered galaxies not visible in the northern hemisphere, now called the Magellanic Clouds. He discovered penquins and llamas. Of more universal fame, it was he who named the Pacific because the great ocean happened to be calm on the first day that he saw it.



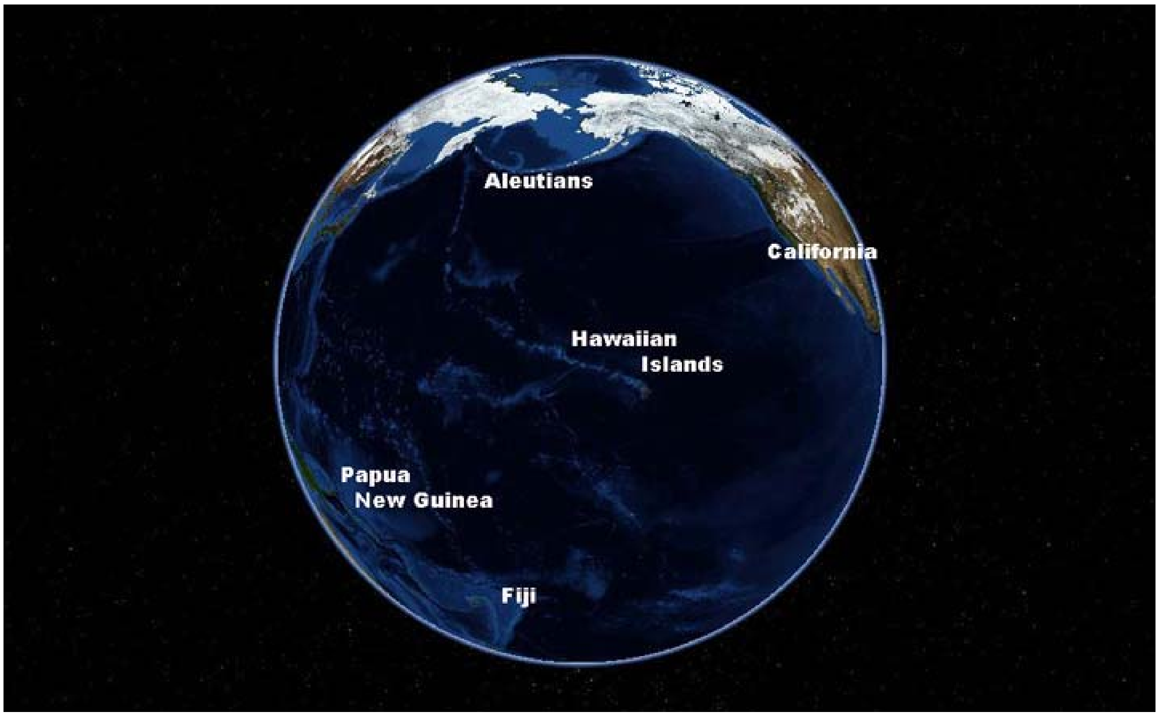
Janna: Although Magellan's expedition lost four of their five ships, the few remaining crewmen still brought back enough cloves and cinnamon to pay all their original expenses and turn a profit. It is difficult to imagine that something for sale today in any grocery store was once so valuable that it spurred the first circumnavigation of the globe. A couple hundred men died for some cloves and cinnamon !

Jordan: Long before Magellan crossed the Pacific from the east, Asians had come from the basin rim to populate most of the islands. Although these people lacked the engineering skill of the Greco-Roman civilization, they proved to be more successful and more daring as navigators.

Janna: The Westerners had preferred to stay within sight of land whereas the Pacific natives rarely saw land along any of their long voyages. They relied upon a wide variety of navigational tools in addition to the star-gazing practiced by the early Greeks.

Jordan: The Pacific natives wisely interpreted wind, wave, and current patterns. Most cunningly, they followed the migratory patterns of birds. Proximity to land was determined by releasing a trapped frigatebird. A frigatebird cannot land on water without becoming too waterlogged to fly, so it would have to return to a native boat if it could not find land. If it did not return, the natives would study the waves because an island forces the waves to bend.

Janna: The distances between some Pacific islands are staggering. For some ancient as well as modern people, the ultimate destination has been Hawaii. Given the number of modern tourists, it is hard to imagine that Hawaii is the most isolated extensive lush place on Earth, separated by about 2000 miles (3200 km) from any other substantial location.

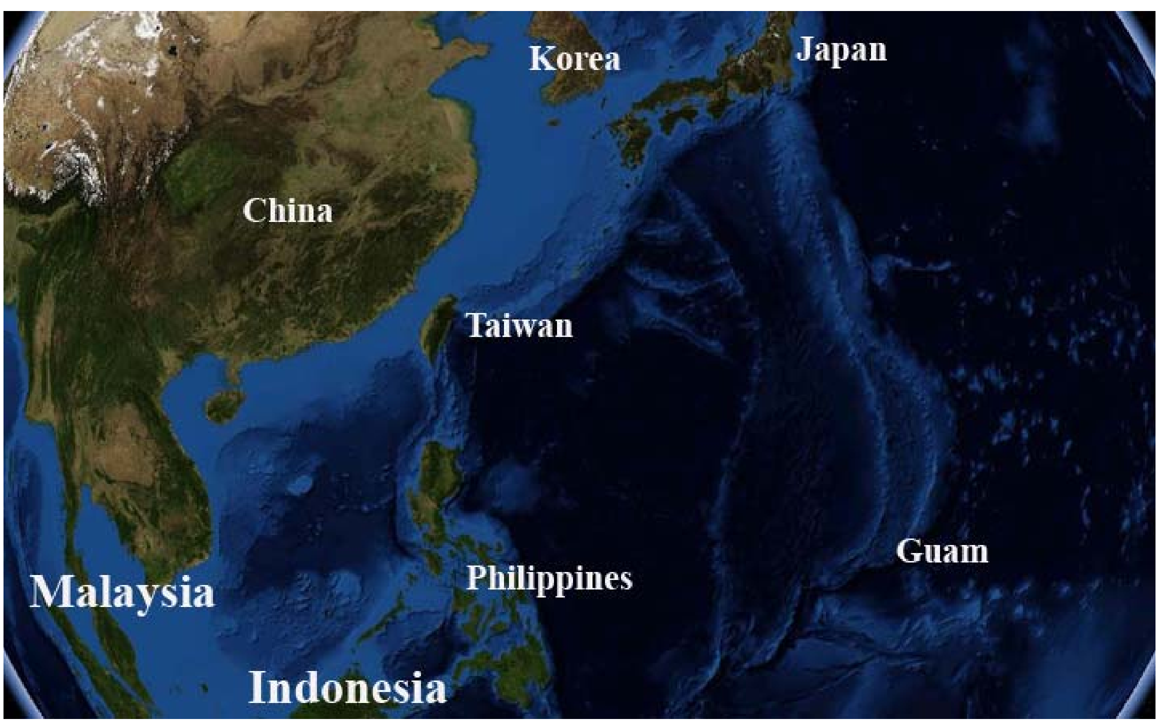


Jordan: The first recorded European tourist to reach Hawaii was the most famous of all British explorers, Captain James Cook. Unfortunately, he became angry when a minor chieftain stole one of his rowboats and Cook tried to hold a Hawaiian king for ransom. Like Magellan, he learned too late that the Pacific Islanders can be deadly when provoked.

Janna: In particular, the natives had the same inclination as did the European combatants, to concentrate on the leader, in this case Captain Cook.

Jordan: It was 1779 before Cook reached the Hawaiian Islands. The Polynesians already had been there for at least eight hundred years. They had not arrived in a massive Navy ship like Cook but in a double-hulled sailing canoe that was a bigger version of the one shown here. Given that they had to go farther than anyone else, they designed a vessel that enabled them to move faster than anyone else on Earth.

Janna: Long before Magellan and Cook crossed the Pacific from the east, Asians had come from the west to populate the Pacific islands. These Austronesian people had first migrated across Asia to reach Taiwan, off the coast of China, about four thousand years ago.



Jordan: From Taiwan, they spread southward to the Philippines, Indonesia, and Malaysia. They also spread eastward to all the sizeable islands across the vast Pacific Ocean. Most scholars assume that the Polynesians, a subset of the Austronesians, paddled northward across the windless equatorial region to reach Hawaii, 2000 miles (3200 km) to the north.

Janna: However, some scholars note that migration from Taiwan also was northward, around the Pacific rim to the Aleutians, and that Hawaii could have been populated from the north.

Jordan: Apparently, there is some DNA evidence to support the theory that native Hawaiians are displaced Alaskans. I must admit that I would have volunteered for that colonizing venture. The southern Polynesians were already living in a tropical paradise. Why would these men risk the longest non-stop voyage that anyone had accomplished?

Janna: Men? If they had all been men, they would not have given rise to the enchanting Hawaiian culture. I need my picture taken in a Hawaiian feather cloak.

Janna: Nowadays, a non-stop flight is the most desirable type of flight but a non-stop voyage in ancient times was to be avoided, given that you were correspondingly more likely to run out of drinking water.

Jordan: Despite having slower ships, Westerners established colonies across the Pacific much more quickly than had the Austronesians a millennium before them. Austronesian populations dwindled with the initial contact, just as the Native American populations diminished catastrophically with the first influx of Spanish.

Janna: Seafaring exploration in the 1500's and 1600's brought devastating diseases to the Americas. This pattern was repeated in the Pacific in the 1700's and 1800's.

Jordan: When Cortez entered Mexico City in 1521, he found that half of the residents were dying of smallpox even though the Spanish had been in Mexico for just a year. This pattern continued for four centuries until the British takeover of Fiji, north of New Zealand. One-third of the native population succumbed to measles in 1875-76.

Janna: Marine exploration could have had the opposite effect. Westerners could have been decimated by native diseases when they traveled westward. In fact, eastward travel by Europeans has repeatedly had the opposite effect. As Europeans pushed eastward again-and-again into India, they kept encountering new deadly diseases.

Jordan: Typhus was unknown in Europe until it was brought back from the Middle East by the First Crusade a thousand years ago. Napoleon attempted to rival the distant exploits of the Crusaders by acquiring Moscow in 1812. In the process, he inherited Moscow's rat population and the typhus-carrying lice on those rats.

Janna: Napoleon and his army tried to escape the resulting typhus epidemic but most died. Typhus proved to be a more potent enemy than either the Russian winter or the Russian army.

Jordan: Like typhus, smallpox was unknown in Europe before the Crusades. Although most other epidemic-generating diseases are carried by a bacterium, smallpox is carried by a virus. In dense populations, it spreads like the common cold.

Janna: Following introduction of smallpox by returning Crusaders, one-third of Europeans died from the disease and another third acquired permanent pockmarks.

Jordan: The survivors produced descendants who could carry the virus without ill effect to themselves but the latent virus produced a devastating effect on the native Americans and Austronesians who they encountered during oceanographic exploration.

Janna: When the British pushed into India, they brought home the first known cholera pandemic. It raged for a decade, starting in 1816. The British brought the disease back to western Europe where both they and the French became hard-hit. A hundred thousand died in France.

Jordan: Outbreaks continued for the rest of the century, with the Russians losing a million people in the third pandemic. Even Tchaikovsky died from cholera.

Janna: In the United States, Chicago lost the most. However, it was cholera in New Orleans that brought down Former President James Polk in 1849.

Jordan: Like smallpox, measles is a virus. Although the European invasion of the Americas doomed the natives with both smallpox and measles, it is those very invaders who have developed vaccines to both diseases.

Janna: Merck®, an American company since 1917, developed the first commercial vaccine for measles in 1963.

Jordan: Three thousand years before a measles vaccine was developed in America, a smallpox vaccine had been developed in India. They took dried pustules from the pockmarks on survivors and rubbed that powder into scratches on people without smallpox.
Janna: This was not an ideal vaccine because roughly 2% of those treated developed full-blown smallpox and died. However, those odds were still better than the 7% chance of dying without vaccination during an epidemic. Consequently, this type of smallpox vaccination became popular in Europe in the 1700's.
Jordan: Meanwhile, Americans were slow to adopt vaccination. Instead, the entire population of Boston abandoned the city in 1721 and wolves roamed through the native villages touched by smallpox. The inhabitants were too weak to defend themselves.

Janna: The history of oceanographic exploration was a sad one for native populations that once controlled more than half of the globe. Their devastation primarily came from enemies that were too small to see.
Jordan: On that note, we conclude our brief review of the history of oceanography.

… Janna and Jordan look at each other, shrug, and remove microphones from their lapels.

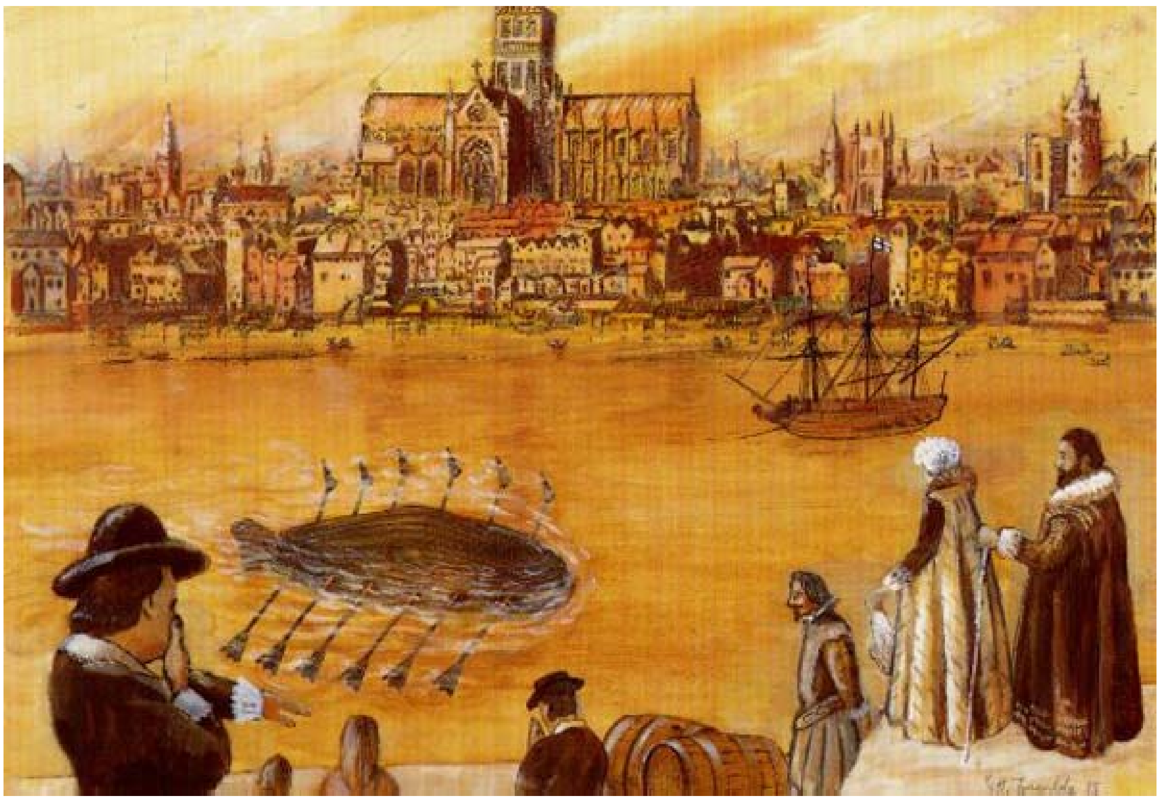
Dr. Bowles: That was pretty good, girls, but I know that Dr. Bubah is going to have a fit. I can hear him now.
Dr. Bubah: Bowles, you wimp, how could you let a pair of women review oceanography? You should have known that they would spend half their time bemoaning the fate of those indolent savages instead of praising the brave oceanographers who guided our expeditions. Those early oceanographers acquired the riches which our society now enjoys. Besides, the history of oceanography did not end with pandemics. Get them to tell us about the amazing

inventions through the past hundred and fifty years. Given those inventions, oceanography has advanced farther in that time interval than it did in all of previous history.

Dr. Bowles: Well, girls, it seems that Dr. Bubah is juiced up again. Do you want me to send him to the Austronesian cannibals where he could be literally stewing in his own juices?

Jordan: That is a tempting prospect but we will try to turn down Bubah's fire by progressing beyond the Austronesian era, the time when ocean explorers brought all remaining human races into contact with Europeans, for better or worse. Oceanography subsequently changed with the introduction of submarines, steel hulls, wireless communication, and diesel engines.

Janna: The first large submarine was invented in 1620 by the same genius who invented the dual-lens microscope, mercury thermostat, and thermometer. His patron, the King of England, became the world's first monarch to travel under water.

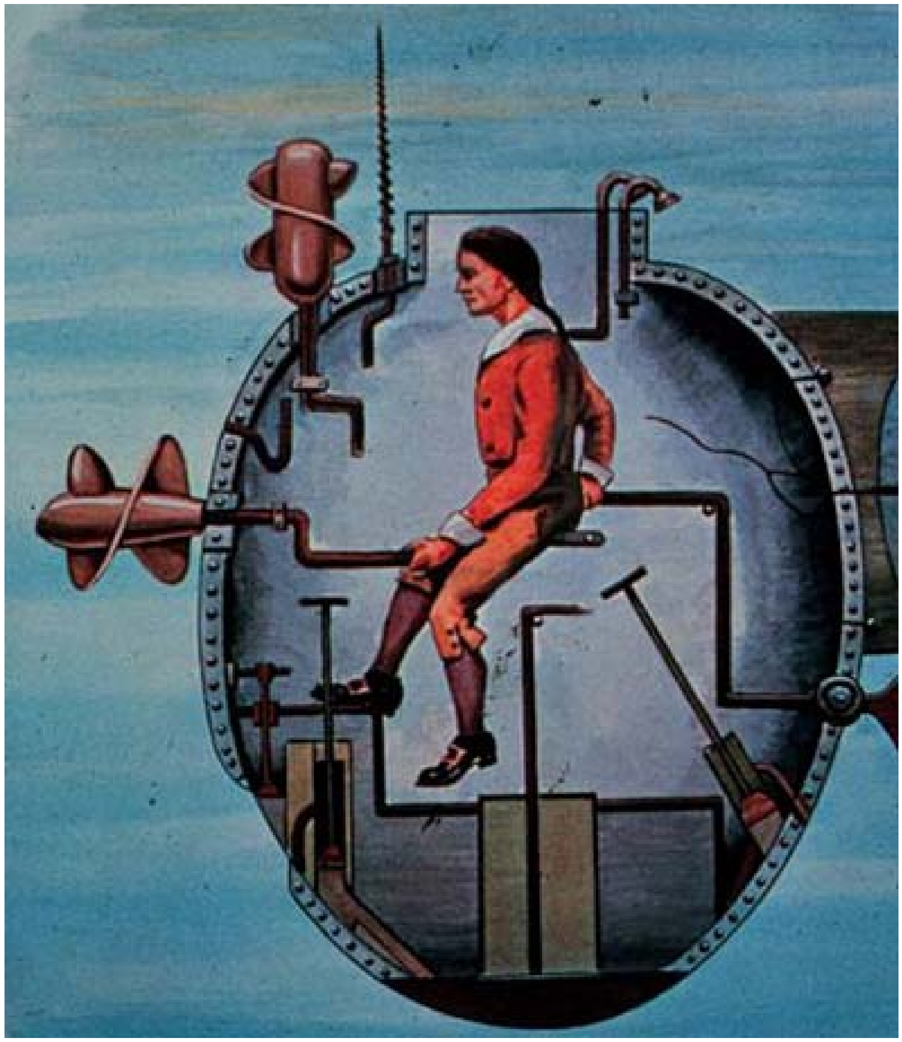


Jordan: As is evident here, the king's submarine was rowed. A crew of 16 kept it submerged about 4 to 5 meters (yards) for up to three hours. The sub had a wooden frame covered in leather.

Janna: Although a scientific success, the Royal Navy could not envision any military application for the submarine, so funding of its development was terminated and its brilliant inventor, Cornelius Drebbel, died in poverty.

Jordan: I can hear those crusty British mariners now. "*Watch out. Here comes Drebbel's pufferfish. It might smear you*".

Janna: A century and a half later, the British were not so glib when they faced an American patriot in the world's first military submarine, financed by George Washington. This one-man sub was designed to drill through the hull of a British warship and implant explosives. A timed fuse allowed the sub to escape.



Jordan: Upward and downward motion where controlled with a ballast pump that admitted or expelled seawater beneath the operator, changing the sub's mass. The sub also had a hundred kilograms (couple hundred pounds) of lead that kept it upright and could be jettisoned for rapid resurfacing.

Janna: The main limitation on operating the device was oxygen supply. Ben Franklin recommended lighting the interior with bioluminescent foxfire, a wood fungus, because a candle would have consumed precious oxygen. However, the foxfire did not work well because its luminescence diminished in the cold marine environment.

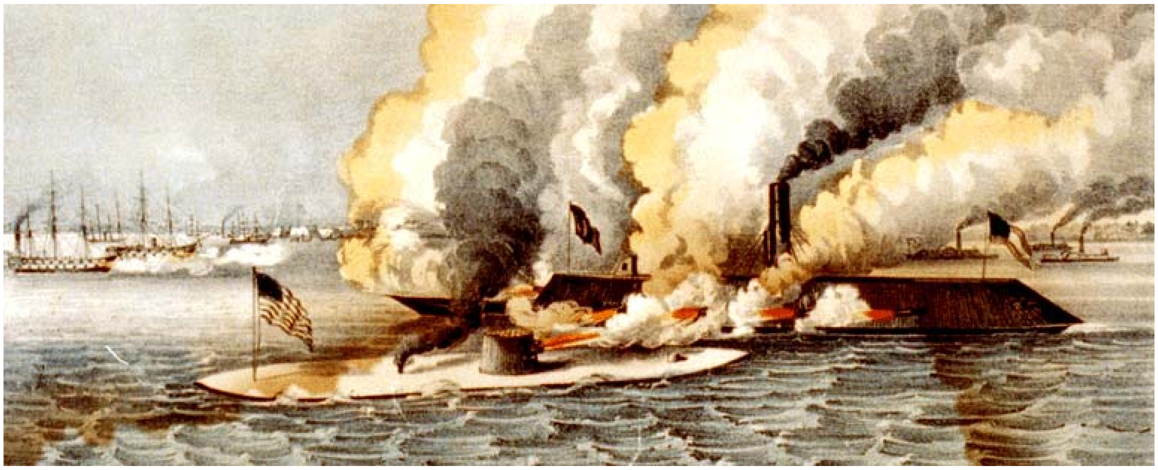
Jordan: One thing that did work well was the screw propellers, both horizontal and vertical propellers that allowed the sub to travel about 5 kilometers per hour (3 miles per hour). This was the first use of screw propellers for locomotion. It would be another century before screw propellers became commonplace on ships.

Janna: Performance of the sub against British warships was poor despite its ingenious design. Implementation of the attack sub required an appreciation of oceanography but the issue of tides and currents was not taken very seriously.

Jordan: The target warship lay off the southern tip of Manhattan where it was blockading the New York Harbor. Here, the interplay of Hudson River current, East River current, and the tide made it impossible to hold the one-man sub against the warship long enough to drill through its copper-clad hull.

Jordan: The sub bobbed to the surface and the British gave chase in rowboats. They could have overtaken the sub but the operator jettisoned his keg of gunpowder and that scared off the British.

Janna: A century later, the American Civil War introduced another major innovation, ironclads. By the time the USS Monitor and the CSS Merrimac-Virginia had given up bouncing cannonballs off each other, every navy in the world was ready to switch to ironclad ships.



Jordan: The Confederates were so confident of their ship's resistance to cannon fire that they equipped it with a ram, reminiscent of the trireme ram of ancient Greece. Ignoring cannon fire, the Virginia's ram proved very effective against wooden ships until the Union's ironclad, the Monitor, arrived.

Janna: The world's biggest naval battle following Napoleon's defeat at Trafalgar was the Russian-Japanese engagement of 1905. The Russians were trying to stop the Japanese from taking Manchuria. They had already lost their fleet in Port Arthur, the port city that commands the bay leading to Beijing and Manchuria.

Jordan: The Japanese mined the exits from Port Arthur, blockading the fleet, and then overran the land defenses with innovative military devices. The half-year-long battle involved huge mortars, rapid-firing howitzers, machine guns, bolt-action magazine rifles, hand grenades, barbed wire, and electric fences. The 28-centimeter (11-inch) mortars could project a 500-kilogram (1100-pound) shell 8 kilometers (5 miles).

Janna: The Russians faced so many massed attacks on their hilltop defenses that they emplaced naval mines on land to interrupt the Japanese assaults.

Jordan: Despite these defensive measures, the Japanese eventually captured the hilltops. From there, they destroyed the blockaded fleet, as shown here. The Russians were sitting ducks.

Janna: With their Pacific Fleet reduced to scrap metal, the Russians decided to bring their Atlantic Fleet around Africa and into the Pacific. The distance was a staggering thirty-three thousand kilometers (eighteen thousand miles). This is more than 80% of Earth's circumference.

Jordan: Russia, a country with sixty times the land area of Japan, was about to be humiliated in one of the greatest naval disasters in history. Heading for Vladivostok, the Russians tried to slip through the Tsushima Strait between Japan and Korea.

Janna: Sailing close to Japan, they were detected and soon faced a massive onslaught from battleships that could move nearly twice as fast as theirs. The Japanese guns had greater range, greater accuracy, and delivered a more potent explosive.

Jordan: The Russians lost virtually their entire fleet in 1905. More than 4000 sailors died and about 6000 were captured. News of the disaster spurred revolutionary activity throughout Russia.

Janna: The Romanov monarchy that had ruled Russia for three hundred years suppressed the revolts and did not modernize the military in time for the First World War. The Romanov czar made his cousin commander-in-chief even though he had not been involved in developing war strategy. Caesar, the role model for the czars, would not have been so dumb.

Jordan: The Russians were thoroughly defeated in the first major battle of the war because they foolishly failed to encrypt any of their messages. They naively believed that none of the Germans could understand someone speaking Russian.

Janna: The Romanovs were intermarried with Germans so they became increasingly unpopular as the war progressed. Russia became the most miserable place in the world's most miserable war. With no country left to govern, the Romanovs abdicated.

Jordan: In came the Communists, led by Lenin, a Russian exile who had been living in German-speaking Switzerland. Lenin soon signed a peace treaty with Germany, allowing Germany to move troops to fight in France.

Janna: Fearing global German ambitions, the United States drafted four million soldiers and looked to its navy to deliver them to Europe despite the threat of German submarines. American submarines accompanied those convoys and the new soldiers turned the tide in the world's deadliest war, a war that killed forty million worldwide.

Jordan: A couple months before the war ended, Lenin was accused of being a German agent and suffered an assassination attempt that left him unable to govern his chaotic country.

Janna: The US Navy then assumed an important role for a couple of years as it supplied the American Expeditionary Force in both eastern and western Russia.

Jordan: In the wake of Russia's political chaos, the American task was to get the trans-Siberia railroad operational again, to feed the starving masses, and to remove 40,000 Czech soldiers left over from the war.

Janna: The most famous humanitarian in this effort was the Norwegian oceanographer, Nansen, who we have previously discussed. Nansen led a Red Cross effort to feed somewhere between seven and twenty-two million Russians who were starving in 1921 and 1922.

Jordan: In 1922, Nansen became the only oceanographer to ever receive a Nobel Peace Prize.

Janna: Given American and Scandinavian help at stabilization, Russia was able to become a more potent enemy against the Germans by the outbreak of the Second World War.

Jordan: By that time, Russian communications had become more sophisticated. The naïve use of battle radios by the Russians in 1914 reminds me that we should review the development of wireless communication in oceanography.

Janna: Wireless communication revolutionized seafaring because oceanographers could then be warned about approaching storms and naval ships could be coordinated centrally.

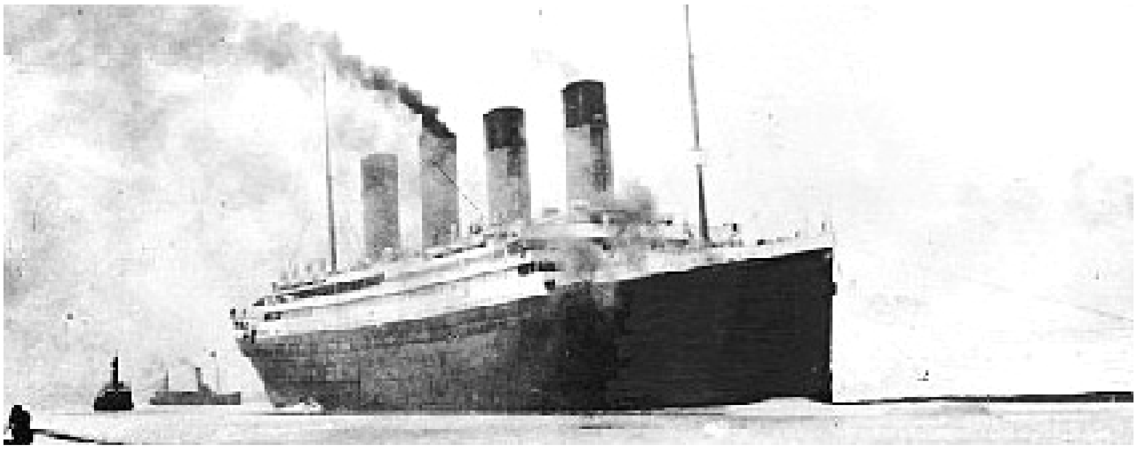
Jordan: Wireless technology was initially developed by the Serbo-American Tesla who alternately worked for Edison and then Westinghouse. However, an Italian-Brit named Marconi was the first person to telegraph a message over a water body.

Janna: Just before 1900, Marconi ushered in a new millennium by transmitting a Morse code message across the English Channel. A couple of years later, he transmitted across the Atlantic Ocean.

Jordan: Tesla responded that Marconi was using seventeen of his patents. However, Marconi continued to prosper and it was his employees who manned the radios on the ill-fated Titanic in 1912 rather than employees of Titanic's parent company.

Janna: Marconi boarded the rescue ship as soon as it docked in New York, looking for his men. Marconi had to testify at the inquiry into the Titanic tragedy, explaining the role of his wireless telegraphy.

Jordan: Discovery of the sunken Titanic in 1985 has been one of the great success stories of modern oceanography. Here is the Titanic leaving port in 1912, followed by a view of its magnificent spiral staircase.

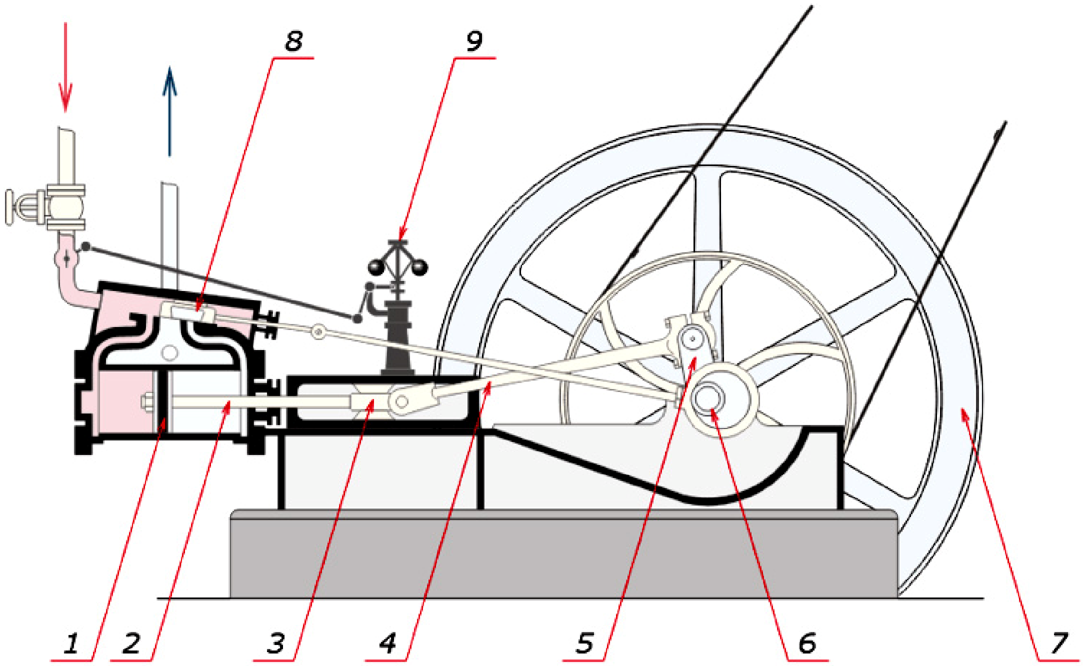


Janna: The staircase was reconstructed for the 1997 blockbuster movie starring DiCaprio. The star-crossed lovers in that movie became enamored with each other while at the bow. After discovery of the sunken ship by Massachusetts' Woods Hole Oceanographic Institute in 1985, we can see that the famous bow is fairly well-preserved.

Jordan: In contrast, the Woods Hole team found that the rest of the ship had collapsed inward as it sank to a depth of 3800 meters (4000 yards). The bow had separated, allowing the inside and outside pressures to equilibrate.

Janna: The Titanic was powered by coal-generated steam and had two types of steam engines, a piston engine and a turbine. In 1769, James Watt had developed the first steam engine that operated at a pressure greater than atmospheric. This revolutionized ship propulsion and initiated the Industrial Era in which we still live.

Jordan: Here is a basic steam engine. The horizontal piston receives high-pressure steam at one end and then the other. As a valve is allowing high-pressure steam to enter one end, the valve at the other end is allowing exhaust steam to escape. The piston is connected through a crosshead bearing to a rod that rotates a flywheel. The flywheel turns a belt that does work such as turning the paddles on a paddle steamer. A centrifugal governor helps to regulate the influx of fresh steam.



1 = piston	**2** = piston rod	**3** = crosshead bearing
4 = connecting rod	**5** = crank	**6** = eccentric valve motion
7 = flywheel	**8** = sliding valve	**9** = centrifugal governor

Janna: An American, Robert Fulton, built the world's first paddle steamer in 1803 and operated it on the Seine of France. Three years earlier, Napoleon had paid him to build the world's first military submarine. Fulton named it the Nautilus.

Jordan: Despite having been born in France, paddle steamers became the lifeblood of the Mississippi by the time of Mark Twain. Some have become reincarnated as modern floating casinos. However, these boats have rarely ventured far into the open ocean because they cannot survive high seas.

Janna: A basic feature of most steam engines is that one may reverse the engine by alternating the steam-entry sequence on opposite sides of the piston. In the Titanic disaster, they tried to steer around the iceberg rather than reverse the engines. If they had reversed the engines while maneuvering the ship, the Woods Hole oceanographers might not have had this great prize to find on the Atlantic seafloor.

Jordan: In our discussion of the British Challenger Expedition, we noted that the steam engine first aided oceanography back in 1872. Without a steam engine, they could not have lifted a depth-sounding weight through miles of seawater.

Janna: Just as the coal-fired Titanic was sinking, the first diesel-powered ships were launched. Since 1960, diesel engines have become the norm for ships just as they have become the norm for locomotives and tractor trailers.

Jordan: A diesel engine is much like a gasoline engine except that ignition is achieved through compression rather than a spark. Incoming air is compressed so strongly that its temperature rises to about 800 degrees Celsius (1500 degrees Fahrenheit).

Janna: When the diesel fuel becomes injected into the hot air at high pressure, it instantly combusts and pushes the piston away, making the characteristic knocking sound of a diesel engine. At the maximum stroke position, the combusted gases are ejected and compression of new air begins.

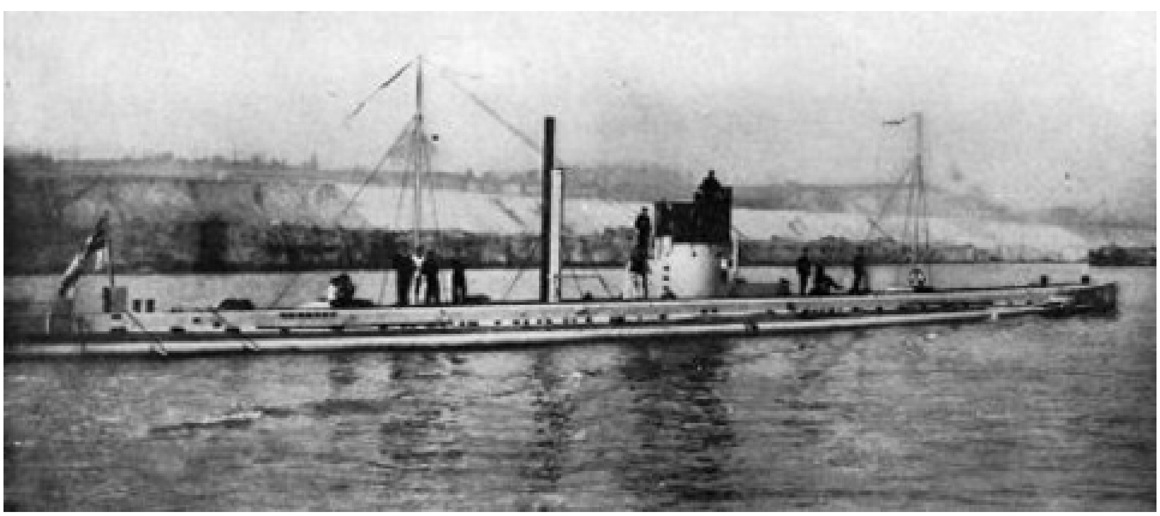
Jordan: In contrast, air and fuel are mixed before they enter a gasoline engine. Maximum compression within a gasoline engine is only about half of that within a diesel engine, or else dangerous pre-ignition might occur.

Janna: Diesel engines do not require such highly refined fuel and are more efficient than gasoline engines, especially if they have a turbocharger that recycles some of the exhaust.

Jordan: The first major marine test of diesels came in the First World War when Germany used them in its submarines.

Janna: The diesel engines needed air, so the subs also had electric motors that were charged by the diesels while running at the surface and then propelled the ship while submerged.

Jordan: Germany started the war with just 29 submarines but used them to great effect. The one shown here, U-9, sank three British warships within a few minutes in 1914.



Janna: Here is a different type of German submarine, the UC-1, which specialized in laying mines. Ironically, this submarine was itself lost to a mine in 1917.

Jordan: This brings us to the end of the world's ugliest war. The global mortality rate was the equivalent of 40% of the US population at that time. Landlubber historians attribute the outbreak of hostilities to the assassination of the Austrian archduke, Franz Ferdinand. However, naval historians point to Germany's construction of modern warships to threaten Britain's navy.

Janna: Upon reflection, most major powers decided that they preferred *Pax Britannica* to an uncertain future with Germany controlling the world's oceans. When the Germans realized that they had lost the diplomatic war, they looked for an excuse to start preemptive hostilities and achieve victory before their assembled enemies could become better organized. The archduke's assassination became a convenient pretext.

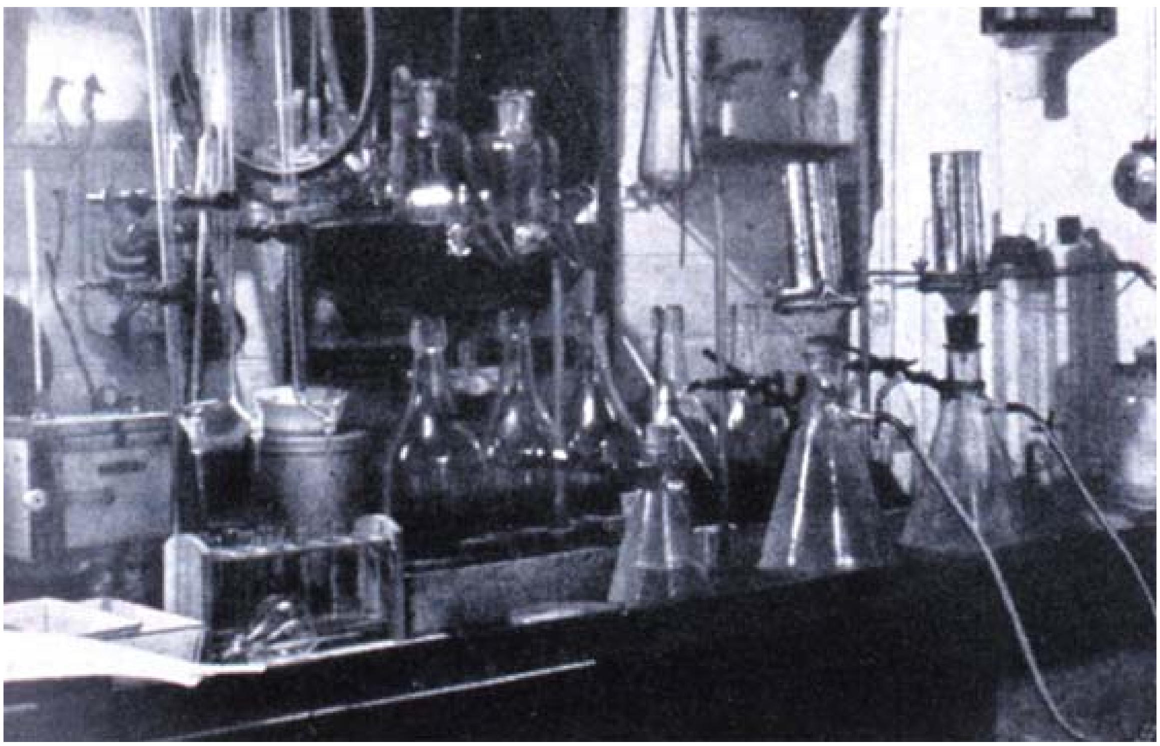
Jordan: The war went well for the Germans at first. They overran the Russian army within a month and sank twice the tonnage that the British sank in the war's biggest naval engagement. However, *Pax Britannica* had assembled too many countries against Germany and the Allies finally wore down Germany's impressive war machine, forcing them to quit and pay war reparations.

Janna: Like all major international wars, World War One brought technological innovations to marine science. Just before the war started, a German physicist had patented echo sounding. That is measurement of water depth by timing the echo from sound that reflects off the seafloor.

Janna: Ironically, it was Germany's obligation to pay war reparations that inspired the application of such an innovation. From 1925 to 1927, Germany crisscrossed the South Atlantic, hoping to find gold-rich seawater so they could pay the 132 billion gold marks stipulated in the Treaty of Versailles.

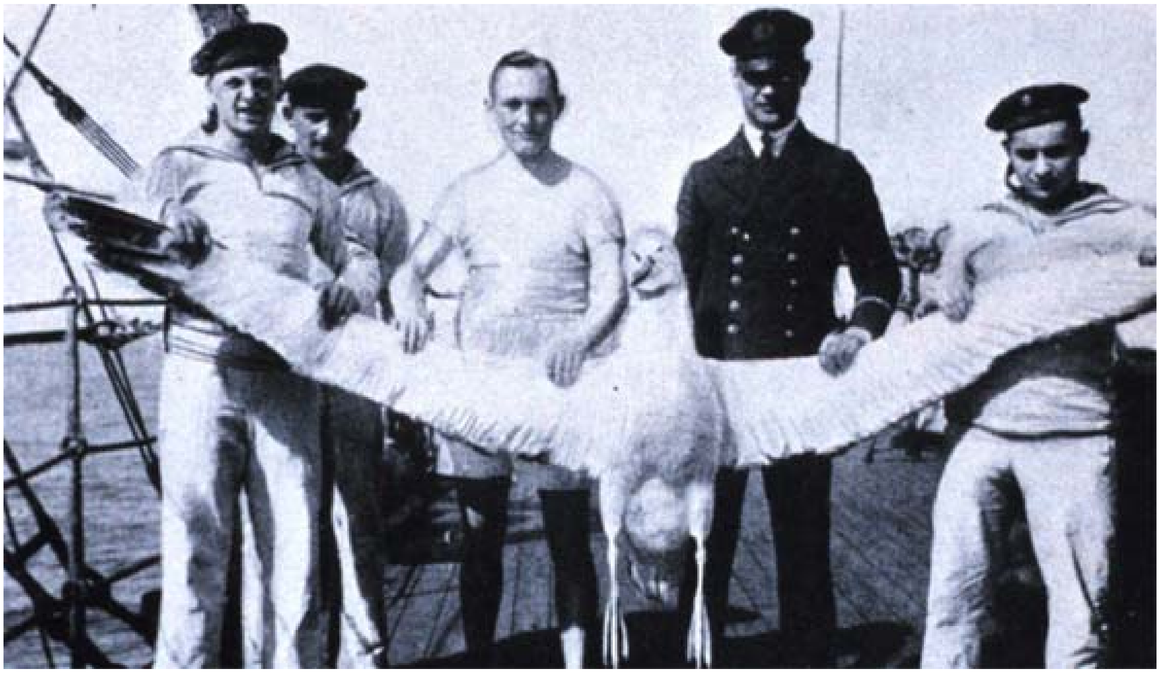
Jordan: Here the crew of the German research vessel, Meteor, is raising a Nansen bottle.

Janna: Seawater extracted from the Nansen bottle was chemically analyzed in the Meteor's laboratory, shown here.

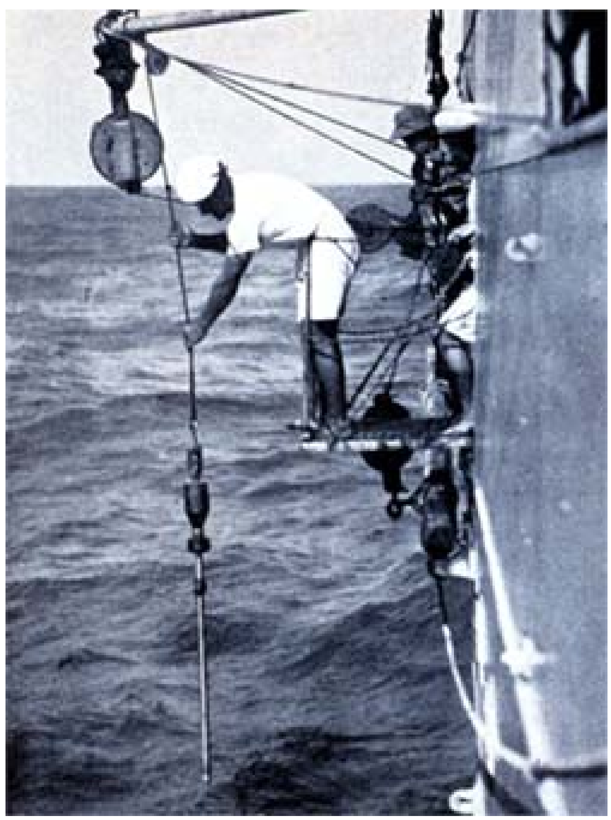


Jordan: The Germans did not find any seawater with enough dissolved gold to merit extraction. Unable to pay their war reparations, they tried the same tactic in 1939 that they tried in 1914. They initiated a pre-emptive war.

Janna: The killing of an albatross by the Meteor's crew, shown here, was a bad omen for that war. Indeed, German battleships did even less well in World War Two than they had done in World War One.



Jordan: Meanwhile, the Meteor did become the most significant oceanographic expedition since the British Challenger expedition, half-a-century earlier. This is probably the first photograph of a gravity corer, designed to retrieve a core of seafloor sediment.



Janna: The Meteor also dragged trawl nets to collect biota for marine biologists. Here they are launching a plankton net.

Jordan: They even launched weather balloons, as shown here.

Janna: As you can see, the Meteor Expedition ushered in the modern age of oceanography. Electronic devices were used for continuous measurement of water depth and current strength.

Jordan: Although the expedition failed to find enough gold to avoid the horror of World War Two, it became a role model for all subsequent oceanographic missions. Consequently, we will conclude our history of oceanography with the Meteor.

… Janna and Jordan both look at the camera for a couple of seconds and then look at each other, wondering what Dr. Bowles is going to say.

Dr. Bowles: I suppose that you had enough combat stories to keep Dr. Bubah happy. However, he will surely complain about making heroes out of the German crew on the Meteor. He is bound to remind me that his great-uncle's ship was torpedoed by a German submarine in World War Two, killing everyone on board.

Janna: I think that Dr. Bubah should go and tour Germany before making disparaging comments. Twice as many immigrants to the United States came from Germany as came from England. Although we speak English, we are genetically more German than anything else.

Jordan: While living in Paris for a couple of years, I took several trips to both Germany and England. Despite difficulty with the language, I felt more at home there than in England or France. Personal interactions in Germany were more like American interactions.

Dr. Bowles: I have had the same reaction myself in Germany but I will not tell that to Dr. Bubah. I will just say that you had to stop with the Meteor story because of a time limit on your chapter. Let us move on to the next chapter, the properties of seawater. After dashing through most of naval history in this chapter, the next one is going to proceed slowly. In some places, we will crawl along like the Antarctic glaciers that nudge their way into the Southern Ocean.

Chapter 4: *Immersion within a Marine Wet Lab*

Janna: When we are submerged in our submarine, there will be lots of chemical reactions going on around us all the time. Some of those could affect our submarine in unexpected ways, so I am glad that you have asked Doctor Bowles for advice before you complete your construction plans and send them to Switzerland.

… Dr. Bowles enters and sits down, facing Janna and Jordan who are seated together.

Prof. Bowles: Hello Jordan. You want construction advice? I am certainly not an expert in submarine design but I will share a hard-earned lesson from one construction project. About twenty years ago, I built a portable support stand for a current meter. The stand was a skeletal pyramid about the size of a tall man, with the current meter suspended at the center. Pieces of the stand had to fit within airline luggage, so they needed to be both light-weight and strong. I used stainless steel for the load-bearing parts and aluminum for the other parts. To my surprise, I found that the aluminum started to exhibit corrosion after a single day on the seafloor. Apparently, the combination of metals acted like a battery in seawater and the current was converting the pure aluminum into aluminum sulfate. Sulfate is the third most abundant solute in seawater, after sodium and chlorine. If you are working with experienced marine engineers, they should be aware of incompatibilities among metals. However, landlocked Switzerland is not exactly a naval giant so it would not hurt to remind those guys. What type of metal have you chosen for your hull?

Jordan: Titanium. It matches the strength of steel but with 45% less weight. Moreover, titanium performs better than stainless steel when it comes to corrosion, both microbial and inorganic corrosion.

Janna: Although the carbon steel of World War One subs limited their diving depth to just a hundred meters, we plan to dive to several hundred meters.

Prof. Bowles: Titanium will cost a lot more but I gather that you guys have deep pockets. What is going to be the overall shape of your sub?

Jordan: We want to go faster than other small research subs so we will need the cigar shape of a large military sub. My dad loves Cuban cigars so I may eventually explain it to him this way: "Dad, we had to choose between the shape of a Cohíba Robustos and a Cohíba Espléndidos. Janna and I like the elegant Espléndidos."

Janna: Nonetheless, we finally opted for the more rugged Robustos design. We both want to live long enough to enjoy lots of life's pleasures, maybe even a few Cuban cigars. Besides, Jordan says that Robustos is your favorite.

Prof. Bowles: Smoking was never allowed during my sub cruises. One hull or two?

Jordan: That sounds like my mother serving sugar cubes to her coffee club. One lump or two?

Janna: Although it almost sounds anti-American, we will use the standard Russian design of a double hull. We are not as brave as the US Navy with their single-hulled submarines. Our outer hull will be thin, like the Russian outer hulls, just two to four millimeters in thickness.

Jordan: By that, she means two to four times the thickness of a dime. We can afford to have a thin outer hull because the pressure between the two hulls will be the same as the pressure outside the outer hull. Consequently, the outer hull will not have to resist being crushed.

Janna: The outer hull will carry impact sensors. Those sensors will immediately reverse the engines away from the point of contact.

Dr. Bowles: I bet that you learned that trick from your review of the Titanic disaster, given that they were too slow about reversing their engines.

Jordan: They also were slow about deducing the damage, or else they would have lowered their life rafts sooner and made sure that they were full. We will have a robotic arm with a camera that we can extend through a hole in the outer hull to check for damage.

Janna: We will also check for hitch-hikers like barnacles that would slow us down. We know that the Russian warships were all "Barnacle Bills" by the time they had sailed two-thirds of the way around the world to fight the Japanese in 1905. They were sitting ducks.

Dr. Bowles: Barnacle Bills? What name have you chosen for your sub?

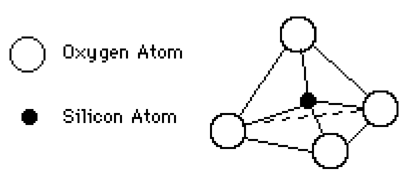
Jordan: We have been thinking about naming our sub the "Nautilus" but that name has been used several times previously. Do you mind if we name our sub after you?

Prof. Bowles: I do indeed. Officially, I know nothing of your scheme and I prefer to keep it that way. Why not name it after your financial backer, something like "Our Batesaway".

Janna: Bill Bates would like that, but I am more interested in returning than getting away.

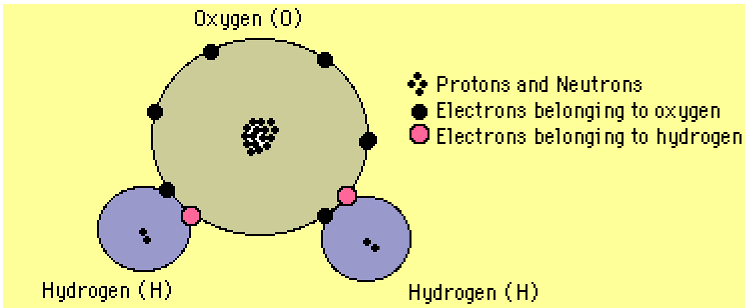
Jordan: Janna tells me that you are planning to talk to us about the properties of seawater. We humans are mostly water and we are going to be surrounded by water in our sub, so I suppose that we should learn as much as possible about this slippery subject.

Prof. Bowles: Nearly five thousand years ago, the Egyptian pharaohs started building huge pyramids as burial chambers. They obviously believed that the pyramidal shape had special meaning. Mother Nature also uses the pyramidal shape for both minerals and water. Her pyramid has an equilateral triangle on each of four sides, including the base. The three triangles that rise from the base meet at a point. In most minerals, each of the four corners of the pyramid is occupied by an oxygen atom, as shown here. This shape is called a tetrahedron, literally "four sides" in Greek. Imagine the pharaoh being buried at the center of the pyramid, where the silicon atom lies.

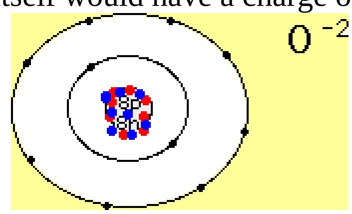


Jordan: I like that analogy. It reminds me of the slave who is watching treasures being carried into the pyramid for the dead pharaoh's afterlife. He exclaims, "Man, that's livin'."

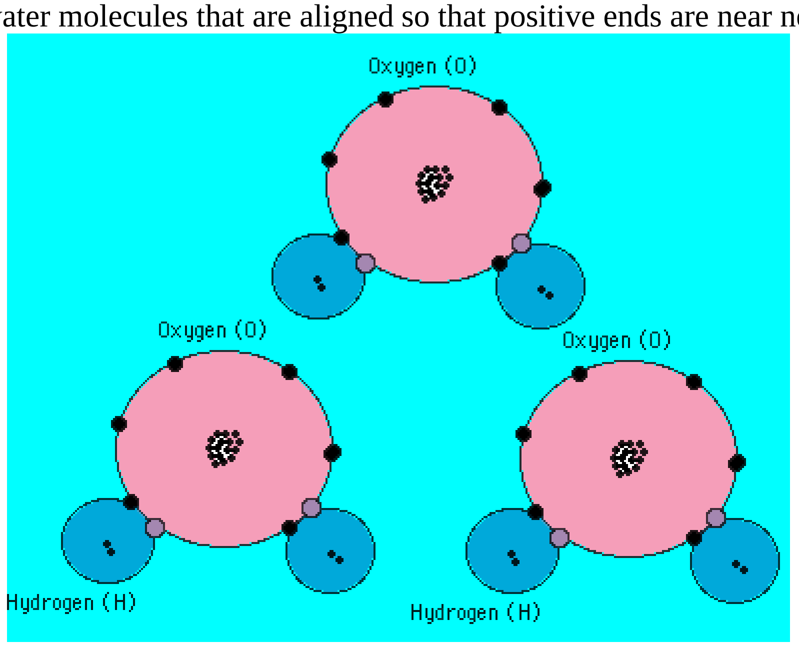
Prof. Bowles: The water molecule is basically similar to the silicon-oxygen molecule except that oxygen now lies at the center of the tetrahedron and only two of the four corners of the tetrahedron are occupied. Each of those corners has a hydrogen atom. The side with the pair of hydrogens has a positive charge on it whereas the opposite side has a negative charge.



A hydrogen atom only has one electron and it bonds with oxygen because oxygen needs that electron to help it achieve the ideal number of eight outer-shell electrons. Hydrogen is more stable with no electrons than its original single electron, so it is happy to donate. However, hydrogen wants its electron to come back home on occasion, so it remains stuck to the oxygen receptor in a shared-electron arrangement. Such a shared arrangement is called covalent bonding. Here is a picture of an oxygen atom that has received an electron from each of two hydrogens, giving it the ideal outer-shell configuration. Although water has no net electric charge, the oxygen itself would have a charge of minus two.



Here are some water molecules that are aligned so that positive ends are near negative ends.



Prof. Bowles: The unequal distribution of electric charge over the water molecule has a major effect on the way water behaves. One peculiarity is that water has substantial structure even in the liquid state whereas the molecules in other kinds of liquids tend to be distributed randomly.

As you know, you can store more items in a container if you organize those items rather than toss them in randomly. The crystalline state is always more organized than the liquid state for any substance. A better-fitting organization generally means greater density. However, pure liquid water is so well-organized at a temperature just above freezing, specifically 4 degrees Celsius, that it is denser than ice. This allows icebergs to float on the sea and menace shipping. If water were like virtually any other substance, the ice would sink rather than sink ships like the Titanic.

Jordan: Dr. Bowles, I know that fresh water freezes at zero degrees Celsius but that the solutes in seawater give seawater a different freezing temperature. In an ice storm, I see the city trucks dumping salt on the streets, so I presume that salt helps water resist freezing.

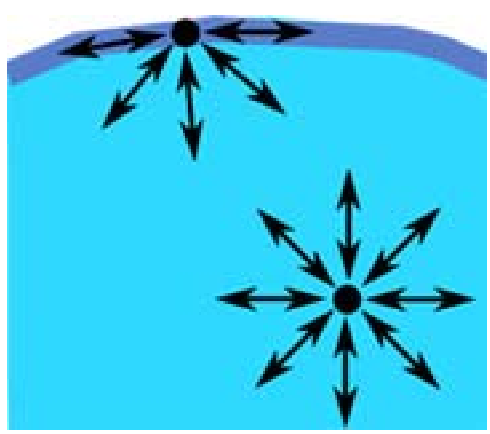
Prof. Bowles: Good observation. The temperature must drop to about minus two degrees Celsius before seawater can freeze.

Janna: Whenever I get bored with my date, I study the ice cubes in my drink. They usually contain bubbles of trapped air. Do bubbles help icebergs float?

Prof. Bowles: Another good observation. In fact, the air trapped within sea ice is the biggest single contributor to the low density that keeps the ice afloat. Let us examine some other properties that result from the electric charges in water. I suppose that the most obvious is water's ability to conduct electricity. A few aspiring actresses have found out the hard way that having a high-powered floodlight fall into a swimming pool can be a shocking experience.

Janna: If I ever get to be a rich actress, I want to sit around the pool sipping mint juleps. If I add too much water to my drink, the water can rise above the level of the glass, defying gravity. How does that work?

Prof. Bowles: Water is indeed a master of gravity-defying feats. We have all seen the way water runs up a Kleenex® tissue that is dipped into a glass of water. That water is defying gravity, just like the water that rises above the rim of a glass if you add the water slowly to a full glass. In both cases, the relevant property of water is its ability to bond strongly to itself, allowing it to form a thin but continuous film.



The arching of water above the rim of a glass is like the arching of a Plexiglas® pane that has been hit by a hockey puck. If the molecules were not strongly bonded to each other, they would all fall down due to gravity. Hydrogen bonding gives water that cohesion when water is acting like a thin film. However, a large volume of water flows quite readily.

Janna: A hockey puck? Prof. Bowles must come from a colder place than we do.

Prof. Bowles: Water moderates Earth's climate in many ways. Although discussions about global warming typically focus on carbon dioxide, they really should focus on water vapor because water vapor contributes much more to global warming than does carbon dioxide. Carbon dioxide constitutes only 0.035% of the atmosphere whereas water vapor constitutes up to a hundred times that concentration. Without the warming effect of water vapor, Earth would be too cold to have any liquid water. There would be extensive glaciers but no oceans and no life, except perhaps around hot vents.

Jordan: I guess that I had better stop complaining about the high humidity around here.

Prof. Bowles: Besides global warming due to water vapor in the atmosphere, we also benefit from equatorial water moving poleward, and thereby moderating temperatures in both regions. Northern Europe would be almost uninhabitable without the warm Gulf Stream, as we will see in our discussion about currents and water masses. To understand the role of water in moderating Earth's temperatures, we should review the concept of heat.

Unfortunately, most textbooks mistakenly give the impression that heat is an object because they describe the movement of heat from place to place. However, heat is not an object so it cannot be moved like a specific entity. Heat is a type of activity, just as work is an activity. In fact, "heat" refers to any activity that is not work.

Work is easier to measure than heat because work involves moving something through a finite distance. Heat may involve a change in the amount of molecular vibration, in other words, a change in the temperature. Alternatively, heat may involve a change in the phase, in other words, a change from solid to liquid or liquid to vapor.

Energy is the sum of heat and work. To show that neither heat nor work is a type of object, you may recall that your professor considers work to exist only while you are actively working. You could move from classroom to classroom and have the capacity to do work in each of those rooms, but you might decide to sleep through each class period and do no work at all. In a similar way, something has to happen for heat to exist.

Janna: So, if Brent refers to one of my friends as being a "hot babe", should that worry me?

Prof. Bowles: To emphasize that heat is a type of energy, I will call it "heat transfer". Much of the confusion in textbooks results from using the single word "heat" to refer to two different concepts. These are heat transfer and observed heat capacity. Heat capacity is the capacity for something to experience heat transfer if its temperature and/or phase changes. Heat capacity is an experimentally-determined value that one can find tabulated for a unit mass of material. Textbooks always discuss experimental heat capacity, such as the heat transfer that occurs during the freezing of one gram of water. This type of heat capacity is called the heat of fusion. Similarly, there is a heat of vaporization.

The confusion about heat comes with discussion of the heat capacity of a dynamic system like the Gulf Stream. Unfortunately, the heat capacity of such a system is commonly called heat. However, heat means heat transfer, not heat capacity. Most textbooks inappropriately talk about the Gulf Stream carrying heat to northern Europe whereas the Gulf Stream actually transports the capacity for heat transfer. In other words, the Gulf Stream carries a type of heat capacity. Despite this, the term, heat capacity, is so firmly associated with laboratory measurements that an alternative term has to be introduced here for natural conditions like the Gulf Stream. That term is potential heat. For example, one may say that the Gulf Stream carries a lot of potential heat to northern Europe. Given that heat is a type of energy, potential heat may be visualized in the same way that we visualize potential kinetic energy.

One way to visualize the potential for kinetic energy is to consider a roller coaster. Ignoring friction, a coasting car alternates between high kinetic energy at the bottom of each trough and high potential gravitational energy at the top of each crest. Like work, kinetic energy is easy to quantify. At any instant in time, kinetic energy is one-half times the mass of a moving object times the square of its velocity ($\frac{1}{2} mv^2$). If the velocity is zero, kinetic energy is zero. If there is no heat transfer, there is no heat. However, there will be plenty of potential heat as long as there are temperature differences between masses of water or air.

Jordan: Hey, what about absolute zero temperature? Can heat capacity exist at absolute zero?

Prof. Bowles: Temperature is the rate of vibration of molecules. There is practically no upper limit on temperature because the rate of vibration always may increase but there is a lower limit where vibration stops. At zero temperature, one can still define heat capacity but it is unidirectional. Heat transfer may only occur into the object.

Heat transfer into the Gulf Stream occurs while the Gulf Stream is passing through the Gulf of Mexico, thereby increasing its potential heat. The Gulf Stream eventually reaches northern Europe where this potential heat results in heat transfer into the cool atmosphere. As the Gulf Stream turns southward toward Morocco and the Canary Islands, it is a cool current that experiences inward heat transfer from the warmer atmosphere. The surface current flows westward along Columbus' path and keeps warming as it returns to the Gulf of Mexico.

Being a form of energy, heat may be represented by any unit of measure used for energy. In physics, the favorite energy unit is the joule. A joule is the energy expended when the point of application of a one-newton force moves a meter in the direction of the force. This definition makes the joule ideal for measuring work but not for measuring heat transfer. A calorie is the ideal unit for heat. A calorie is defined to be the heat transfer that is needed to raise the temperature of a gram of water by one Celsius degree.

By this point in our discussion, we have introduced several metric units such as meters, grams, and degrees. Before proceeding farther, an overview of the metric system would be helpful. One reason that the French invented the metric system is that they wanted to simplify conversion of linear measurements to square measurements. Metric conversions involve factors of ten which require nothing more than moving the decimal point.

For example, every child beyond the third grade in a metric country knows how to calculate land area in the standard metric unit, the hectare, whereas only a negligible proportion of the American public knows how to calculate the number of acres in a square tract of land with known distances along its edges. Although Americans commonly call their system the English system, it has long since been abandoned by the English. In the American system, there are factors of three, twelve, and sixteen rather than ten.

Prior to the French Revolution, every country on Earth had an American-type system because factors like three, twelve, and sixteen may be divided in several ways by mental arithmetic. That facilitates dividing goods when one lacks a weigh scale. However, modern America has plenty of weigh scales, so there must be a political rather than scientific reason for rejection of the metric system. It would take Americans about five years to become comfortable with the metric system, given the experience of Canadians when they converted thirty years ago.

Jordan: I must admit that I have been reading about the number of acres in various bays of coastal America and thinking that I had an appreciation for those sizes. However, I could not tell you the length of an acre's edge, so I do not really know what an acre is. If we want to tour the world, we might have to join the rest of the planet and start using the metric system.

Janna: I suppose that knowing the metric system would make international travel a lot easier. Of the couple hundred countries on Earth, only Liberia and Burma join America in avoiding metric measure.

Jordan: Yes, and we have no intention of visiting either of those backwater places.

Janna: If we want the Swiss to build our sub, all the plans will have to be metric, so we might as well take the plunge, so to speak. However, I am still going to use American units in some conversations because I cannot think that fast in metric.

Prof. Bowles: The French wanted their units to seem natural so they based them on natural features such as Earth's circumference and the most readily-available pure substance, water. A meter is one ten-millionth of the distance from the equator to the North Pole. Once a meter was defined, all other distances automatically became multiples of ten. A hundredth of a meter is a centimeter, about one-third of an inch. To define the basic mass unit, a gram, the French took a cubic centimeter of water at its maximum density. The maximum density occurs at a little less than four degrees Celsius. Zero degrees Celsius is the temperature at which pure water freezes. A hundred degrees Celsius is water's boiling point.

Jordan: Definitions are cute but they do not help me visualize actual measurements. Until I get used to metric measurements, I will need a scheme to convert metric numbers to the American equivalents.

Prof. Bowles: As we have noted, every country originally had an American-type system with multiples of twelve and sixteen, before adopting the metric system. Even the French resisted conversion to the metric system, so Napoleon had to let his subjects return to their familiar scheme temporarily. Anyone who tries to change from one system to the other inevitably lives within both of them for a while, converting every new number into the old number so that they can visualize the size.

Jordan: That reminds me of trying to use foreign currency while living in France with my family. I was constantly converting all the prices to dollars in my mind.

Prof. Bowles: Conveniently, a meter is just a little longer than a yard and may be equated to a yard in casual oceanographic parlance. A kilometer is sixty-two hundredths of a mile. When doing a quick mental calculation to estimate how much diesel fuel one needs to reach the next port, one may consider a kilometer to be half a mile. I have already noted that a centimeter is a little bigger than a third of an inch. A millimeter is a little less than the thickness of a dime. A penny is a little more than one-and-a-half millimeters thick and weighs exactly two-and-a-half grams. A nickel is nearly two millimeters thick and weighs exactly five grams.

Janna: My history teacher told me that the US made its coins metric in 1873 so that they could compete with French coins for being the world standard.

Jordan: Yes, but then we popularized vending machines in which low-value French coins worked only too well, so we have been trying to make our money unique since then.

Prof. Bowles: If a nickel is five grams, then one gram is too small to be a practical unit of mass. Groceries are sold in thousands of grams, kilograms. One kilogram is 2.2 pounds but this may be rounded to simply two pounds for mental arithmetic. Now that we appreciate kilograms, we can examine density variations in water expressed in kilograms.

The temperature of seawater rarely exceeds thirty degrees Celsius. Each Celsius degree is almost twice as big as each Fahrenheit degree and there is an offset of thirty-two degrees between the two systems. Consequently, thirty degrees Celsius is thirty-two plus nearly sixty degrees, making it eighty-four degrees Fahrenheit. A table of density variation with temperature shows little change through the range from zero to thirty degrees.

Density of Water

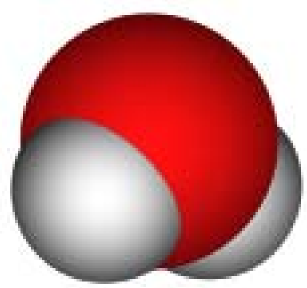
Temperature		**Density at Earth's Surface**
deg Celsius	**deg Fahrenheit**	**kg per m cubed**
0	32.0	999.843
4	39.2	999.975
15	59.0	999.103
20	68.0	998.207
25	77.0	997.048
37	98.6	993.332
50	122	988.04
100	212	958.367

Nonetheless, even this small variation has a big effect on circulation in the oceans because just the smallest increase in density causes water to sink. Sinking water must be replaced by rising water somewhere else. Heat transfer generally occurs whenever a water mass moves, whether vertically or laterally, so let us take another look at heat capacity and heat transfer. We recall that heat capacity is the amount of heat transfer that is needed to increase either the temperature or the disorder of a given mass.

For liquid water, the heat capacity is 4.18 joules per gram. We have noted that a joule is the standard metric unit of energy, the energy expended when a force of one Newton acts through a meter. However, chemists generally prefer the original metric heat unit, called the calorie, because it is defined to have a value of one when the temperature of water rises or falls by a degree. Consequently, a calorie equals 4.18 joules. This calorie should not be confused with the Calorie content reported for food because the so-called Calories of food are really kilocalories. Contrary to all the food labels you have ever seen, each of us consumes a couple million calories of potential heat in food each day, not a couple thousand.

Janna: Just by touching different items, I can tell that the heat capacity of water differs a lot from the heat capacity of other substances. On a winter day, I try to avoid picking up metal because it feels much colder than wood, even though the wood and metal are at the same temperature. Heat transfer into the metal occurs much more readily than into the wood, lowering the temperature of my hand.

Prof. Bowles: The extremely high heat capacity of water makes marine currents very effective at moving potential heat from the tropics to high latitudes where heat transfer into the atmosphere makes such places as northern Europe habitable. Let us compare water's heat capacity to that of metals like iron and aluminum. The heat capacities of iron and aluminum are only about one-tenth and two-tenths of that of water, respectively. The high heat capacity of water is attributed to the strong bonding between its molecules. As we have previously noted, water's positively-charged hydrogen atoms are not distributed symmetrically around its negatively-charged oxygen atom, and the resulting hydrogen bonding between opposite charges makes water a polar molecule.



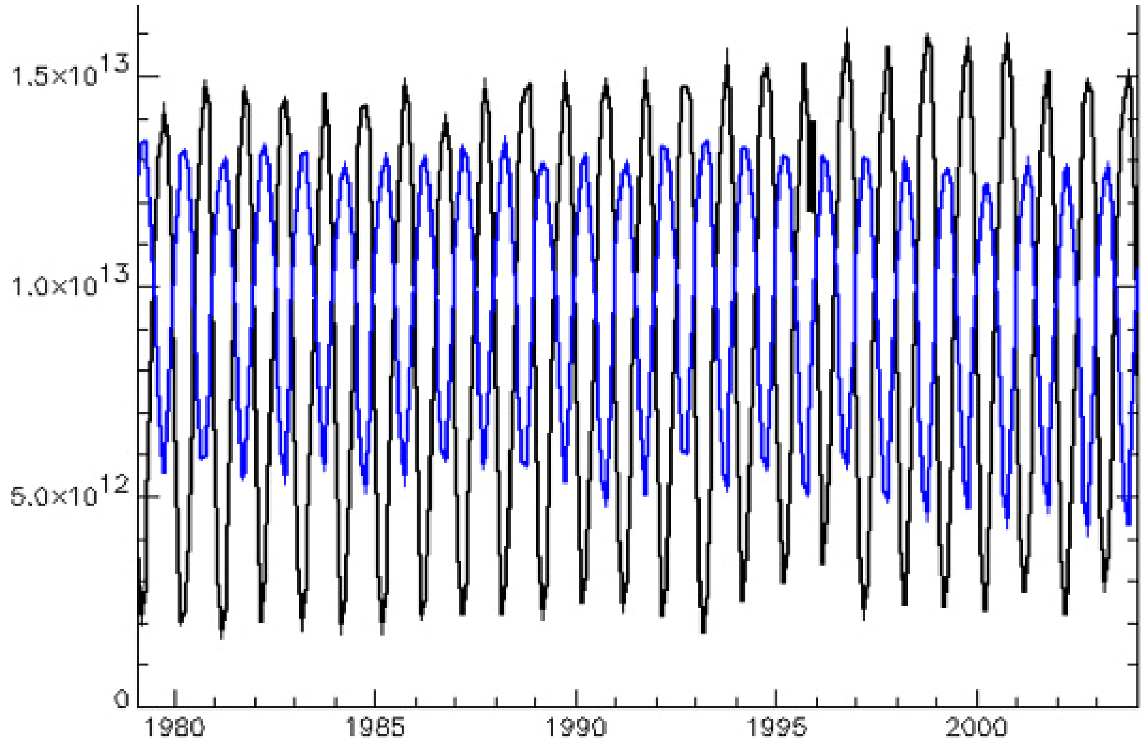
Other substances with hydrogen bonding, such as gasoline and ethanol, also have high heat capacities, more than half that of water. Per gram, the heat capacities of water vapor and ice are both about half that of liquid water. A century ago, Nansen of Norway pioneered the measurement of heat transfer in sea ice while his boat spent four years trapped in the Arctic.

Jordan: If I had been Nansen, I would have put in for a transfer to somewhere hotter.

Janna: Heat transfer through the walls of our sub may be so efficient that we will feel like we too are trapped in ice unless we remember to design good heaters. Submariners in the Atlantic must have been cold because they were heavily dressed in their photos.

Prof. Bowles: We have looked at the variation of water's density throughout the temperature range of its liquid state. As the temperature drops from four to zero degrees Celsius, the density of water drops by just a hundredth of a percent. However, upon freezing, the density drops by more than eight percent.

Everyone takes it for granted that ice crystals float on water but this is actually very peculiar behavior because crystals of other substances generally sink through the liquid from which they have crystallized. If icebergs were to sink, that would expose more seawater to cold air and produce more ice. Ice reflects sunlight better than does seawater so the whole world would become colder, resulting in more ice crystallization. As it is, an area of sea ice that is comparable to that of Russia alternately freezes and melts every year, as shown in the foregoing chart. The bigger seasonal swings in this chart refer to Antarctica because more pack ice can form there in the southern winter. The smaller swings represent the Arctic.

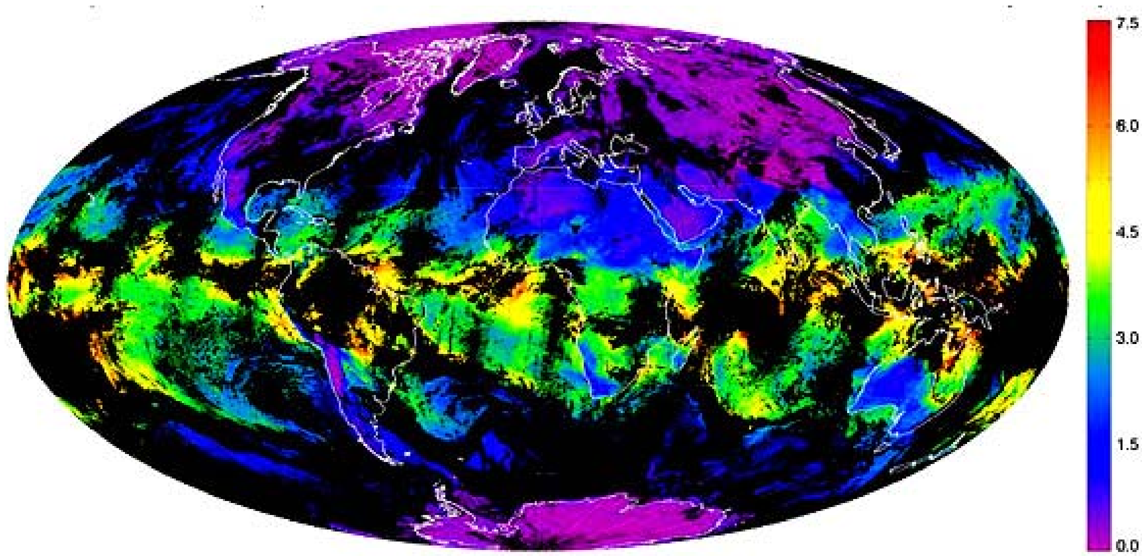


Of course, I should note that the freezing point of seawater is lower than zero degrees, the freezing point of pure water. Solutes stabilize seawater, so seawater does not freeze until the temperature drops nearly two more Celsius degrees below zero. The change in phase from liquid to solid requires heat transfer even if there is no change in temperature. That heat transfer is called the heat of fusion. To appreciate water's heat of fusion, consider cooling some water from its boiling point of a hundred degrees Celsius down to its freezing point of zero, and then compare that heat transfer to the heat transfer required for freezing, water's heat of fusion. The heat of fusion is 80% of the heat transfer from 100 degrees to 0 degrees.

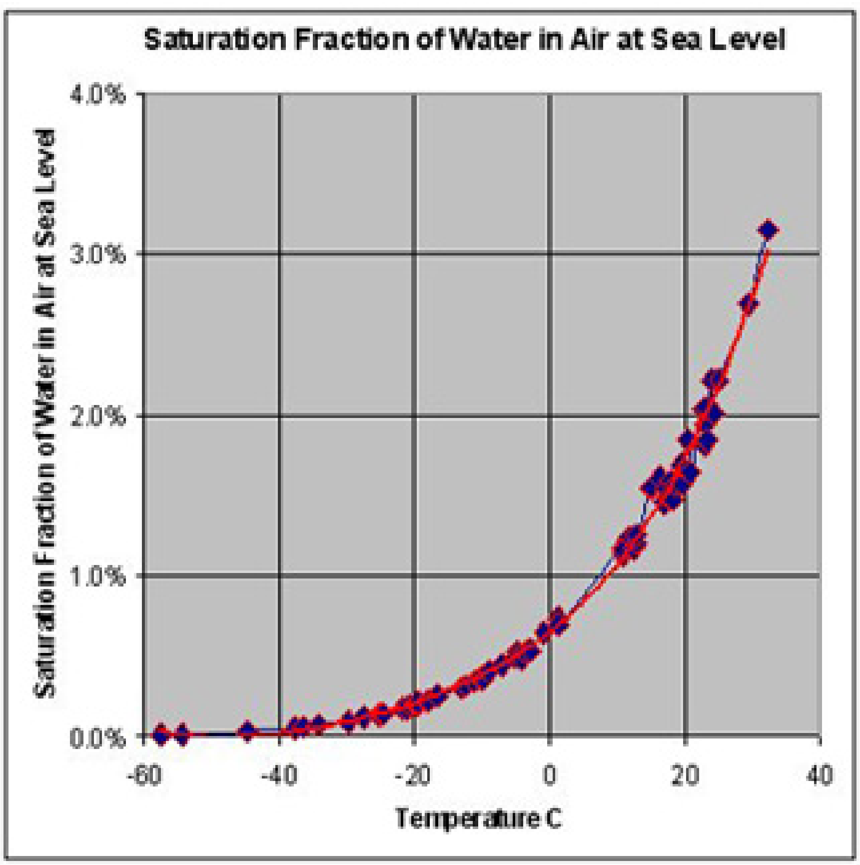
Janna: All this ice is making me shiver. I hope that he soon warms up his story.

Dr. Bowles: While discussing water's heat of fusion, we should also discuss its heat of vaporization. That is the heat transfer needed to turn liquid water into vapor without increasing its temperature above the boiling point. This is a big number, nearly five-and-a-half times more heat transfer than is needed to heat water from its freezing point to its boiling point. Of course, boiling of seawater is restricted to active volcanoes, but vaporization occurs nearly everywhere, evaporating about a meter of seawater every year. This evaporation requires more energy than the heat of vaporization since the energy must be the equivalent of both raising the temperature and changing the phase.

Given that we live on a planet that is mostly covered by oceans, the meter of evaporated seawater returns as nearly a meter of rainfall over the entire surface. If the oceans were not losing a meter every year, the land would not receive enough rainfall to support existing agriculture. Here is a snapshot of humidity, showing a tropical band of high values.



It is difficult for surface temperatures to change much in the tropics because the heat capacity of humid air is so much greater than that of dry air. The higher the heat capacity, the more energy is needed to effect any change in temperature. The capacity of air to hold water vapor increases exponentially with temperature, as seen here. This graph corresponds to the foregoing map. Surface temperature varies predictably with latitude on that map and there is a maximum humidity which may occur at each temperature, as shown in the following graph. The tropics are said to have thermal inertia because of the constancy of temperature.



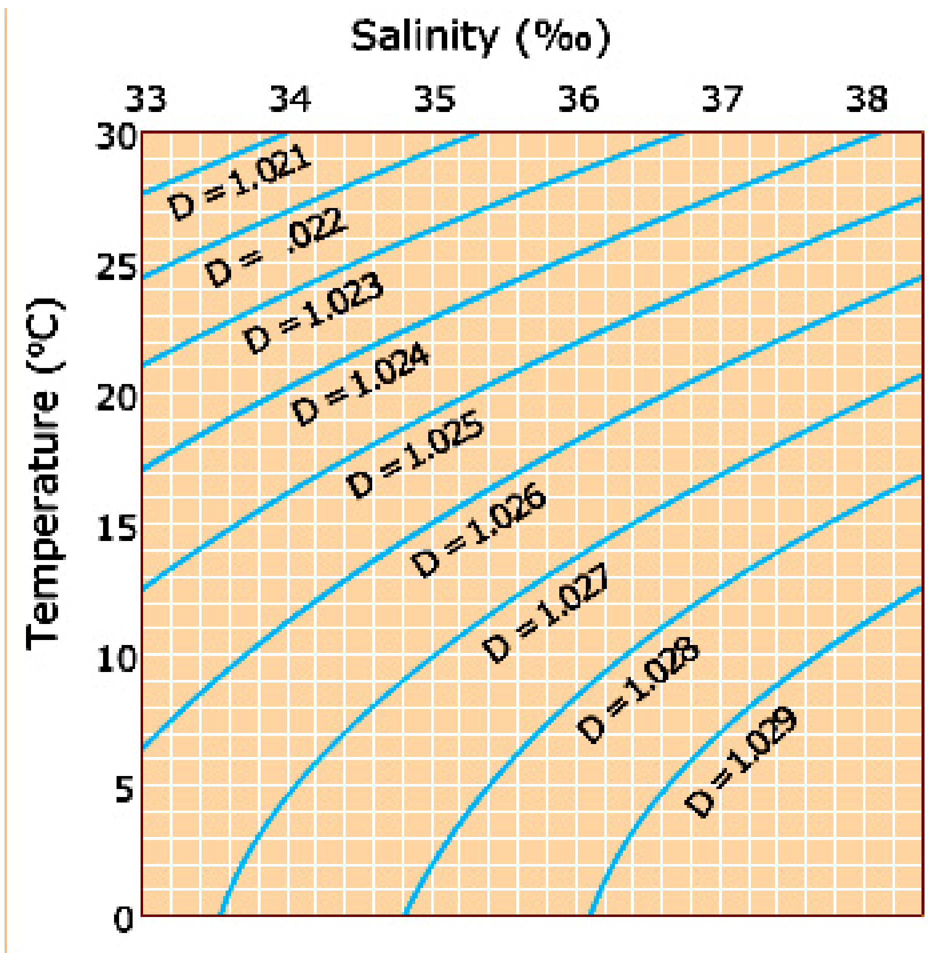
The thermal inertia of any water volume exceeds that of any comparable volume of air because water is about a thousand times more massive and requires vastly more energy for excitement of that greater mass. The total range of temperature in the upper ocean is correspondingly small, only about thirty-four Celsius degrees. This range of 34 degrees extends from a high of 32 near the equator to minus two degrees Celsius where seawater is freezing.

In contrast, the total range of air temperature around the world is more than four times greater, from nearly sixty degrees Celsius in the Saharan desert to minus ninety near the South Pole. As shown in the foregoing map, polar regions resemble deserts in having low humidity, giving them little thermal inertia.

Jordan: We are not likely to end up in the Sahara and we are definitely not going to the South Pole, so we should think of some other places to study high and low thermal inertia.

Janna: I hear that San Francisco has little temperature variation through the year and I would love to sneak into San Francisco harbor on the pretext of studying that phenomenon.

Prof. Bowles: We have seen that the density of water depends upon its temperature. It also depends upon salinity, so one may construct a chart that relates density to both salinity and temperature simultaneously, as shown here.



The density is in units of grams per cubic centimeter. We have learned that the French defined the gram so that the maximum density of fresh water is exactly one gram per cubic centimeter. However, the dissolved salt in seawater always makes it denser than that, by about two-and-a-half percent. Dissolved salt means the same as “solutes” and we will use that term rather than simply say salt, to avoid the misleading phraseology of several textbooks. Technically, salt is solid and that is not what those authors mean to say.

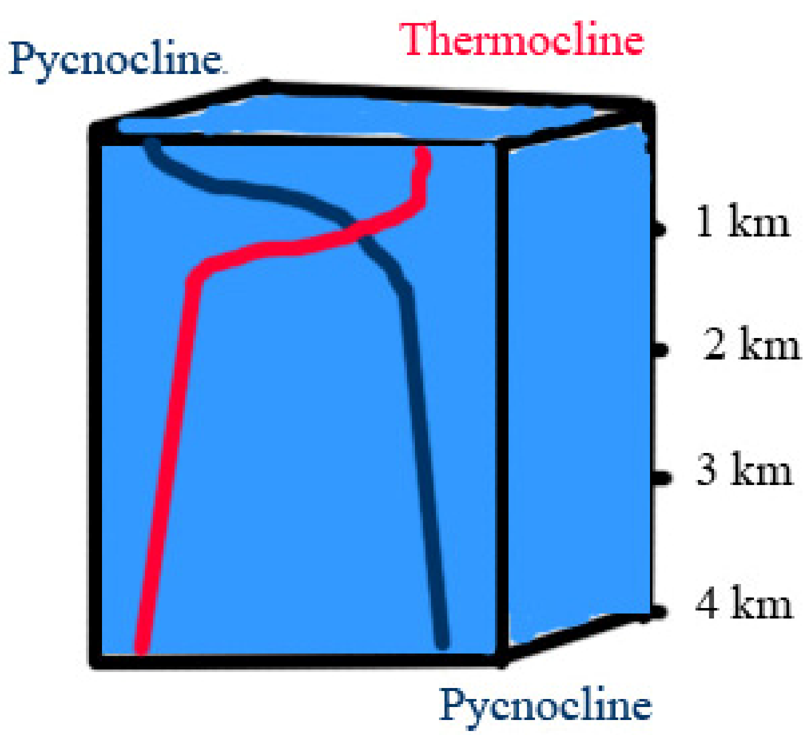
The average surface temperature of the ocean is seventeen degrees Celsius and a typical salinity is thirty-five parts per thousand. Using the foregoing chart, it should be apparent why I picked a common density of about 1.025 grams per cubic centimeter. The salinity units of “parts per thousand” are just like the units used for property taxes. In the case of property taxes, they are called a “mil rate” because “mil” means a thousand in Latin-based languages such as Spanish. The government divides the value of each property by a thousand and applies a rate factor to determine the taxes due.

Jordan: My dad ends up paying enough taxes on our home that the city can put in sewer and water lines for whole new subdivisions.

Dr. Bowles: The oceans are density stratified. The wind mixes the surface water so that its properties are fairly uniform, but there is a sharp increase in density below that mixed zone. The density profile shown below is steeply inclined in the transition zone below the mixed zone. The steeply inclined portion is called the pycnocline.

Janna: Knowing Dr. Bowles, the first syllable in pycnocline is not going to be spelled like the pick in an ice pick but some weird Greek spelling.

Dr. Bowles: Given the strong incline of the density profile in the ocean, as shown here, the “pycno” in pycnocline comes from the Greek word meaning “strong”. The profile of density in the ocean is typically about the same as the profile for salinity, the so-called halocline. As salinity increases, the density increases. Consequently, the halocline need not be shown here. In contrast, as temperature increases, the density usually decreases, so those two profiles crisscross each other. The warmest part of the ocean is at the surface where the Sun’s rays penetrate it.

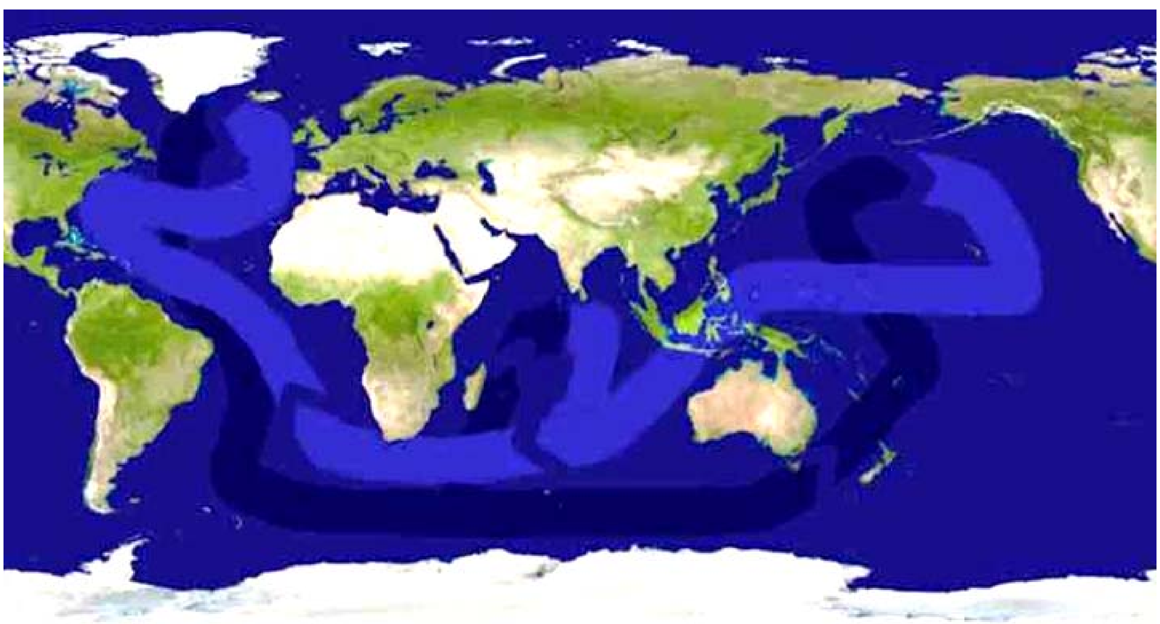


Janna: When I learned how to SCUBA dive deeper than most tourists, I found that the Sun's rays do not penetrate very far.

Dr. Bowles: The obvious differences between the upper ocean and the deep ocean are due to several factors, mostly solar heating of the upper ocean, evaporation of surface water, influx of river water, melting of polar ice, and mixing by wind. The lower ocean is much more uniform than the upper few hundred meters (yards) of water depth. The thermocline sketched here is typical of temperate to tropical regions. In polar regions, the surface water is not much warmer than the deep water, so the thermocline is almost a straight line downward.

Sinking of water occurs in those regions whenever salty water from the tropics reaches polar regions, within such currents as the Gulf Stream. Cooling makes seawater denser, so it sinks. It might not sink all the way to the bottom of the ocean but it will sink to an appropriate depth along the pycnocline. Seawater with a similar history tends to form a distinct water mass within the ocean. That water mass has a characteristic salinity and temperature. This combination gives it a characteristic density, so the water mass may be found occupying a specific depth range within the ocean.

Here we see continuous thermohaline circulation. If we arbitrarily start with the Gulf Stream, the paler path shown here, we see that much of that water sinks when it becomes cold off Iceland. The darker path is the resulting intermediate-depth water that reaches the middle of the Pacific Ocean before it upwells to become a surface current again. That surface current passes through Indonesia before returning to the Caribbean.



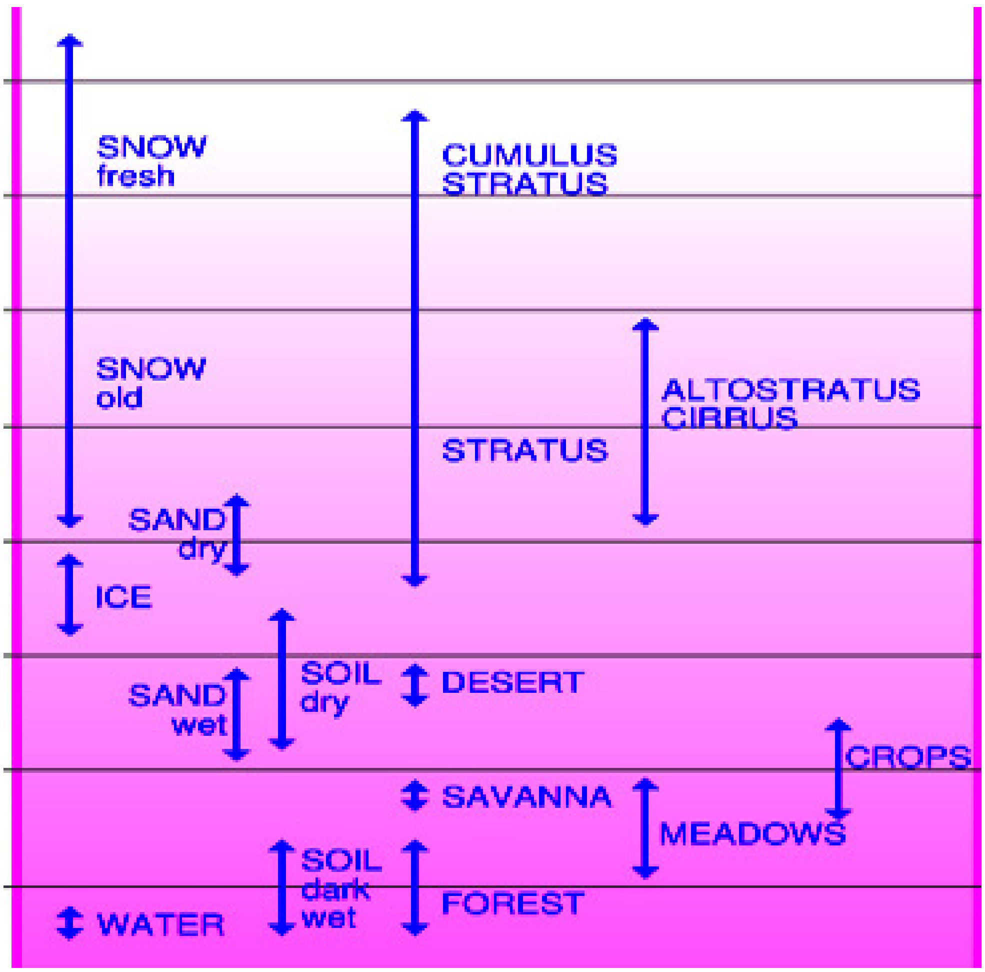
Jordan: Maybe we could let thermohaline circulation carry our sub and save on fuel.

Janna: I suppose, but only if you are willing to wait a few hundred years to get around the world instead of just one year.

Dr. Bowles: The warmest surface water on Earth is found on the western edges of the two main ocean basins, the Pacific and the Atlantic, because the Earth spins toward the east, spinning the solid Earth under the oceans. The surface water appears to flow westward through the hot tropics and reaches its maximum temperature when it gets to the western rim of its ocean. Within the Atlantic, that would be in the Caribbean and Gulf of Mexico whereas it would be around Indonesia within the Pacific. Using the Celsius scale, those maximum temperatures would approximate 28 to 30 degrees C. To put that into perspective, a room temperature of 68 degrees Fahrenheit equals 20 degrees Celsius. At the upper end, 30 degrees Celsius equals 86 degrees Fahrenheit.

Jordan: The Caribbean and Gulf of Mexico lie well north of the equator. Why does the Atlantic's hottest water not lie along the equator?

Dr. Bowles: The Earth is not a well-balanced place when it comes to land versus water. The area of the oceans is more than twice as great as the total land area. Moreover, this land is not evenly distributed because the Northern Hemisphere has about twice as much land as does the Southern Hemisphere. Land does not absorb solar radiation as well as water does. Reflectivity of sunlight is called albedo. One may compare albedo for various natural materials. In the following chart, we can see that seawater does not reflect as much as does typical land. Seawater is able to absorb this solar energy because it has a high heat capacity. In contrast, fresh snow is quite reflective, so sunlight cannot warm it very much.

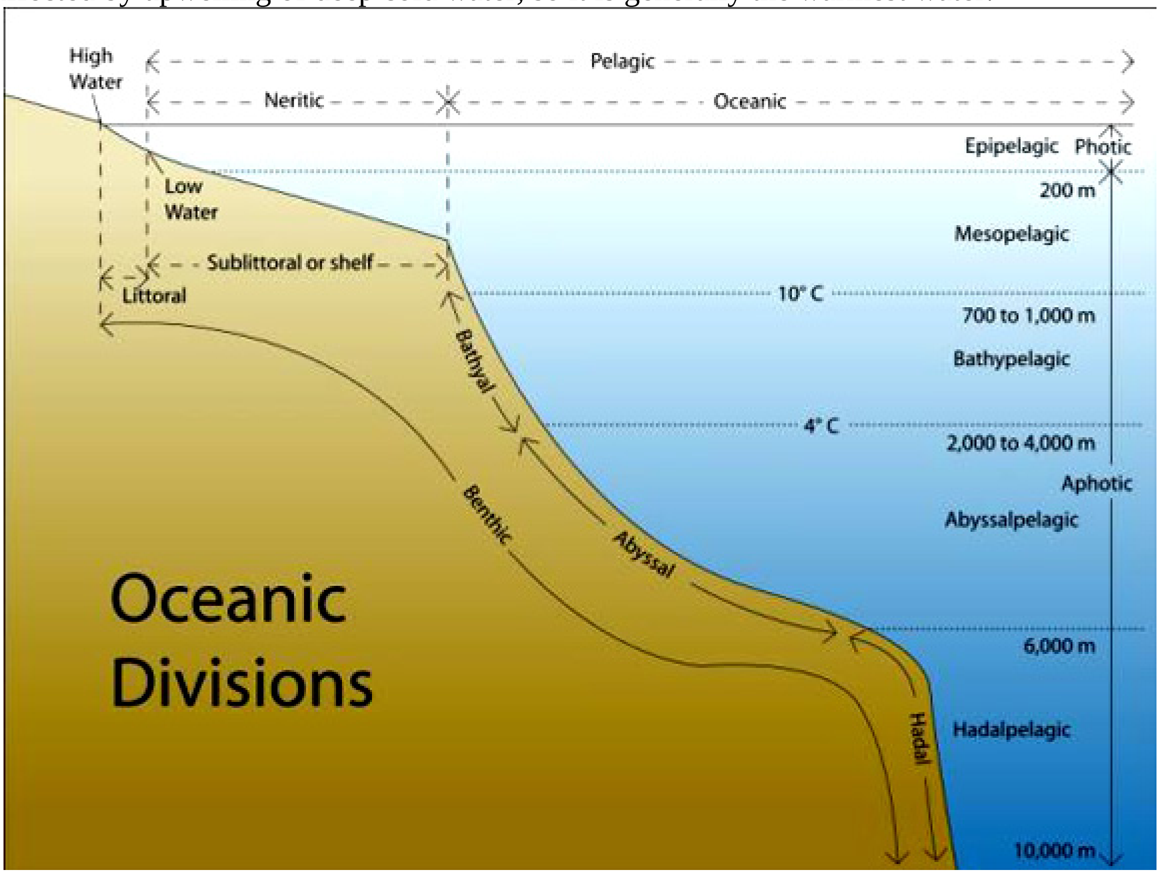


With all its seawater, the Southern Hemisphere is warmer on average than is the Northern Hemisphere. For purposes of meteorology and long-term climate, the Southern Hemisphere extends five latitudinal degrees across the equator into the Northern Hemisphere. The warm seawater along the western edge of the Atlantic and Pacific basins is accumulating along the meteorological equator rather than the geographic equator.

Jordan: Although other students dream of sailing a yacht, we plan to dive in our submarine, so we should pay more attention to the vertical profile of temperature in the oceans.

Janna: I bet that the oceanographers have invented more names for depth-related subdivisions of the ocean than you or I will ever want to remember.

Dr. Bowles: Here is a cross-section through the ocean to show how we label the various depth and temperature zones. Some of these labels are more important than others. For example, the littoral zone occurs along the shore. Some oceanographers limit it to the zone exposed at low tide but most extend the littoral zone at least into the surf zone. The littoral zone is little affected by upwelling of deep cold water, so it is generally the warmest water.



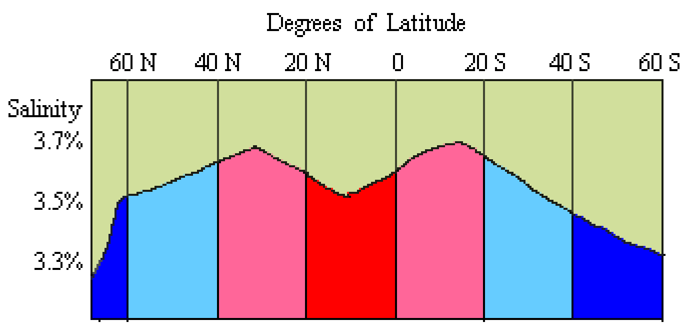
Everything beyond the narrow littoral zone belongs to the pelagic zone. As shown, the pelagic zone is subdivided into successively deeper depth zones using Greek prefixes. "Epi-" means "upon". "Meso-" means "middle". "Bathy-" means "deep". "Abyssal" means "unfathomable" and "Hadal-" means "the Underworld".

Jordan: It seems that the oceanographers cannot count. Their Mesopelagic zone is definitely not in the middle of the range of ocean depths, given that the Mesopelagic zone extends from 200 meters to just 700 meters. The middle depth of an average ocean is four times deeper than that, nearly two thousand meters deep.

Dr. Bowles: The average temperature at the top of the ocean lies somewhere between 15 and 17 degrees Celsius. That is 59 to 63 degrees Fahrenheit. Global warming is estimated to have increased this value by half a degree Celsius through the past half-century. That is equivalent to one degree Fahrenheit. Global warming turns snow and ice into seawater. In a previous chart, we saw that seawater absorbs solar energy vastly better than either snow or ice. Melting therefore produces water that can absorb more energy and thereby warm the world. The result is a type of runaway process, a process that feeds on itself.

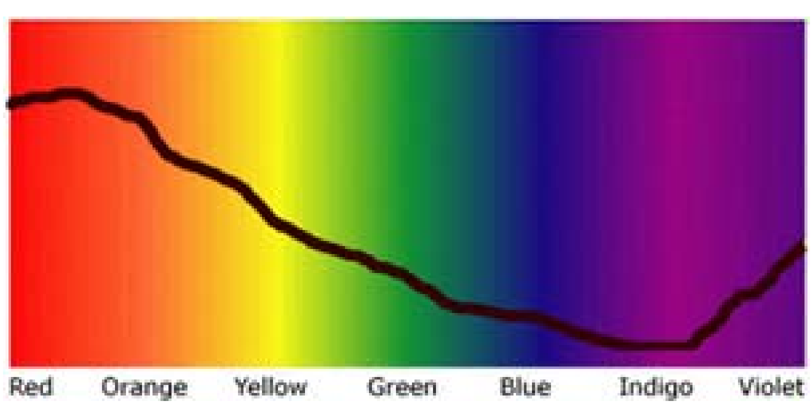
Janna: Oh. Oh. I hope that Dr. Bowles is not becoming Dr. Strangelove. I do not want the world to melt before I get to try out my submarine.

Dr. Bowles: Let us return to salinity. Here is a typical north-south transect of salinity in surface water, out in the middle of an ocean where rivers have no effect. You can see that there are two peaks in salinity away from the equator, one around thirty degrees north and another around fifteen degrees south. The minimum salinity in low latitudes is similarly offset toward the north. It is offset by about a dozen degrees in this particular transect. We will explain this double-humped pattern in more detail when we discuss atmospheric circulation. In the meantime, we will simply note that the northward shift shown here is related to the occurrence of the meteorological equator around five degrees north.



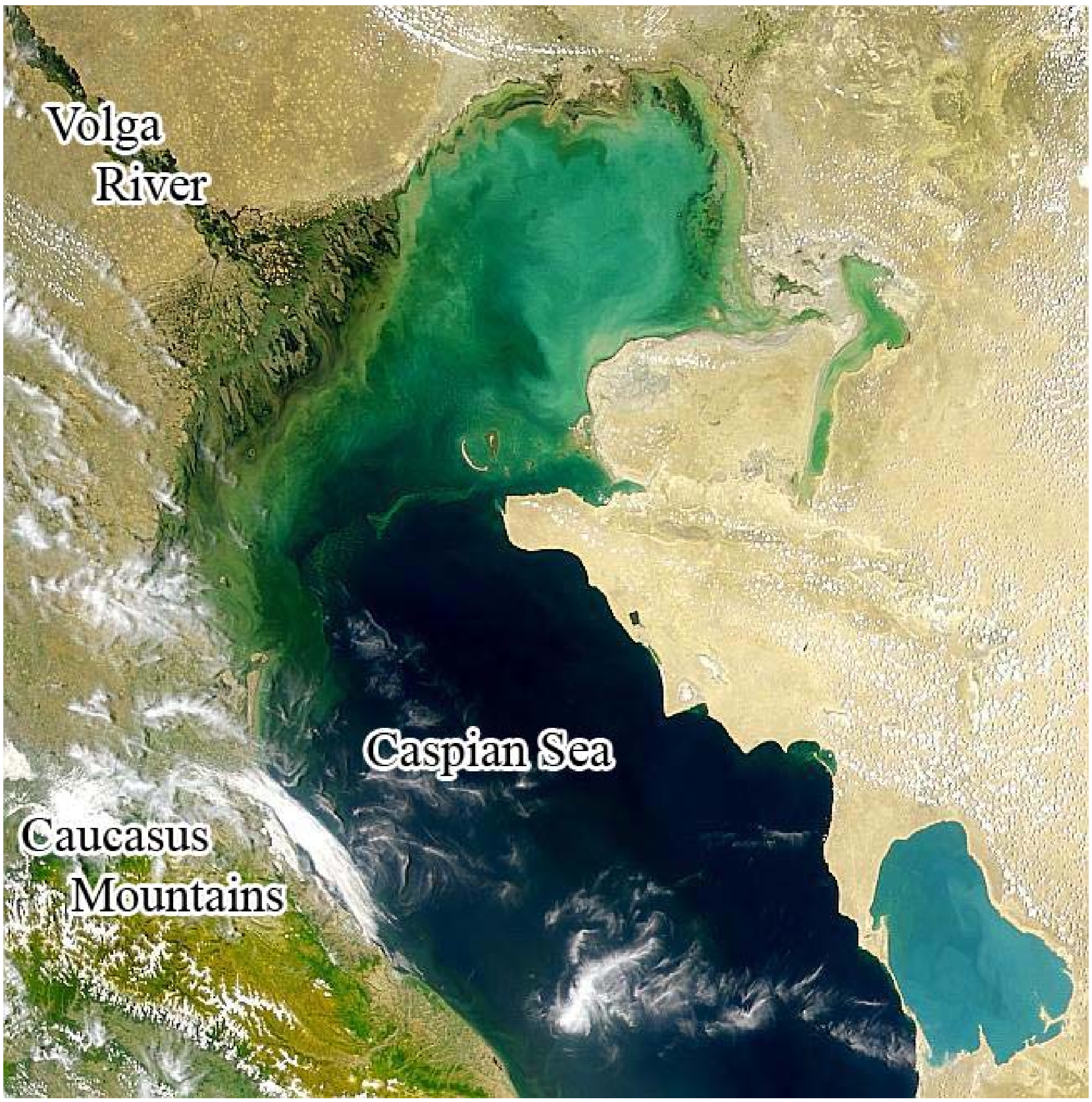
Jordan: I am getting tired of talking about heating the ocean and adding a dash of salt. When is he going to add a dash of something a little spicier?

Dr. Bowles: Let us consider sunlight in a new light. We have already noted that light energy heats the ocean efficiently because of the high heat capacity of water. Of course, light also allows us to see marine creatures and seafloor features. Light becomes rapidly attenuated in seawater, both by scattering and by absorption. Seawater contains bubbles, dust particles, and even solutes that scatter light, sending the light off-course. Eventually, light energy is converted into heat energy in the process of absorption. Absorption varies with the wavelength. As shown below, ultraviolet, blue and green wavelengths are absorbed less efficiently than other colors. Consequently, those colors keep going while reds and yellows become converted from light energy into a faster vibration of the water molecules. In other words, the water temperature rises very slightly as the reds and yellows disappear.



The zone penetrated by sunlight is called the photic zone. In the foregoing chart that subdivided ocean depths, the epipelagic zone was equated to the photic zone. Both extend a couple hundred meters into the ocean in that chart. However, the photic depth varies greatly. The photic zone is generally shallowest close to shore. Here sunlight reaches just a few tens of meters because of suspended particles and bubbles. Of course, most SCUBA diving occurs nearshore, so those divers experience attenuation of sunlight first-hand.

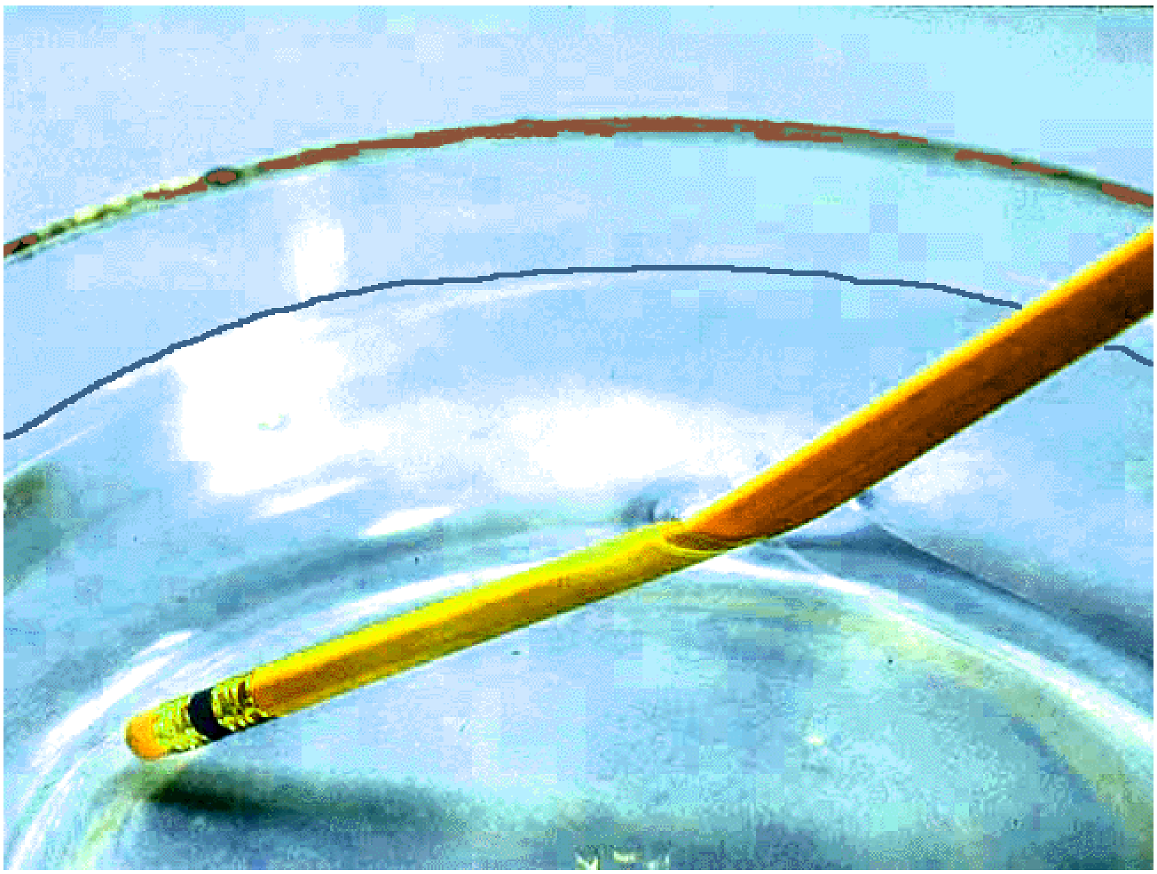
In the following NASA photo, we can see an example of how turbid the water becomes near a delta. This is the Volga Delta as it enters the Caspian Sea, from the northwest. In contrast, little sediment is being eroded from the Caucasus Mountains in the southern Caspian Sea. For scale, the Caspian is about 300 km (200 miles) across.



Even though the foregoing depth chart shows the photic limit reaching a depth of 200 meters, a hundred meters is more typical for the open ocean. Exceptional clarity permits sunlight to reach as deep as 600 meters in the tropical ocean.

Janna: When I went diving in the Caribbean, there was plenty of light deep into the ocean but everything seemed greenish blue. I could recognize some fish from their outline but their normally vibrant colors were subdued. They all looked dull unless I used a strobe light to illuminate their true colors.

Jordan: Another surprise for me is that when I reach down into the water to grab something, it is not where it seems to be. The light must bend as it passes from the submerged object to my eye. This refraction of light is even apparent when I stick a pencil into a glass of water, as shown here. If refraction affects light energy, does it also affect sound?



Dr. Bowles: I am sure that everyone has heard about whale songs and how they can be transmitted for great distances in the ocean. Sound travels about five times faster in water than in air because the molecules are much closer together in water. There is less distance to pass a signal from one molecule to the next. The proximity of molecules is a function of density. Of course, the five-to-one difference in sound velocity for water-versus-air is small compared to the thousand-to-one difference in density for water-versus-air.

Jordan: While in Paris, my parents dragged me to the opera where I saw that the most powerful singers had the dimensions of a whale.

Dr. Bowles: Sound moves amazingly fast through water, at nearly a mile per second, and the champions of this sound transmission are indeed the whales. Whales are mammals like us and change their tunes about as often as we do on our hit parades. Our submarines can detect whale music across distances of several kilometers. Here is a humpback whale surfacing off Massachusetts Bay.

Sound may be transmitted through an ocean for thousands of kilometers if it becomes channeled into the depth range of minimum sound velocity. This depth range lies about one-quarter of the distance down from the surface, at a depth of roughly a kilometer. Whales can dive to this depth and produce sound that travels as if it were sandwiched between two layers. In this case, the enclosing layers are water that can transmit sound more efficiently. If a sound wave wanders into the upper or lower higher-velocity layer, it becomes bent back into the minimum-velocity zone. This bending is a form of refraction, just like the refraction that bent the light rays in the foregoing image of a partially submerged pencil.

Fortunately, whales are not a serious threat to people. A big wartime threat has been torpedoes from submarines. They have sunk a vast amount of shipping in World Wars One and Two. Submarines typically reflect sound waves, so the world's navies have invested heavily in studying the transmission, reflection, and reception of sound in the oceans. The German research vessel, Meteor, was the first to use reflected sound to map the seafloor in detail, a decade after World War One.

Nowadays, we have a side-scan sonar device with multiple emitters and receptors to capture a three-dimensional image of the seafloor features. This is particularly helpful when searching for a seafloor wreck, whether it may be a ship or a downed airplane. If looking for an enemy submarine, the hunter may use a type of sonar that relies on background oceanic sound rather than emit a sound that the submarine could hear.

Jordan: Passive sonar sounds like the ticket for us. After learning about all the new weapon systems on navy ships, I may try to talk the Star Wars people into developing a cloaking system for our little sub.

Dr. Bowles: Having studied sight, sound, and salinity in the oceans, we will switch to chemistry. We will learn more about salinity in our next discussion because we will address ocean currents, and those currents are partly driven by salinity variation. Although I have interchanged water for seawater on several occasions in this discussion, seawater is only ninety-six-and-a-half percent water. Solutes make up the other three-and-a-half percent.

Some oceanographers consider seawater to be the universal solvent because a tiny amount of virtually every naturally-occurring element on Earth is dissolved in seawater. Of course, the two elements in table salt, sodium and chlorine, top seawater's list. Neither sodium nor chlorine is saturated in seawater because seawater has to evaporate down to just one-tenth of its original volume before table salt will precipitate. In contrast, seawater is saturated with respect to calcium carbonate, the mineral in seashells, so it is easy for clams and corals to make their houses from seawater. Once precipitated, calcium carbonate has little tendency to dissolve. No animal tries to make its shell from a highly soluble mineral such as table salt.

Most precipitates from evaporated seawater exhibit ionic bonding. In that type of bonding, an electron is permanently transferred from one kind of atom to another. For example, sodium becomes more stable if it transfers an electron to chlorine. This sodium-chloride compound is the ionically-bonded mineral that is popularly known as table salt. The formal name for this mineral is halite.

Sodium and chlorine are just two of eighty-eight naturally-occurring chemical elements. As you know, the elements are well-organized within the periodic table. Various versions of the periodic table invariably include more than the naturally-occurring 88 elements. The additional elements are all radioactive and have such brief half-lives that we will never find them in nature. They instantly convert to something else. Oceanographers do not usually attempt a systematic examination of the periodic table but that is what I would like to do here.

{ring-ring-ring} Dr. Bowles answers his cell phone and talks into it for a few seconds. Then he puts it away. …. Wow, my program manager in Washington has invited me to attend a symposium in Singapore, with all expenses paid. Why don't you guys go study the periodic table and then teach each other until I get back? You could just march through the table, commenting on how each element occurs in seawater.

Janna: I suppose that we can try that, but seawater is such a dry topic.

Dr. Bowles: Dry seawater, how cute! You will probably have to provide some basic information about each element to show how it is useful. If you get stuck, you can call me, but please remember the difference in time zones. Singapore is thirteen hours ahead of us. I will try to negotiate mooring your sub there.

Jordan: Now I know what grad students endure. We had better hit the books on the periodic table.

Dr. Bowles has left. Jordan and Janna are puzzling over seawater chemistry.

Jordan: I found that the textbooks normally discuss seawater solutes in their order of abundance, starting with chlorine and sodium and proceeding to sulfate and magnesium.

However, Dr. Bowles has asked us to march through the periodic table from hydrogen onward. Maybe he wants every element to get its fifteen seconds of glory.

Janna: I think that we should describe five types of substances in seawater. These five consist of: (1) the solvent water, (2) the inorganic solutes dissolved in that solvent, such as chloride ions, (3) dissolved gases, such as nitrogen trapped from the atmosphere, (4) organic solutes, such as hydrocarbons, and (5) minute particles suspended in the water.

Jordan: Dr. Bowles has already described water, so we can start with the inorganic solutes and dissolved gases. Most inorganic solutes are either negatively charged and called anions or are positively charged and called cations. Here is our guide. It's **the** table, period.

Periodic Table of the Chemical Elements

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	*Tc*	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

La*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac*	Th	Pa	U	*Np*	*Pu*									

Janna: We cannot successfully separate the solutes from the dissolved gases because elements such as carbon can rapidly exchange between these two states. Whenever you watch soda pop de-gas, the soda is not only losing its dissolved carbon dioxide but is also generating more carbon dioxide from solutes. A positively-charged hydrogen solute and negatively-charged carbon-hydrogen-oxygen-bearing solute combine to make water and more of the electrically-neutral carbon-dioxide bubbles. The decline in positively-charged hydrogen can be measured directly with a pH meter. Specifically, the pH rises as the hydrogen ion reacts.

Jordan: Although we are going to talk about more elements than usual, you may be relieved to learn that you can forget about most of the elements because they are very scarce in seawater.

Janna: Everyone knows that hydrogen and oxygen are the dominant elements in seawater because water is H_2O. Both of these elements also occur as solutes because water contains small amounts of hydrogen ion and hydroxyl ion. Hydrogen ion is just hydrogen without an electron whereas hydroxyl ion consists of a hydrogen atom bonded to an oxygen atom, with an overall electric charge of minus one.

Jordan: Solutes generally have some kind of electric charge. Hydrogen ion has a charge of plus one because it has lost its only electron.

Janna: Lithium, beryllium, and boron are all scarce in the solid Earth because little of these elements ever becomes manufactured within stars. All elements heavier than hydrogen and helium are produced by nuclear fusion within stars but some elements are made in vastly greater quantities than others. Lithium, beryllium, and boron are not favored products. Nonetheless, the small amount of boron that Earth possesses is concentrated in the oceans, making boron as significant as fluorine and silicon are in seawater.

Jordan: Given that all life depends on carbon, the carbon in seawater is obviously important for life processes.

Janna: The inorganic carbon solutes are carbonate and bicarbonate, mostly bicarbonate. A bicarbonate anion consists of a carbon atom, a hydrogen, and three oxygens, with an overall electric charge of minus one. It could accommodate another hydrogen atom. This capacity to hold more hydrogen offers a buffer against acidity. The concentration of hydrogen ions in seawater is directly related to acidity, so accommodation of hydrogen limits its increase.

Jordan: The observed pH of seawater is 8.2. This is a little more basic than neutral pH which is 7. Besides being the observed value, 8.2 also is the theoretical value that one may calculate for a solution in equilibrium with an atmosphere that contains as much carbon dioxide as our atmosphere, about 0.035%, provided that the theoretical solution contains as much bicarbonate and carbonate as does observed seawater. Bicarbonate is HCO_3^- and carbonate is CO_3^{2-}

Janna: Of course, this theoretical calculation may be just coincidental because bicarbonate is just a minor component of seawater and carbon dioxide is just a tiny fraction of our atmosphere. However, this is the only calculation that coincides with the observed pH of seawater.

Jordan: Nitrogen and oxygen gas dominate within our atmosphere, at 78% and 21%, respectively, but the solubility of both of these gases in seawater is very low. In tropical seawater at 25 degrees Celsius, the solubility of nitrogen is about ten parts per million. In other words, a million parts of seawater would only have about ten parts of nitrogen. For oxygen, the solubility is even lower in warm seawater, around four parts per million.

Janna: One has to seriously wonder how tropical fish can survive on such a small concentration of dissolved oxygen. Cold water close to freezing may contain more oxygen, about ten parts per million, but that is still a very tiny concentration. We land animals have it easy because we breathe air in which oxygen is 210,000 parts per million (21%).

Jordan: Like dissolved carbon dioxide, dissolved oxygen readily reacts to produce solutes. In contrast, dissolved nitrogen does not, despite the fact that nitrogen is essential for all life processes. Nitrogen largely enters the ocean as trapped air and its concentration does not vary much, just as the concentration of chloride ions does not change much throughout the ocean.

Janna: Oxygen gas is generated by photosynthesis at the surface of the ocean but there is no oxygen-generating process below that. Moreover, the settling corpses of surface critters consume dissolved oxygen as they decay.

Jordan: The resulting variation in dissolved oxygen throughout the ocean helps oceanographers characterize masses of deep seawater. The farther that a water mass travels through the deep sea after sinking from the surface, the more depleted it becomes in dissolved oxygen.

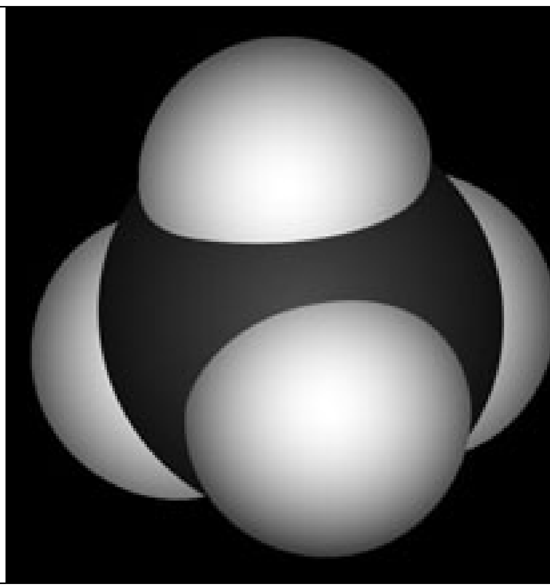
Janna: The image of settling corpses reminds me of dissolved organic compounds. Theoretically, these should all be destroyed by oxidation even though seawater contains little dissolved oxygen to accomplish that. However, some organic compounds do persist in seawater just as we mammals persist in an atmosphere that should oxidize us.

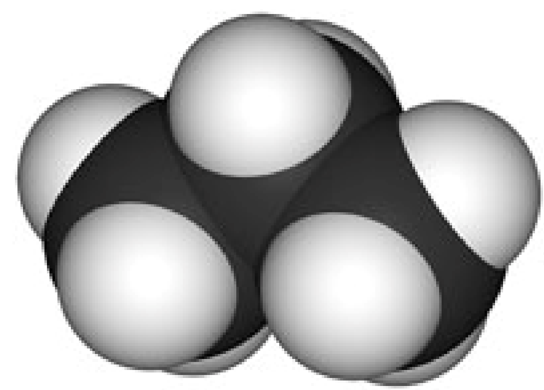
Jordan: Organic compounds that occur in seawater include carbohydrates, hydrocarbons, amino acids, carboxylic acids, humic substances, and steroids.

Janna: Steroids? I would like to see the baseball commissioner try to drag the Roman god of the sea, Neptune, into court over his use of steroids.

Jordan: Carbohydrates have a simple formula that is a combination of carbon and water molecules. To a first approximation, all of life can be reduced to the simplest carbohydrate formula. That is CH_2O.

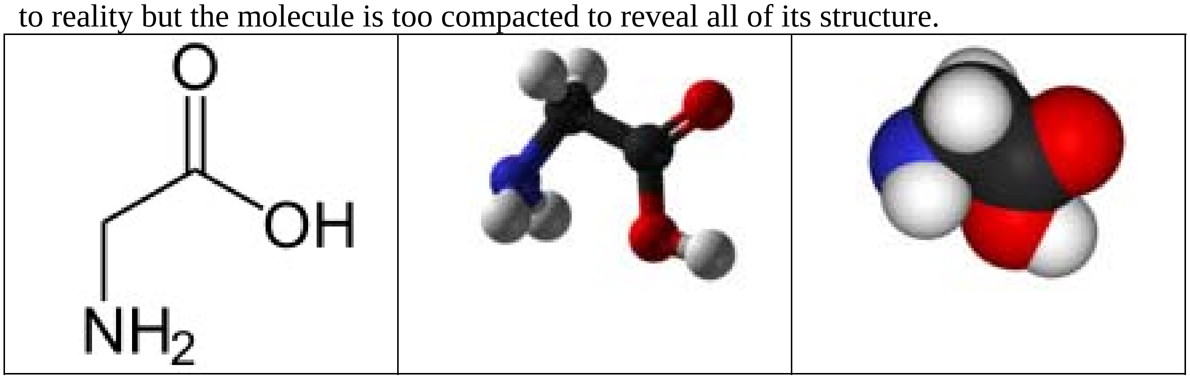
Janna: Hydrocarbons are even simpler than carbohydrates. They have only carbon and hydrogen. The number of hydrogen atoms is two more than twice the number of carbon atoms. The simplest hydrocarbon is methane, CH_4. There are several other famous hydrocarbons, such as propane, C_3H_8, and octane, C_8H_{18}. Here we see methane, CH_4, and propane, C_3H_8. They have four and eight hydrogen atoms, respectively, surrounding the central carbon atoms.



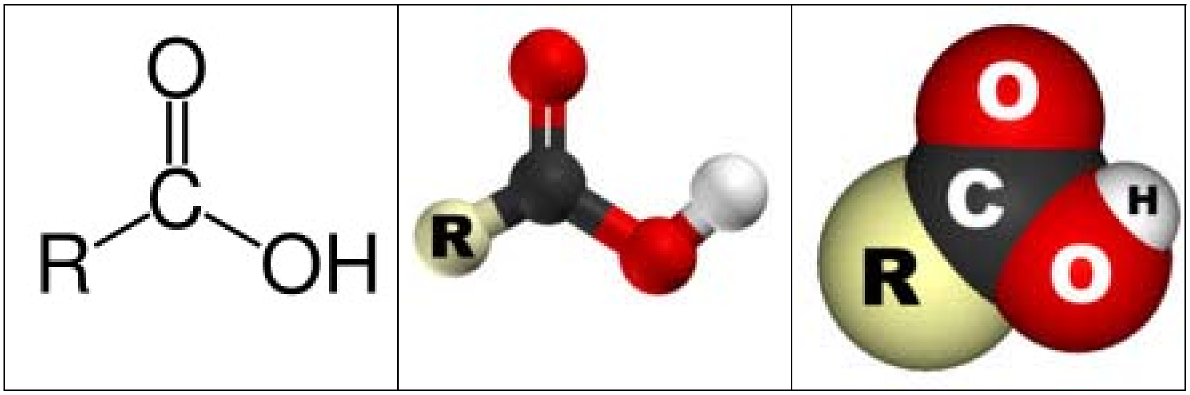


Jordan: Proteins are composed of amino acids. Amino acids always have some nitrogen in the form of NH_2. Here is a simple amino acid called glycine, $C_2H_5NO_2$. Glycine may be represented in three different ways, as shown here.

Janna: The central sketch is the clearest. The stick diagram on the left is missing both of glycine's carbon atoms and also lacks a couple of hydrogen atoms because an expert would know about those and would not need to have them specified. The sketch on the right is closest to reality but the molecule is too compacted to reveal all of its structure.



Jordan: Carboxylic acids are exemplified by vinegar and by the chemical that an insect injects to sting you, formic acid. In formic acid, the generic **R** that is shown here in the sketches refers to hydrogen. Vinegar is more complicated and its **R** represents CH_3.



Janna: Whenever an oil tanker ruptures, it makes front-page news and is described as being a major ecological disaster because of the hydrocarbons introduced into the sea. However, natural oil seeps have always introduced more hydrocarbons annually to the ocean than manmade oil spills, so the ocean must be able to handle these organic solutes fairly well.

Jordan: With each major oil spill, you get to see pathetic pictures of birds with wings that are so mired in oil that they cannot fly and will probably die.

Janna: However, you do not get to see the trillions of microorganisms that live better after an oil spill because that spill provides nutrients. Carbon is not very abundant on Earth and each oil spill provides free carbon to the marine ecosystem.

Jordan: In the long run, oil spills augment marine life, including the number of seabirds.

Janna: Whenever considering an environmental issue such as oil spills, you first have to decide on the time scale. Oil spills are always bad on a time scale of a few weeks but usually good on a time scale of decades.

Jordan: Media reporters always work on short time scales so they always consider oil spills to be bad. They usually imply that the oil will cover the sea for a long time but the oil actually reacts fairly quickly with oxygen and seawater, making it sink. Here is a view of the world's most famous oil spill, the Exxon Valdez in coastal Alaska, back in 1989. Small ships are attempting to contain and pump the oil. The foregoing bird was a victim of the Valdez spill. This poor bird became an international "poster child".

Janna: For the cleanup, Exxon paid 2.2 billion dollars to hire 11,000 workers and 1400 ships. However, Mother Nature eventually would have removed this oil by herself. Ironically, Exxon introduced voluminous additional chemicals to the environment during its cleanup.

Jordan: All organic solutes are unstable in the presence of dissolved oxygen. The solutes disappear from seawater by either going up into the atmosphere or down into the seabed. Most petroleum solutes become denser upon reaction with dissolved oxygen and sunlight.

Janna: You have seen this process yourself if you have watched the day-by-day changes in either gasoline or motor oil that has been spilled on the ground. After a while, it becomes "thicker", more viscous. In the ocean, that makes it denser and it eventually sinks to the seabed where it is virtually harmless.

Jordan: Exxon's impatient payout of 2.2 billion dollars was a huge boost to the local Alaskan economy and made some otherwise unemployed Alaskans dream of more oil spills. Exxon is lucky that there have not been subsequent "accidents".

Janna: Organic compounds have a seemingly infinite variety of matchups among carbon, hydrogen, oxygen, nitrogen, phosphorus, and related elements. In contrast, inorganic solutes are rather simple, so we will return to our place in the periodic table and discuss fluorine.

Jordan: Like lithium, beryllium, and boron, fluorine is a light-weight element that is scarce throughout the Earth because not much of it is made during the nuclear burning that makes stars shine. If more fluorine were available, we could have sodium fluoride oceans instead of the existing sodium chloride oceans.

Janna: As it is, seawater contains only about one part per million of fluoride whereas it contains nearly twenty thousand parts per million of chloride. Humans and other life forms concentrate fluorine by a factor of about thirty compared to seawater and that fluorine is essential for life processes in at least some animals, particularly clams.

Jordan: Animal bones and human teeth take up available fluorine to incorporate it within the mineral that constitutes our bones and teeth.

Janna: That mineral is called apatite. It is a calcium phosphate mineral that usually contains hydroxyl instead of fluorine. At the outset, we noted that hydroxyl is an anion that consists of one oxygen and one hydrogen atom. Fluoride also is an anion and it can readily replace the hydroxyl anion.

Jordan: When this happens, the apatite becomes harder and more resistant to bacterial attack. Most people around the world now use fluorine-rich toothpaste to help protect themselves from tooth decay.

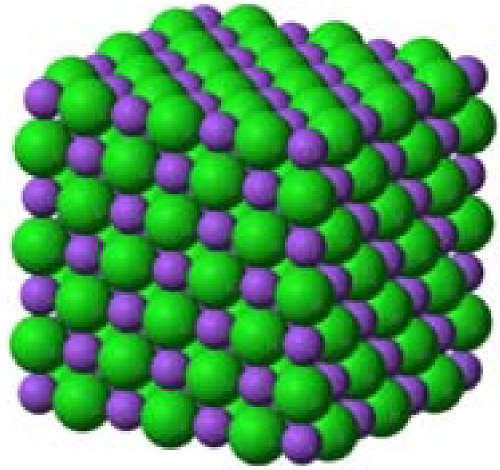
Janna: I suppose that nibbling on fish bones would have been an old-fashioned way of increasing one's intake of fluorine. Let's move on to the next element, neon. On second thought, let's not. We have already skipped helium and we can safely skip all the other inert gases because they are scarce and they are, well, inert.

Jordan: The inert gases are mostly trapped from the atmosphere. One inert gas, argon, constitutes nearly 1% of the atmosphere and so argon is the only inert gas of any consequence. Even so, argon is just six-tenths of a part per million in seawater. The other inert gases are all less than one part per billion, so there will be no further mention of them.

Janna: Moving on to sodium, we finally find a superstar. Sodium is abundant in rocks and dissolves readily to become a major component of seawater. Being the first major solute that we have encountered in the periodic table, sodium must be less dense than the others.

Jordan: Abundance of a solute in seawater is normally expressed in mass units. For example, we have talked about one unit of solute mass per million units of seawater mass. Sodium is so abundant that we can express this as a percentage, 1.08% of seawater mass.

Janna: Whenever anyone mentions sodium in seawater, they automatically mention the other superstar solute, chloride. Here is sodium chloride, better known as table salt.



Jordan: As you can see, there are comparable numbers of sodium and chloride ions in table salt, also known as halite. In a similar way, there are comparable numbers of sodium and chloride in seawater. As shown here, each chloride ion is bigger than each sodium ion, given that chlorine occurs farther along the periodic table. As a result, chloride ion constitutes a bigger mass proportion than does sodium, 1.94% of seawater's mass versus 1.08%.

Janna: We cannot overemphasize the roles of sodium and chloride in seawater. For starters, these solutes make seawater more stable with respect to freezing and boiling, depressing the freezing point to nearly minus two degrees Celsius and elevating the boiling point to nearly a hundred and four degrees Celsius.

Jordan: How did all this sodium and chloride get into the oceans? Three hundred years ago, the namesake for Halley's Comet, Edmond Halley, proposed that rivers have supplied most of the solutes. Elements like sodium and chloride which are particularly soluble have remained in seawater while less-soluble elements have precipitated.

Janna: Halley's comet was named for him because he successfully predicted its return in 1758. He correctly believed that previous sightings had occurred in 1456, 1531, 1607, and 1682. Halley, shown here, inherited money from making soap and devoted his life to natural science. He had a major impact in various ways. For example, he paid the publication costs for Newton's brilliant proof of Kepler's Laws regarding planetary motion.

Jordan: Halley captained the first English vessel that had a purely scientific mission. When his crew disobeyed him on the grounds that he was not a trained Navy officer, he returned to England and obtained a temporary Navy commission as captain. Back at sea, he produced the first map of the oceans with lines of equal magnetic declination. He became so famous that they carved this bust. Getting busted was a good thing back in Halley's day.

Janna: It is no wonder that other scientists took note when he explained the salinity of seawater in 1715. His stony gaze would have been enough to convince most people.

Jordan: Of course, rivers are not the only source of solutes to the oceans. Some volcanoes erupt directly into the sea, providing gases that become solutes. Desert dust also spreads across the sea and becomes partially dissolved by the microscopic marine organisms that need some of the chemical elements locked within those minerals.

Janna: Halley concluded that sodium and chlorine are dominant because of their high solubility, not because of their high supply. I test this solubility theory every time I jump out of the ocean and work on my tan. After a while, the seawater evaporates and I am left with just a white powder that tastes like table salt if I lick it.

Jordan: Seawater has to lose 90% of its water before it becomes sufficiently concentrated to precipitate halite, table salt. However, other solutes in seawater are not that soluble. The salty crust which precipitates while you are tanning contains more than halite, sodium chloride. It also contains hydrated calcium sulfate, a tasteless mineral known as gypsum.

Janna: We could try to calculate how much seawater has to be lost before gypsum will precipitate. To do that, we would have to look up the theoretical solubility constant for gypsum.

Jordan: A mineral's solubility constant, also known as its solubility product, is the maximum amount of solutes that can exist without those solutes trying to get together and precipitate the mineral.

Janna: Although the solutes occur in seawater in specific concentrations such as 1.08 percent for sodium, we use a corrected concentration, called an activity, rather than the measured concentration. The activity takes into account how the given solute behaves when involved in chemical reactions. Most solutes act as if they are not as concentrated as they really are.

Jordan: I have found the published solubility product for gypsum. It is a dimensionless number. Like most solubility products, it is very tiny, just 2.5 times ten raised to the minus five.

Janna: That tiny number should equal the activity of calcium times the activity of sulfate times the square of the activity of water, given that the chemical formula for gypsum is calcium sulfate with two water molecules. As you can see, the activity of the water molecules becomes squared in the solubility product because there are two water molecules in the chemical formula for gypsum.

Jordan: The solutes in seawater tend to be strongly influenced by the surrounding solutes when they become engaged in chemical reactions, so their activities are typically rather different than their measured concentrations. However, H_2O is so dominant in seawater that its activity may be approximated as being very close to one, simplifying the calculation of the solubility product. The square of one is still one.

Janna: In average seawater, the product of the calcium and sulfate activities is 4.7 times ten raised to the minus six. This observed ion-activity product would have to be increased by a factor of five to reach the solubility product for gypsum. To accomplish this, the volume of seawater would have to be reduced to one-fifth of the original volume. To achieve this reduction, about 80% of the water would have to evaporate away.

Jordan: This theoretical calculation is pretty close to what we observe for gypsum precipitation. However, gypsum usually starts to precipitate before 80% of the water has evaporated. A comparable calculation for halite, sodium chloride, comes closer to the observation that halite precipitation begins when 90% of the water has evaporated.

Janna: After sodium's place in the periodic table comes that of magnesium. Sodium and magnesium are the #1 and #2 cations in seawater. As with sodium, magnesium's position in the periodic table makes it seem less important than it really is when compared to its prime associated element. In the case of magnesium, the prime associated element is calcium.

Jordan: The mass of magnesium is three times that of calcium but magnesium's number of atoms is greater by a factor of five. When it comes to chemical reactions, it is the number of atoms that counts. Nonetheless, tables of seawater composition almost invariably use units of mass instead of numbers of atoms, thereby favoring heavier elements like calcium.

Janna: Although very similar to calcium, magnesium is universally rejected by marine animals that build houses for themselves from seawater solutes. Biologic consumption of calcium helps to keep its concentration low in seawater even though rivers supply more dissolved calcium than magnesium to the oceans every year.

Jordan: Metallic sodium and calcium are both unstable under atmospheric conditions because they will spontaneously oxidize. In contrast, metallic magnesium has found extensive use in the automobile and aircraft industries, given that it is light-weight and yet has good mechanical and electrical properties.

Janna: In the first half of the twentieth century, Germany precipitated a lot of magnesium from seawater because Germany did not have access to enough mineral resources to support its military ambitions. The supply of magnesium in seawater was effectively infinite. I know that Dr. Bowles took advantage of this seawater precipitate by driving a Volkswagen Beetle when a student. By using a magnesium alloy for the engine block, the Beetle did not need a radiator. Passive heat transfer by the magnesium was sufficient.

Jordan: The Beetle was originally designed by Dr. Porsche in 1931 with some stylistic input from Hitler himself. It went on to become the world's top-selling car until production ended in 2003. Other cars that have included magnesium components have been the Porsche itself, BMW, and Corvette.

Janna: The Germans found that getting magnesium from seawater was not all that difficult. They simply had to grind up limestone, dissolve it, and mix that calcium-carbonate solution with seawater. The calcium tended to precipitate with some of the seawater's chloride to become calcium chloride. Calcium chloride is the salt that we spread on roads during the wintertime. It is a popular misconception that we spread sodium chloride, table salt, but that would wash away too quickly and would rust cars too readily.

Jordan: When you swim in the ocean, you do not get an electric shock, so all the negative charge of the anions must be balanced by the positive charge of the cations. If some anion like chloride precipitates as calcium chloride, then an equal amount of some cation must precipitate to get rid of an equal amount of positive charge.

Janna: The ocean has more sodium than magnesium cations but it prefers to dump its magnesium because magnesium is less soluble. Magnesium precipitates as magnesium carbonate.

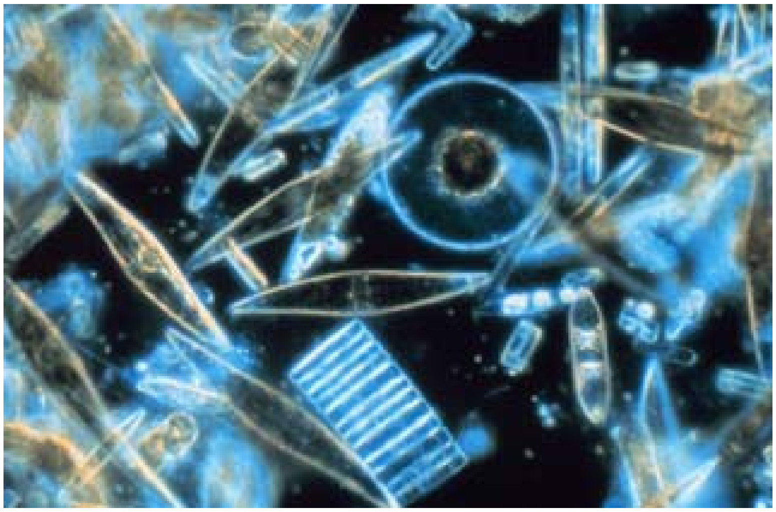
Jordan: The magnesium-carbonate crystals are filtered from the treated seawater and placed within a bath that has electrodes in it. Magnesium carbonate dissolves in the bath and an electric current plates magnesium metal onto one of the electrodes.

Janna: The Germans certainly did well for a while, extracting metal from seawater and petroleum from coal. However, all that ingenuity just prolonged the World Wars. Ultimately, they did not have enough natural resources to be competitive. My dad claims that they were too smart for their own good.

Jordan: Well, none of our friends have that problem, so let's move on to aluminum. Aluminum is peculiar in that it is even more stable than magnesium when refined into the metallic form, and yet it latches onto oxygen so strongly under natural conditions that it precipitates onto the seafloor rather than become an abundant seawater solute, the way magnesium does.

Janna: There is essentially no dissolved aluminum in seawater, just one part per billion, even though aluminum is the third-most-abundant element in the continental crust, running 8% of the crust.

Jordan: Let's slide to the next element, silicon. This is the second-most abundant in the continental crust and it too can be refined into a stable metal despite having a strong affinity for oxygen. However, its solubility is not quite so low, at three parts per million. Otherwise, we would not see so many tiny plants and animals with glass houses, like these diatoms.



Janna: Diatoms are a type of green alga that has a cell wall made of silica. As shown here, they have extremely variable shapes. It took decades for the British Challenger expedition to create line drawings of the diatom species they had discovered in the 1870's. Our current count is about a hundred thousand species. We will learn more about diatoms and other siliceous organisms when we focus on life in the oceans.

Jordan: Given the global input of a little volcanic and desert dust, trivial amounts of silica are constantly available to the silica-secreting organisms. Elemental silicon constitutes about 27% of the mass of the dust.

Janna: Although dissolved silica is scarce in seawater, there are voluminous deposits of silica on the seafloor, the accumulated remains of diatoms and radiolaria. The throughput of silica into these organisms must be efficient.

Jordan: This is like the tiny concentration of carbon dioxide in our atmosphere, compared to the large volume of trees that have all grown from that carbon dioxide.

Janna: Phosphorus is our next element and this element poses an even bigger conceptual problem than does silica. This is because the difference between the low solute concentration in seawater and the enormous volume of marine phosphate deposits is even more difficult to explain than the comparable comparison for silica.

Jordan: Siliceous deposits are forming extensively on the modern seafloor so we can understand their genetic processes. In contrast, there are no modern phosphate deposits that resemble the ancient beds that supply our modern fertilizer industry. Phosphate occurs as fish and mammal bones but their rate of growth is not like diatoms and radiolaria.

Janna: The literature is full of genetic models for phosphate deposits that are based on some type of upwelling but simple calculations show those models to be inadequate, given no known process of efficiently separating the trivial amount of dissolved phosphate from the rest of ordinary seawater.

Jordan: Ordinary seawater contains about ten parts per billion of dissolved phosphate. That is my definition of nothing. Rather than dreaming of ways to precipitate ten parts per billion, the genetic modelers could try thinking about ways for seawater to acquire a vastly higher concentration of phosphate.

Janna: Until we find a modern analog, we are unlikely to understand how phosphate deposits form. We have found modern analogs of other types of ore deposits while exploring with a submarine, such as hydrothermal-vent deposits of copper, lead, and zinc, so perhaps that is how we will find a modern analog for phosphate deposits.

Jordan: Modern analogs invariably reveal genetic process that we could not clearly envision by looking at an old ore deposit because rocks are dead, and dead men tell few tales.

Janna: Virtually any type of sedimentation that occurs on the seafloor involves life processes and those living organisms decay upon burial. We end up wildly guessing what the organisms may have been doing while alive.

Jordan: Let me put it this way. If Martians come and kill us all, how much human physiology will they be able to deduce, given just our skeletal remains to study? Not much.

Janna: Going back to phosphorus, the prime reason that fertilizer is so important is that without fertilizer, little phosphorus is available in natural environments.

Jordan: Phosphorus is essential to all life. In fact, one could write a simple chemical formula for living organisms to show the essential role of phosphorus. That formula would be 106 molecules of the simplest carbohydrate, CH_2O, 16 molecules of ammonia, NH_3, and one molecule of phosphoric acid, H_3PO_4.

Janna: Although life processes require phosphorus, organisms have a difficult time acquiring it because it is so insoluble. Phosphorus likes to be within a mineral called apatite, the calcium-phosphate mineral that constitutes our bones and teeth. Here are the bones of the world's largest animal, the blue whale.

Jordan: Moving on to sulfur, we find another element that is essential to life processes. Unlike phosphorus, sulfur is abundant in seawater, almost entirely as sulfate, an anion that consists of four oxygen atoms in addition to one sulfur atom. It has a charge of minus two and is the third-most-abundant solute in seawater, after chloride and sodium.

Janna: Seawater contains about a quarter of one percent sulfate. In a few restricted basins like the Black Sea of Turkey and the Cariaco Trough of Venezuela, dissolved oxygen is depleted from seawater and the dominant sulfur solute is hydrogen sulfide, H_2S, instead of sulfate. Here is the Black Sea.

Jordan: As you can see, the Black Sea is surrounded by land, except for a tiny connection to the Mediterranean. Density stratification keeps the oxygen-rich surface water of the Black Sea from sinking to the two-kilometer-deep seafloor.

Janna: The decay of settling organic matter has consumed all the dissolved oxygen and even the oxygen that was bound within dissolved sulfate, leaving the deep water full of poisonous hydrogen sulfide. This lifeless water body has rightfully earned its name, the Black Sea.

Jordan: Normal seawater contains so much sulfate that the evaporite mineral, hydrated calcium sulfate, is a voluminous precipitate. We have already shown that this mineral, called gypsum, precipitates more readily than does halite, table salt. If evaporation reaches 80% but not 90%, only gypsum and calcite will precipitate, and that precipitate will not taste salty.

Janna: Upon deep burial, the gypsum loses its water molecules and becomes anhydrite, anhydrous calcium sulfate. One of the most famous sedimentary beds in Texas is the Castile Formation with its rhythmically-alternating anhydrite and calcite, shown here.

Jordan: The Castile covers more than 2600 square kilometers in West Texas and southeastern New Mexico. The Gulf of Mexico has retreated a lot in the three hundred million years since it extended that far inland.

Janna: Theoretically, it is possible to precipitate anhydrite instead of gypsum from seawater, but the activity of water must be well below one. In other words, evaporation must have removed so much water that water starts to become influenced by the surrounding solutes rather than completely dominate the solution the way it does in dilute water.

Jordan: In a chemical reaction which converts gypsum into anhydrite, water is the only variable in the equilibrium product. The reaction depends entirely upon the activity of water.

Janna: It is not surprising that the Castile contains so much calcite since seawater is saturated with respect to calcite, even without evaporation. However, calcite normally is precipitated by organisms rather than inorganically.

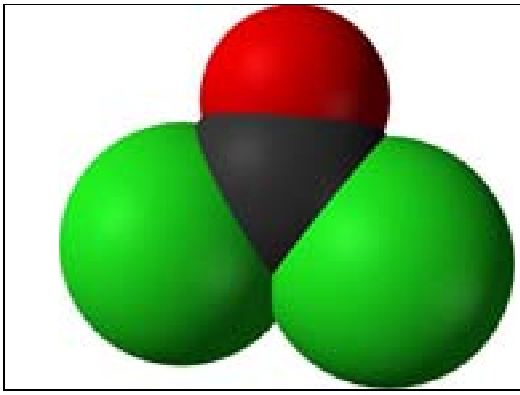
Jordan: If the Castile calcite organically precipitated onto the ancient seafloor, then the original shells have all dissolved and reprecipitated into crystals that lack any trace of a biologic origin.

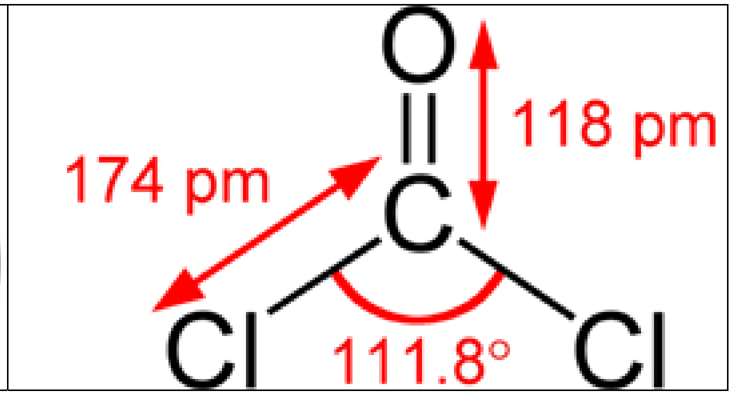
Janna: This brings us to chlorine, the queen of seawater solutes. Admittedly, this queen can be volatile when she wants to be, and chlorine gas was produced in large quantities by both the Germans and the French in World War One.

Jordan: Voluminous chlorine was obtained by placing electrodes into a sodium-chloride solution. The negatively-charged chloride ion would give up its extra electron to the anode, the positively-charged electrode, and become electrically-neutral chlorine gas.

Janna: The electrodes collected not just chlorine gas but also hydrogen gas for dirigibles and sodium hydroxide, a type of bleach known as lye. Chlorine also is used in bleach.

Jordan: Thousands of troops on both sides were exposed to deadly chlorine gas in the early phase of World War One, resulting in blindness or death. When the mortality rate was deemed too low, they introduced even deadlier chlorine-bearing compounds called mustard gas and phosgene. Besides two chlorine atoms, a molecule of phosgene also contains a carbon atom and an oxygen atom. Here we see two alternative views of phosgene.





Janna: On the right side, we see the angle between the chlorine atoms. We also see the distances between the central carbon atom and both the oxygen and chlorine atoms. These distances are in units of picometers. A picometer is very tiny, just one-trillionth of a meter.

Jordan: Phosgene was more deadly than chlorine gas because it was odorless, so the troops would breathe it without suspecting anything. In the lungs, phosgene would react with water to produce hydrochloric acid that destroyed lung tissue.

Janna: Ever since World War One, we have used chloride on another type of enemy, microbes that try to sneak into our public water supply. Unlike sodium, chloride is not abundant in fresh water, so the microbes do not expect it. We catch them unawares and zap them.

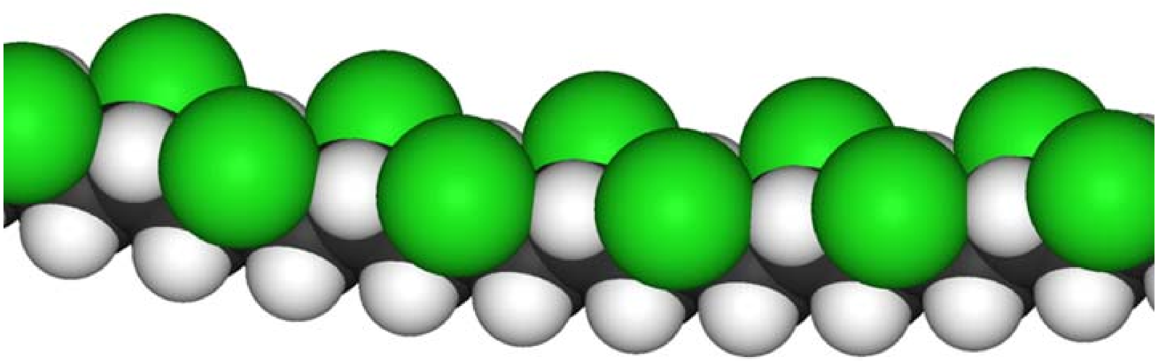
Jordan: Although deadly in the gaseous form, chloride solutes that come from ingesting table salt are absolutely essential to human metabolism. We seem to have a love-hate relationship with this element.

Janna: The supply of chloride in seawater is practically infinite because there is not sufficient room on Earth for all the people it would take to use even the smallest fraction of the available chlorine.

Jordan: Consequently, we use chloride every chance we get. You find chloride in a wide variety of products, such a PVC pipe, made of polyvinyl chloride.

Janna: Although other plastics are made entirely from petroleum, PVC is 57% chlorine by weight, so our infinite supply of seawater chlorine is helping conserve our very finite supply of petroleum whenever we can substitute PVC for other plastics.

Jordan: Here is the PVC polymer with its big chlorine atoms. For every chlorine, there are two carbon atoms and three hydrogens.



Janna: Of course, the prime users of chlorine are not humans but the marine organisms. They can rely upon finding a virtually constant ratio of chlorine to sodium no matter where they roam. Technically, we say that that ratio is conservative because it does not vary much.

Jordan: The British Challenger expedition of the 1870's was the first to discover how little the chlorine-to-sodium ratio varies worldwide. Off the mouth of a big river like the Amazon, one finds some dilution of seawater with fresh water. However, the chlorine-to-sodium ratio remains virtually the same.

Janna: While talking about sodium, we should move on to sodium's best pal in seawater, potassium. These two guys are so similar that they tend to travel together in chemical processes.

Jordan: Nonetheless, sodium travels better because it is smaller. We will see this pattern for some other pairs of elements within the same column of the periodic table, such as magnesium and calcium.

Janna: In the continental crust, there is about 2.5 times more sodium than potassium. In contrast, the ratio of sodium to potassium in seawater is ten times greater. There is 25 times more sodium than potassium.

Jordan: Within the periodic table, there is a tendency for the lighter elements to occur as either solutes or gases whereas the heavier elements tend to be more concentrated within minerals. Sodium and potassium exemplify that trend.

Janna: Potassium is the dominant cation within animal cells, including human cells. This is rather peculiar since sodium is the dominant cation in animal blood, just as it is in seawater. Moreover, the smaller size of sodium naturally makes it easier to migrate. The walls of all animal cells must be very good at excluding sodium.

Jordan: When one becomes dehydrated, it is more important that potassium be replenished than sodium. Gatorade® has capitalized on this knowledge by having a sodium-to-potassium ratio of five-to-one, vastly smaller than the sodium-to-potassium ratio in table salt.

Janna: Potassium does not even appear in some chemical analyses of table salt. Given that table salt is the marine product that we most commonly ingest, perhaps we should think about what is in it.

Jordan: We have noted that seawater has essentially the same ratio of solutes everywhere, so let's consider salt from the arid western coast of Australia, from WA Salt Supply®. Sodium chloride is 99.7% of their salt. Sulfate precipitates of all kinds total 1200 parts per million. That is 0.1% of the salt. Calcium is 400 parts per million and magnesium is 120 parts per million. Insoluble material amounts to only 200 parts per million. Perhaps that was windblown dust in the evaporite basin where the salt precipitated.

Janna: The Western Australians do not even list potassium in their analysis, so table salt is an inefficient way to acquire vital potassium.

Jordan: Morton® sells Lite Salt™, a potassium-enriched table salt. If I were severely dehydrated, that would be the salt for me.

Janna: Plants need potassium just as much as animals do. The potassium ion is needed for both protein and starch synthesis, and for opening and closing the tiny pores in their leaves. Consequently, potassium is a standard ingredient in fertilizer.

Jordan: Seawater is the ultimate source of the potassium in fertilizer, given that we extract potassium from evaporate deposits.

Janna: A quarter of the world's production of potassium comes from a very unlikely place, the Canadian province of Saskatchewan, mostly around the city of Saskatoon.

Jordan: There are a couple of reasons why one might not expect to find billions of dollars worth of potassium-bearing marine evaporites around Saskatoon, Saskatchewan. The first is that the white material in the NASA image shown here is snow clouds. The second is that Saskatoon is just about as far as you can get from the sea anywhere in the Americas.

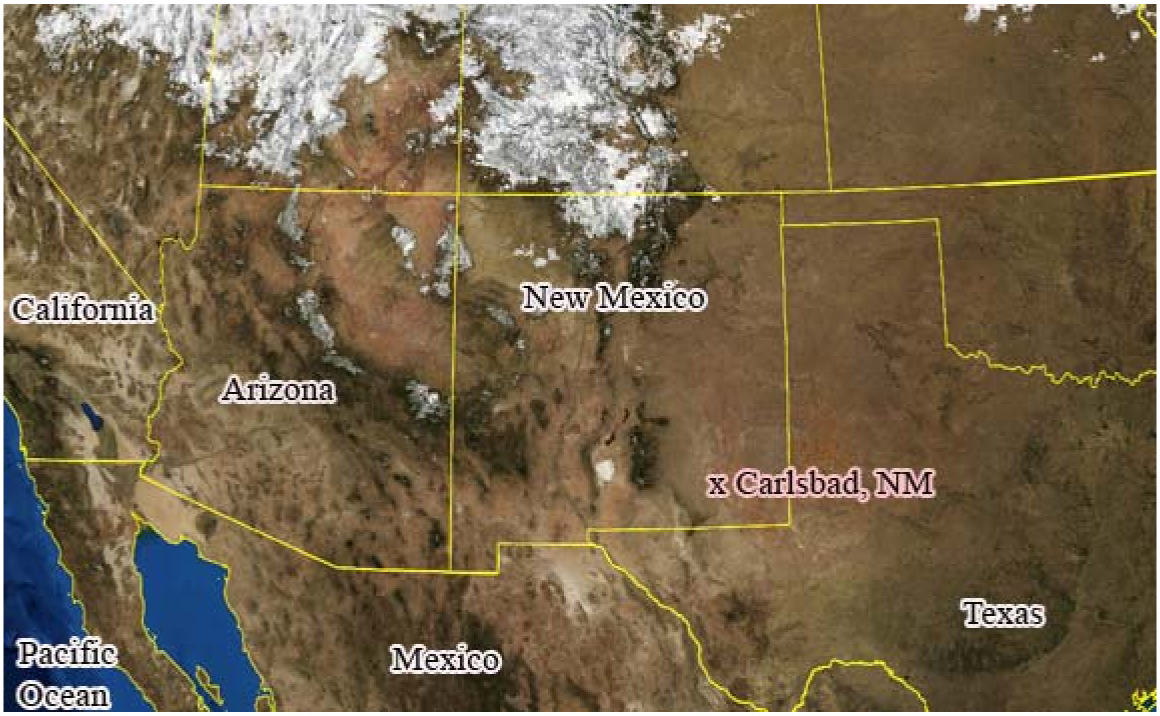
Jenna: Admittedly, the evaporite deposits are 350 million years old and even slow geologic processes can create a lot of change in that much time.

Jordan: Calcium sulfate and magnesium salts are also mined from these extensive evaporites but potassium chloride is the most-prized evaporite ore mineral in Saskatchewan because potassium is less abundant elsewhere in the world.

Jenna: The evaporites around Saskatoon are called bittern salts because they lack table salt and are very bitter to taste. Bittern salts precipitate from the last drops of evaporating seawater and include elements that remain in solution until the bitter end.

Jordan: One of the bittern salts is magnesium sulfate, better known as Epsom salts. This has been used as a laxative for time immemorial and more recently has proven beneficial during some types of heart attacks.

Jenna: The great distance of Saskatoon from a deep ocean actually promoted the precipitation of bittern salts because the ancient sea extended very shallowly across the continental interior and readily became separated into basins that completely evaporated. Obviously, the Saskatoon area was a lot warmer 350 million years ago than it is presently. Bittern salts of a similar age near Carlsbad in southern New Mexico also formed far from a deep ocean.



Jordan: It must seem strange to be exploring for potassium ore, potash, so far from the ocean from which it came.

Jenna: After potassium's place in the periodic table comes that of calcium, an element that we have already discussed with magnesium. If I had a dollar for every student who has been incorrectly told by a teacher that their bones are made of calcium, I would be a billionaire. Everyone's bones are made of apatite, a phosphate mineral that contains calcium.

Jordan: If my bones were actually made of calcium, I would be even more volatile than I already am because my bones would be fizzing way, reacting with water and carbon within my body. That would be nasty.

Jenna: Yes. That would also be fatal. Although no animal uses native calcium the way virtually every teacher implies, almost every animal uses some kind of calcium-bearing mineral for their hard parts, either as an exoskeleton or an endoskeleton. Our calcium-phosphate vertebrae form an endoskeleton. Clams have an exoskeleton made of calcium carbonate.

Jordan: Even some very tiny animals have exoskeletons made of calcium carbonate. The foraminifera are the calcium-carbonate equivalent of the siliceous radiolaria that we have already mentioned.

Jenna: Seawater has a lot more calcium and bicarbonate ions than dissolved silica, so seawater provides more raw material for the foraminifera to make their calcium-carbonate shells than it provides for the radiolaria to make their siliceous shells.

Jordan: Both foraminifera and radiolaria average about a millimeter in size, comparable to the thickness of a dime. Diatoms are much smaller.

Jenna: Existing and fossils shapes of foraminifera are even more numerous than the species variation seen in diatoms or radiolaria, numbering about 275,000 species.

Jordan: Why does Mother Nature need 275,000 species of foraminifera? What ever happened to survival of the fittest? Why doesn't one foraminifera call himself "Rambo" and go beat up on the rest?

Jenna: I agree. The enormous diversity of marine life has got to have a more complicated biologic basis than Darwin's cute little phrase. Let's explore marine biology in a subsequent discussion.

Jordan: I have a friend at the University of Texas who wears a T-shirt that proclaims, "Keep Austin Weird". Maybe even the weird guys have their place in the ocean.

Jenna: Not just in the ocean. Have you looked around the Data Structures class?

Jordan: Be careful. My boyfriend, Grayson, is in that class.

Jenna: So is my friend, Brent. However, I will refrain from commenting on whether Grayson proves my point about weirdos in that class. Before we get into a boyfriend war, we should move beyond calcium in the periodic table.

Jordan: There is a whole lot of nothing when you add up the fourteen elements past calcium, unless you happen to think that a part per million or a part per billion here and there amounts to something.

Jenna: Let me see if I remember the forlorn fourteen. They are scandium, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, gallium, germanium, arsenic, and selenium.

Jordan: Very good. Lost in the middle of that group is iron, the most abundant element in planet Earth, if you include the core and mantle. Iron also is the fourth-most-abundant element in the continental crust. However, seawater contains less than one part per billion of iron, effectively zilch.

Jenna: Considering that iron is virtually absent from seawater, iron has become surprisingly controversial recently.

Jordan: Some oceanographers have proposed dumping iron chloride or iron sulfate into the ocean to act as a stimulant for the growth of floating algae, phytoplankton. These photosynthesizing organisms supposedly would convert atmospheric carbon dioxide into organic matter and help alleviate the problem of global warming.

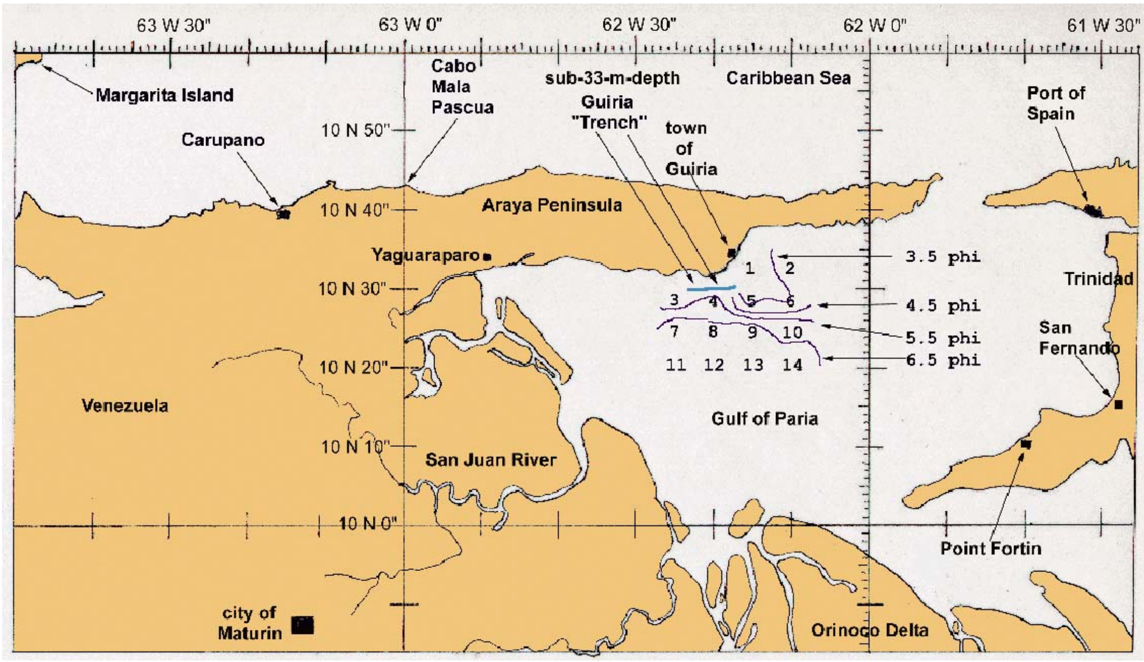
Jenna: The researchers claim that higher concentrations of iron in seawater correlate with higher organic productivity. Although this may be true, I doubt if dumping a pure iron compound would augment organic productivity.

Jordan: I too am doubtful. The observed higher concentrations of iron in some oceanic regions must come from either enhanced atmospheric dust or degassing of the deep Earth. In either case, iron would not be the only element being added. Plants need so little iron that the smallest amount of dust would satisfy them.

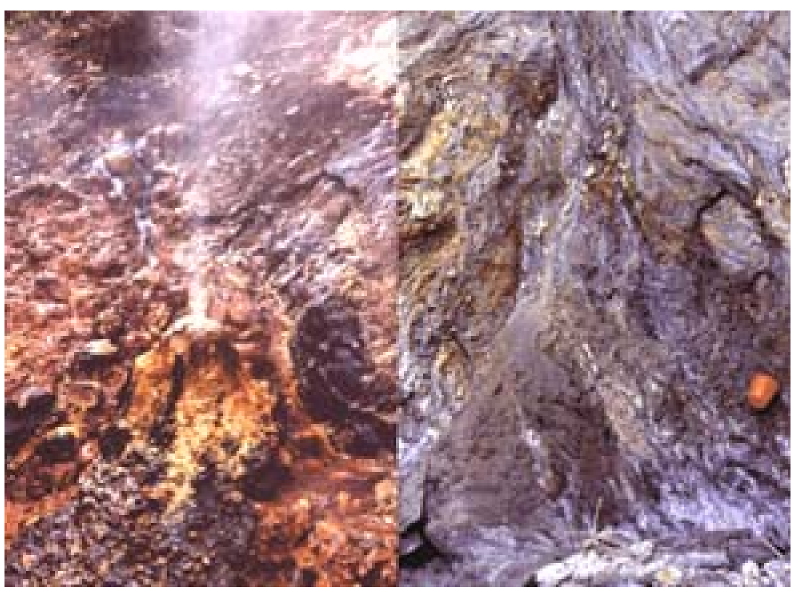
Jenna: Although I cannot imagine that iron would ever be a limiting element, many other elements in both dust and hydrothermal emanations are essential plant nutrients, and they could be limiting. Whenever iron is added naturally, other elements also will be added. Even in the case of manmade iron chloride or iron sulfate, one would not be adding just iron because these manmade materials are never pure. There is no reason to believe that a pure iron compound would be of any use whatsoever.

Jordan: There is another controversy concerning marine iron. We all depend on machines made of steel. All that steel comes from marine iron deposits. These deposits are enormous. Iron formations are some of the most voluminous sedimentary beds on Earth. If iron is effectively insoluble, then what was the marine source of all that iron?

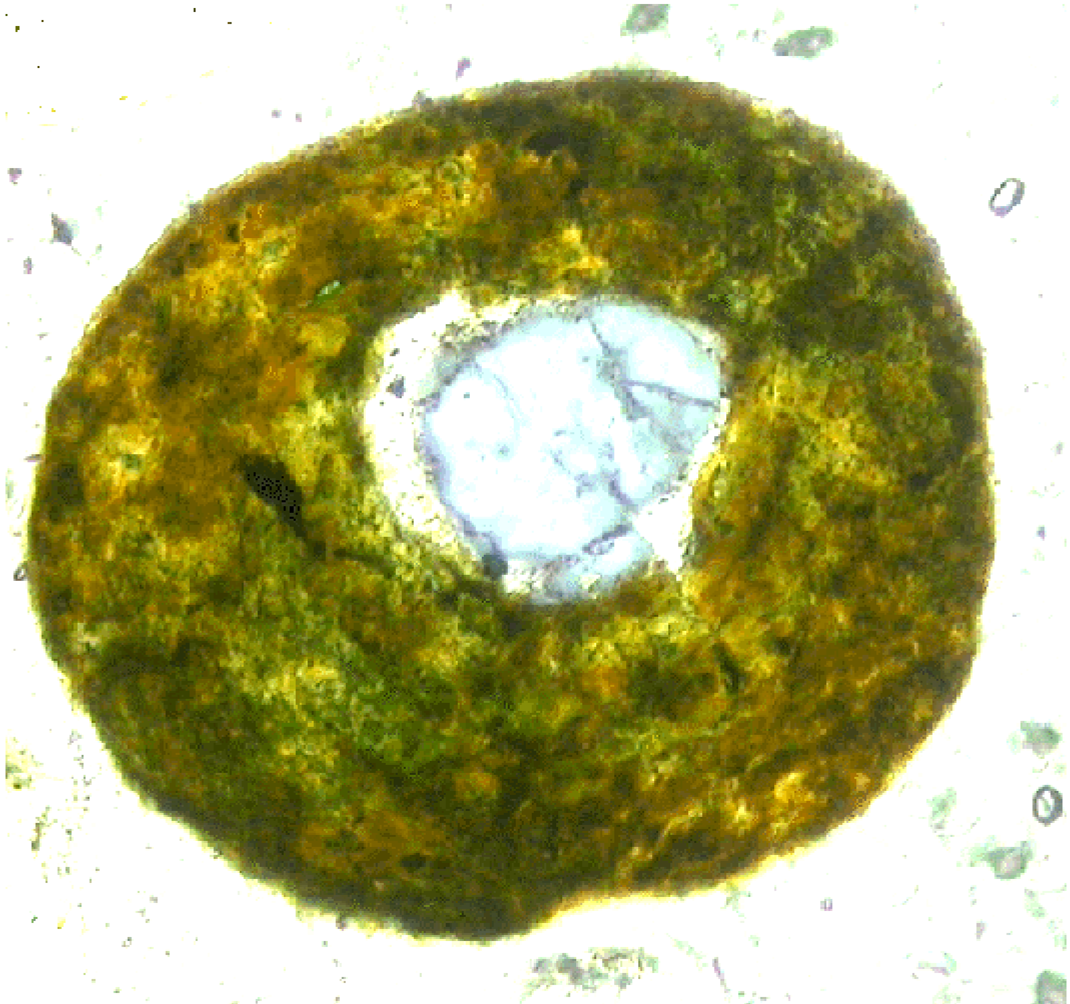
Jenna: This reminds me of the Sound of Music song, "Nothing comes from nothing; nothing ever could." Some oceanographers have proposed that seawater chemistry was vastly different in the past and that iron was more soluble. However, a modern iron deposit has been found in the northern Gulf of Paria, between Venezuela and Trinidad, where there is nothing strange about the seawater chemistry.



Jordan: There are active and dormant hydrothermal vents on the nearby mainland, so the iron is probably being delivered by subsea vents, independent of seawater chemistry.



Jenna: Marine iron deposits typically look like a collection of tiny onions, called ooids, especially those which have formed in the past six hundred million years. Here is a modern ooid from coastal Venezuela and some 2.7 billion-year-old ooids from northern Canada.



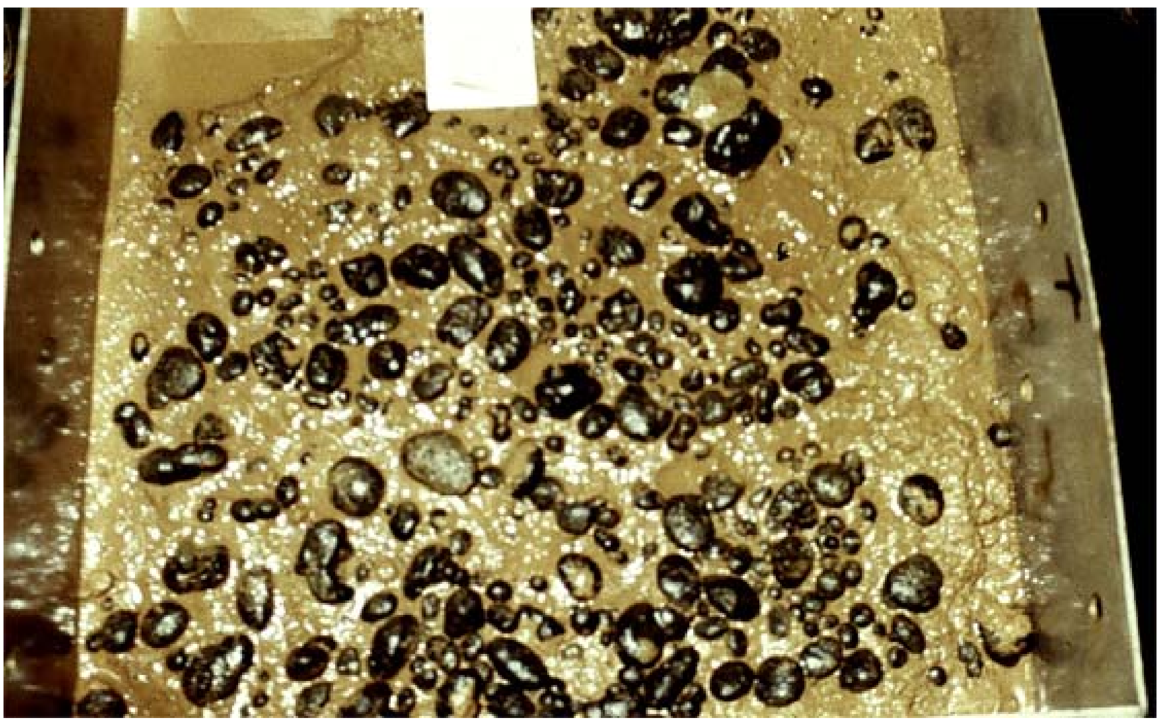
Jordan: If nothing comes from nothing, then no iron deposits come from seawater. The solutions which bring the iron from deep within the Earth must blast into the atmosphere like a volcano, allowing the highly insoluble iron to precipitate quickly.

Jenna: The precipitates could then agglomerate onto the onion-like ooids, layer-upon-layer, before falling back into the ocean. This would resemble the growth of hailstones.

Jordan: Manganese was another of our forlorn fourteen and it forms ore deposits like those of iron, albeit not so numerous or voluminous, in keeping with the iron-to-manganese ratio of about fifty in Earth's crust.

Jenna: Nonetheless, the bedded manganese deposits generally resemble the iron deposits and can be assumed to have had a similar origin.

Jordan: Bedded manganese deposits are distinct from the manganese nodules that locally cover the modern seafloor. These nodules look like huge iron ooids and do contain substantial iron in addition to their namesake manganese. Here are some nodules from the tropical Pacific seafloor, with a small notebook for scale.



Jenna: Ever since the British Challenger expedition first found these nodules to be widespread on the seafloor, a debate has waged over their origin. One side has called for the input of dissolved manganese into the ocean from seafloor vents whereas the other side has attributed the nodules to normal processes of sediment alteration on the seafloor.

Jordan: Manganese nodules are different from the voluminous bedded manganese deposits but the nodules probably also represent hydrothermal activity, albeit rather wimpy and widespread when compared to the ore-forming activity than can make the rare but voluminous manganese beds.

Jenna: Following the forlorn fourteen, we find bromine, the element directly beneath chlorine in the periodic table. As expected, bromine is fairly abundant in seawater, at about 85 parts per million.

Jordan: The highly concentrated brine of the Middle East's Dead Sea contains about 1% bromide. At this high concentration, the bromide ion may be extracted by simply pumping chlorine gas through Dead Sea water.

Jenna: The excess electron on the bromide ion hops onto the uncharged gaseous chlorine, turning it into a chloride ion. Meanwhile, the bromide ion, having lost its electron, becomes uncharged bromine gas. The bromine gas bubbles off and is easily collected.

Jordan: Being more than twice as heavy as chlorine, bromine is used to make dense solutions for oil drilling. A drill bit has to be continuously lubricated and cooled but the drilling fluid needs to be as dense as possible to prevent a blow-out of valuable oil.

Jenna: Any oil or pore water that is encountered during deep drilling may be under great pressure. Besides losing valuable oil, a blow-out could threaten the drill crew.

Jordan: Rubidium is our next chemical element. At just a tenth of a part per million, rubidium is a sleeper. In contrast, the element beside it, strontium, does better, at about eight parts per million.

Jenna: Calcium carbonate minerals always contain some strontium because calcium lies immediately above strontium in the periodic table, making them chemically similar.

Jordan: The two dominant strontium minerals in sedimentary rocks are like the two dominant calcium minerals in sedimentary rocks. These are the carbonate and sulfate minerals.

Jenna: Following strontium, we step into a desert that stretches on forever. The only minor oasis in this barren landscape is iodine, and even iodine does not reach one part per million in concentration.

Jordan: At well below the part-per-billion threshold, we find the rare-earth elements. Despite their virtual absence from seawater, thousands of analyses of iron deposits have been made by researchers who cling to the hopeless notion that trends in the rare-earth elements will reveal the source of the major elements in those deposits.

Jenna: Nothing comes from nothing.

Jordan: Nothing ever could.

Jenna: Having reached a state of nothingness, we will end our discussion of seawater chemistry in the expectation that Professor Bowles has made it back from Singapore, ready to talk about "movers and shakers" in the marine world. Besides the stuffed-shirt administrators, the "movers and shakers" are marine currents, atmospheric currents, waves, tides, and tsunami.

Jordan: I bet that Singapore was just a cute story to disguise a trip to Bangkok.

Jenna: You know that he uses boarding passes for bookmarks. That should give him away.

Chapter 5: The Current View of the Oceans

Janna: All those chemical elements in seawater were beginning to make me seasick. Where did they get all those strange names? Two-thirds of them ended in "um". Why was that?

Jordan: My theory is that the discovery of new elements took so much lab time that the chemists became hermits who avoided conversation. When a chemist finally called a press conference to announce his great discovery of a new element, it went something like this. "I have just discovered, um, two new elements. I have decided, um, to name them niobi, um, and molybden, um. Any questions?"

Janna: When the stuttering chemist saw the names, niobium and molybdenum, in newspaper headlines the next day, he had to stick with them to avoid admitting that he was just saying "um" accidentally.

Jordan: Accidentally? I hope that we do not have any accidents with our sub. Otherwise, we might become listed on a newspaper's back pages rather than grab the headlines.

Janna: Dr. Bowles is scheduled to explain marine and atmospheric currents to us today. If our sub loses power, he might give us some idea where the currents will take us.

Jordan: Here comes Dr. Bowles now.

Prof. Bowles: Hello Jordan and Janna. Are you ready to be swept away by the Gulf Stream?

Jordan: And sink when we get to Iceland? Maybe we could start by visiting coastal Miami and then let the ships fall where they may.

Prof. Bowles: OK. Let's launch your rubber ducky into the Gulf Stream off Miami Beach. Which type of ducky do you prefer? Do you want baby duck, devil duck, reindeer duck, cross-eyed duck, or dark-shades duck?

Jenna: Who could resist the cool dude with the sunglasses?

Prof. Bowles: OK. Now, your rubber ducky is rolling northward so fast that you must think he is being chased by a shark. A quick pace for a walking duck is one mile per hour (1.6 kph) but your floating duck is moving about five times faster, around five miles per hour (8 kph). The water mass carrying him is a hundred times greater in width than depth, about a hundred kilometers (60 miles) wide by a thousand meters (yards) deep. In the Florida Straits where your rubber ducky starts his voyage, the flow is about thirty times greater than the combined flow of all the rivers on Earth.

Jordan: I have heard that the unit of water flow is named for the Norwegian pioneer, Sverdrup, who found the Sverdrup Islands north of Canada about a century ago.

Jenna: That's right. We talked about him when we reviewed the history of oceanography.

Prof. Bowles: History proves useful once again. A sverdrup is a flow rate of a million cubic meters per second. If you take the length of a football field and make that into a cube, then roughly that volume would have to flow past you within a second to equal a sverdrup.

Jordan: So, you are telling me that when I look out of my aunt's condominium on Key Biscayne, I am looking at thirty times that flow in the Florida Straits. Those thirty sverdrups must be carrying a lot of warmth northward to places that could use it.

Prof. Bowles: Yes, and the flow rate increases to eighty sverdrups by the time it passes North Carolina's Cape Hatteras and starts to move offshore, toward the northeast. Ben Franklin was the first to map the north-to-northeast change in direction. As you know, the Outer Banks of North Carolina are so consistently windy that the Wright brothers came there seeking lift for their heavier-than-air prototype airplane. This same wind induces evaporation of the Gulf Stream, thereby cooling the water.

Jenna: Is that like the cascading water tower which I see in the power plants for big buildings? I am told that the imitation waterfall helps the air-conditioning plant because the water cools as it partially evaporates.

Prof. Bowles: Yes. It takes a lot of energy to change water from the liquid state to a vapor and the temperature drops as energy is used for that process.

Janna: What is driving the Gulf Stream along the coasts of Florida, Georgia, and the Carolinas? In my high school, the Gulf Stream was compared to the convection that one sees on a stovetop, moving a hot fluid to a cooler region. However, the distance from Florida to Iceland seems too great for this to work. There would be too much friction along the way.

Prof. Bowles: You are right. Convection is not a big enough motor to drive something as fast and voluminous as the Gulf Stream. A temperature drop of 20 Celsius degrees from Florida to Iceland is not big enough, but it does help the flow. The Gulf Stream is mostly wind-driven. You can reproduce this effect by filling a glass full of water and then steadily blowing across the top of the glass. You will soon learn that this is not a particularly efficient process because you have to blow about fifty times faster than the motion you produce in the water. Nonetheless, the water will definitely move.

Jordan: If wind is the prime propellant of the Gulf Stream off the Southeastern US, then perhaps we should learn something about global wind systems before we continue tracking our rubber ducky.

Prof. Bowles: Good idea. Perhaps we will learn why the Brazil Current, the southern hemisphere's equivalent to our Gulf Stream, is both weaker and shallower than our Gulf Stream. Atmospheric and oceanic currents are definitely coupled, so it makes sense for us to take a top-down approach to this topic. Unfortunately, some textbooks fail to emphasize that all measurements of these currents are biased by our frame of reference. Everyone measures the world relative to themselves. If anyone stops moving, they believe that they are stationary. However, they are not. If someone takes a submarine down to the equator and parks it there to go fishing, they will not really be parked but will be travelling eastward at about a thousand miles an hour.

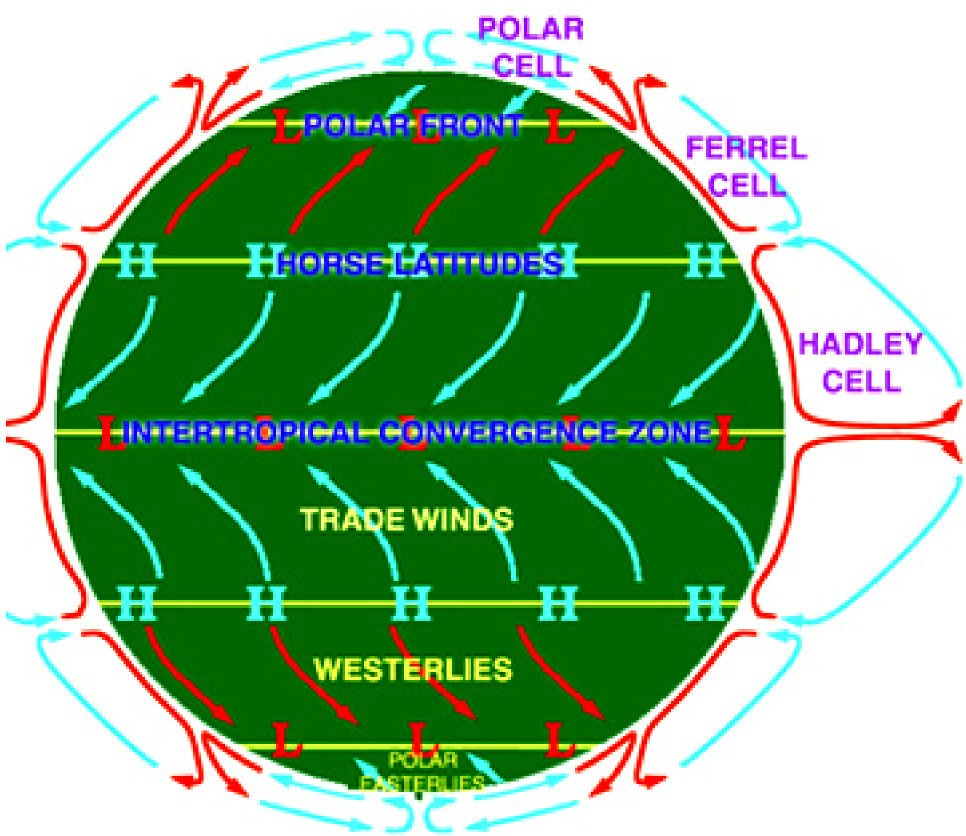
Jenna: A thousand miles an hour !! I thought that the equatorial region was called the doldrums because nobody hustled down there.

Prof. Bowles: When the French invented the metric system, they defined the circumference of the Earth to be 40,000 kilometers. That is 24,860 miles. Given that we all spin around the Earth in 24 hours, the lateral velocity works out to be roughly a thousand miles an hour at the equator, or 1660 kilometers per hour. Of course, the Eskimos do not go far when they spin around the world each day and Santa Claus at the North Pole is barely moving at all.

Jordan: The atmosphere is not bolted to the solid Earth so it must be disturbed by this wildly spinning object beneath it. Is that the Coriolis effect?

Prof. Bowles: Yes. That disturbance strongly affects north-south movement of air masses because they keep encountering other air masses with different rotational velocities. Of course, it also means that our favorite reference frame is not consistent from place-to-place.

Jenna: Would meteorology and oceanography make more sense if we had somebody reporting about the Earth's currents while observing them from the Moon?



Prof. Bowles: Absolutely. However, the Moon is a pretty hostile environment so we are stuck reporting on a game in which the goalposts keep moving. A hockey goal commonly does move when a forward crashes the net, but that stops the game. Let's continue our game with an overview of atmospheric currents.

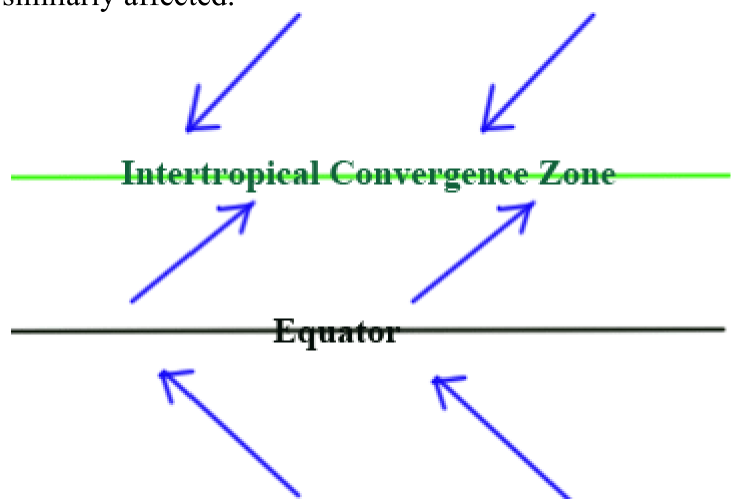
Jordan: Given all the different winds on Earth, I am not surprised that a global overview looks so busy. I see that the doldrums are now called the intertropical convergence zone, abbreviated to the ITCZ. Is that more politically correct than doldrums?

Prof. Bowles: I suppose. However, if you ever had to work in that high-temperature, high-humidity environment, you would still want to call it the doldrums. The ITCZ and all the other illustrated circulation zones move seasonally. The westward convergence of the Trade Winds moves northward in the northern summer and southward in the southern summer. Of course, it is the convergence of the Trade Winds that generated the name, intertropical convergence zone.

Jordan: The illustrated paths of converging airflow remind me of the classic African joke that compares African politicians to a bunch of bananas. They are all yellow and there is not a straight one among them. None of the airflow paths is straight. Moreover, the paths curve in different ways in different latitudinal zones.

Prof. Bowles: On average, the ITCZ does not lie along the geographic equator, as shown here. When discussing ocean chemistry, we noted that the ITCZ averages about five latitudinal degrees north of the equator because most of Earth's land is in the northern hemisphere. The oceans are correspondingly more extensive in the southern hemisphere. This additional covering of water absorbs more of the Sun's incoming energy because seawater has a higher heat capacity than does the land. The amount of energy required to heat a given volume of water is not only greater than for land, but sunlight is able to penetrate much deeper into water than into land, so there is a vastly larger volume that absorbs solar energy. The temperature of the southern-hemisphere oceans does not change much from summer to winter, compared to seasonal changes in the northern hemisphere. The ITCZ heads southward during the northern winter but does not get much south of the geographic equator.

Jenna: If the ITCZ is the band of rising air, then air must be flowing into that band from both the north and the south. Air from the south would have to cross the equator and that would cause the Coriolis acceleration to switch from leftward to rightward. Wind-driven ocean currents must be similarly affected.



Prof. Bowles: Here is where your lunar observer would get a straighter view than you. However, we have agreed that we would forego the Moon and use the Earth as our frame of reference, like everyone else.

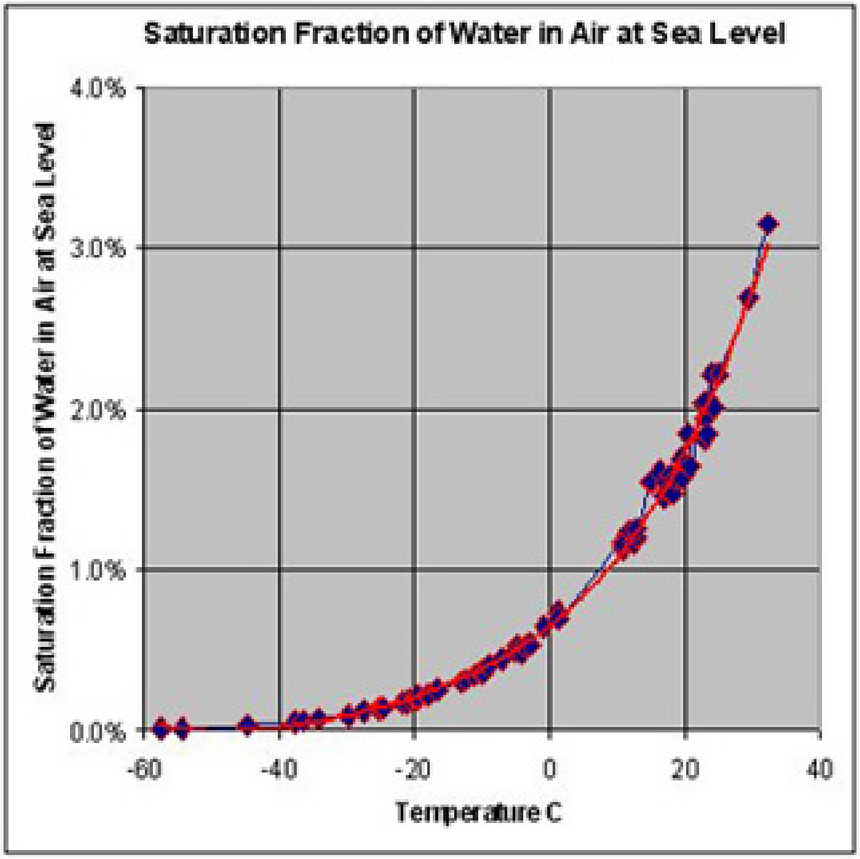
Jordan: The illustrated divergence around the equator must cause upwelling because the water heading to the right north of the equator will be fed by deeper water, as well as water crossing the equator. Given all the solar energy there, I bet that the plant life, the phytoplankton, can make good use of the abundant nutrients supplied by that upwelling.

Prof. Bowles: The plant life does indeed flourish. Let's take a different view of the ITCZ. Let us suppose that you were to become a ballooner instead of a submariner. If you get tired of working in the doldrums, you could lift off some afternoon.

Jordan: Balloons like this have always been a good way to make some sort of statement.

Prof. Bowles: When you get up to a high enough elevation, all that humid tropical air that has risen with you is going to cool and become incapable of carrying so much water vapor. Do you remember the graph showing the maximum water vapor that air of a given temperature can carry? Here it is again. At a tropical temperature of 30 degrees Celsius, about 3% of the air is water vapor.

However, air cools as it rises, as you must know if you have ever driven up a mountainside. The rate of cooling is called the lapse rate. Air cools about 6.5 degrees Celsius for every kilometer of increased elevation. That's about 3.6 degrees Fahrenheit for every thousand feet. This lapse rate is predictable worldwide for the same reason that the fluid in your refrigerator's coils will cool predictably if you allow that fluid to expand. There is less pressure on the upper atmosphere because there is less material above it, pushing down on it. Air automatically expands and cools in the upper atmosphere. By rising five kilometers, about three miles, even the warmest tropical air will become colder than the freezing point and will lose five-sixths of its water vapor, as rainfall.



Jordan: I suppose that that rain falls back to the tropical land from which it had evaporated earlier in the day. If we want to make a quick stop in an equatorial port with our submarine, we should plan on getting there in the morning because the afternoon rainfall will make us think that we are like our sub, drenched in water, when walking around the downtown.

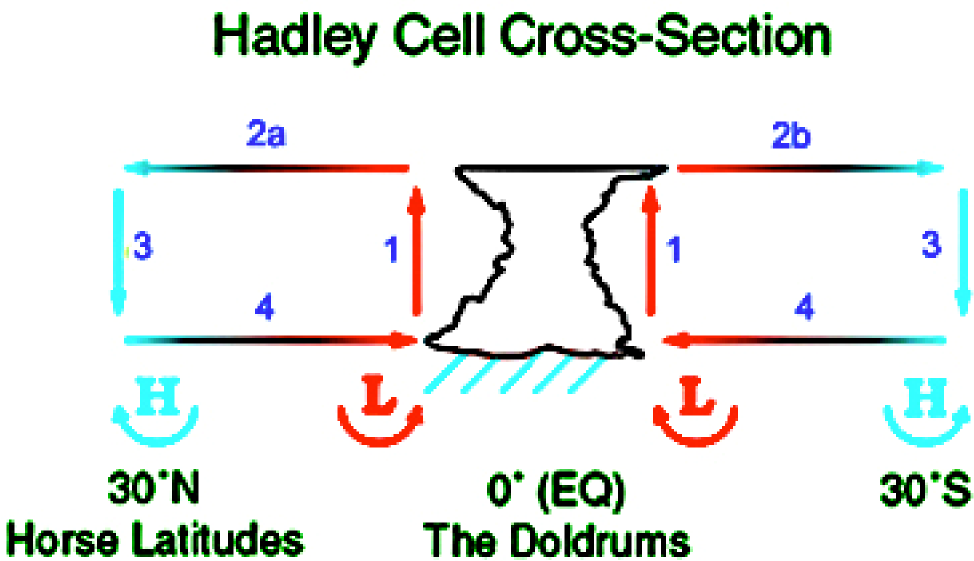
Prof. Bowles: Although the water vapor falls, the air around your balloon may continue upward until it reaches the top of the troposphere, at about 8 kilometers (5 miles). At that height, the lift that came from tropical heating will be exhausted and the pull of gravity will keep the air from going higher. Like churning soup on your stovetop, when the air stops rising, it will head away in either direction, away from the equator. A little of the air will get all the way to a pole and descend onto the Earth's surface, but most of it will not get past the latitudinal belt that lies twenty-to-thirty degrees away from the equator.

Janna: I know that you have previously explained how everyone at a particular latitude is heading eastward at a unique velocity, ranging from about a thousand miles an hour at the equator to zero miles per hour at a pole. If I were some equatorial air mass that ran into a twenty-to-thirty-degree air mass, it would be like hitting a slow-moving car in my own lane. I would be moving eastward faster than that air mass, so I would hit it and drop back toward the Earth's surface.

Prof. Bowles: Indeed you would, and you would become compressed as you felt more-and-more air pressing down on you as you sank lower. Compression would have the same effect on you that it has on the fluid in the compressor of your refrigerator. Your compressor is kept well away from the interior of your refrigerator because compression heats the fluid. In fact, every refrigerator induces more heating than cooling.

Jordan: As the air falls, it must create a high-pressure zone at the Earth's surface.

Prof. Bowles: Yes. Like a bucket of falling water, it splashes in all directions when it hits the ground, sending some air back toward the equator from which the air mass originated. This equator-bound circuit is called a Hadley cell, as shown here.



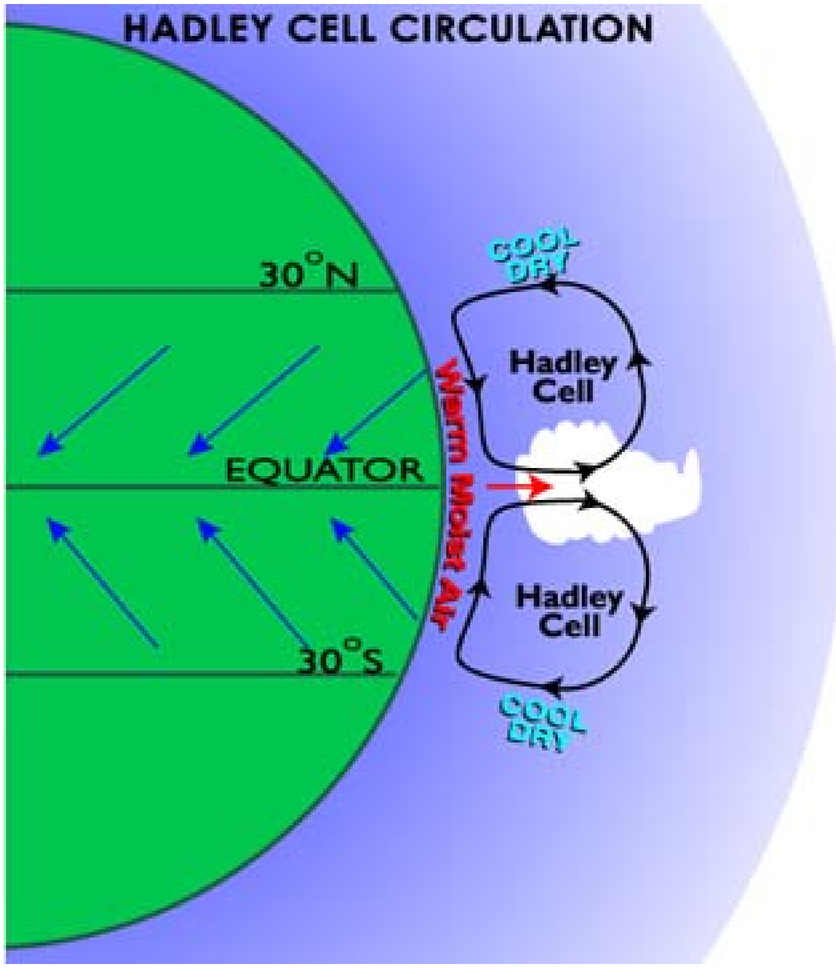
Jordan: I like the tropical thundercloud in this sketch and I am glad that somebody still uses the poetic term, doldrums. Who was this guy, Hadley, and which cell was his?

Prof. Bowles: George Hadley actually did understand prison cells because he was an English lawyer. He brazenly confronted the most prominent oceanographer in his country, Edmund Halley, and proclaimed that he was guilty of airy-fairy thinking.

Janna: I remember Halley. He was so famous that he got "busted".

Prof. Bowles: No sculptor made a bust of Hadley because nobody appreciated his work until long after he died. Both Halley and Hadley were trying to explain the Trade Winds, these dependable winds that come from the east in the tropics. Edmund Halley incorrectly attributed the direction of the Trade Winds to the Sun's apparent path from east to west, heating the lower atmosphere progressively along its illuminated area.

Hadley correctly attributed the wind direction to a different aspect of the Earth's continuous rotation. He understood that air traveling from 30 degrees latitude toward the equator would approach a region that was rotating faster than the region from which it originated. The approaching air would appear to veer toward the west since the equatorial region was heading eastward so quickly, leaving that approaching air behind it. This easterly source of the wind on both sides of the equator is illustrated here. Any meteorologist would describe this wind as easterly because meteorologists consistently name wind by the direction from which it comes. In contrast, oceanographers are rather inconsistent in describing marine currents, sometimes citing the direction where it is headed and other times its source.

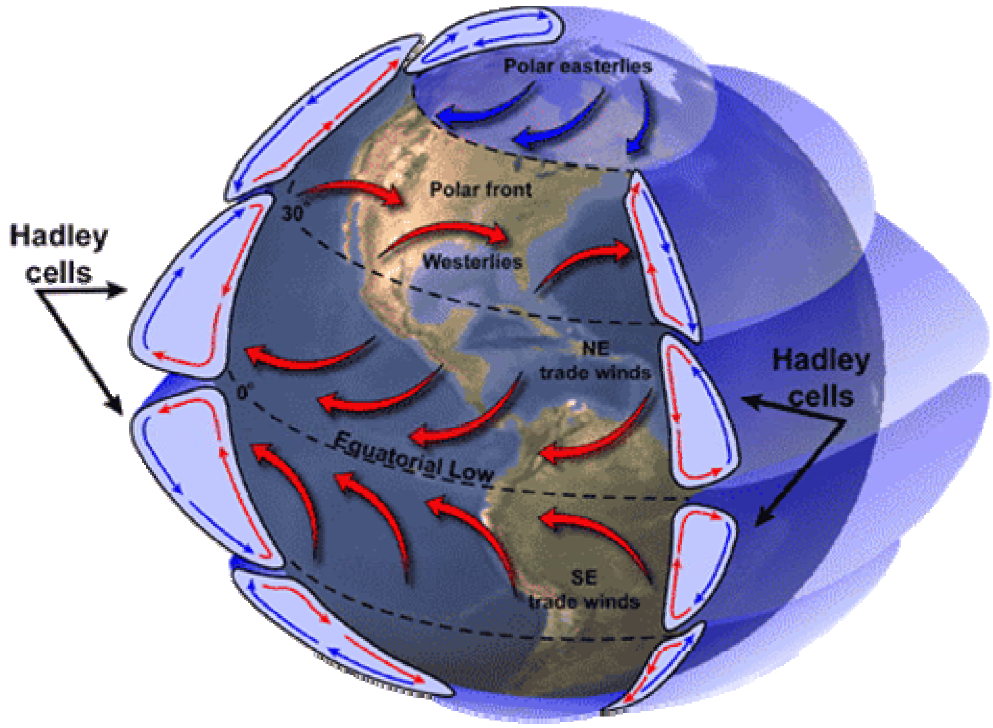


Jordan: By definition, the equator is a fixed line, but I doubt if you really mean a fixed line when referring to the center of the Hadley cells, given that they move with the seasons. Don't you really mean something that could be called the solar or thermal equator? This is the latitude where the Sun's rays come straight toward the surface, the Sun's zenith line.

Prof. Bowles: I have been teaching you too well if you are starting to talk back. It is true that the Trade Winds change somewhat seasonally, following the shift in the solar equator.

Jenna: I fondly remember the Trade Winds from a vacation on the ABC islands in the southern Caribbean, the Dutch-speaking islands of Aruba, Bonaire, and Curaçao. The winds were consistent in strength and direction, about 20 kilometers per hour from 70 degrees east of north. That made wind-surfing a lot easier for a beginner like me. Shifty winds in other places still make me capsize.

Prof. Bowles: Only the Hadley cell appears in the immediately overlying diagram whereas a previous diagram showed a couple other cells, the Ferrel cell and polar cell. These cells appear on the following sketch but are not labeled. The Ferrel cell always lies between a Hadley and a polar cell.



In general, the Ferrel and polar cells are not as well-developed or persistent as the Hadley cell. Even the Hadley circulation is less consistent than implied in introductory textbooks. Rather than a single Hadley cell that extends around the world, there are really several such cells that interact with each other in complex ways. Another complication is that the surface winds which we experience are not integral members of the illustrated cells, despite all the textbook illustrations which show that. The surface winds that we feel are certainly strongly influenced by the named cells which overlie them, but technically are separate air masses.

Jordan: Whatever happened to that portion of the poleward-bound air which did not descend in the twenty-to-thirty degree latitudinal belt but continued to the pole?

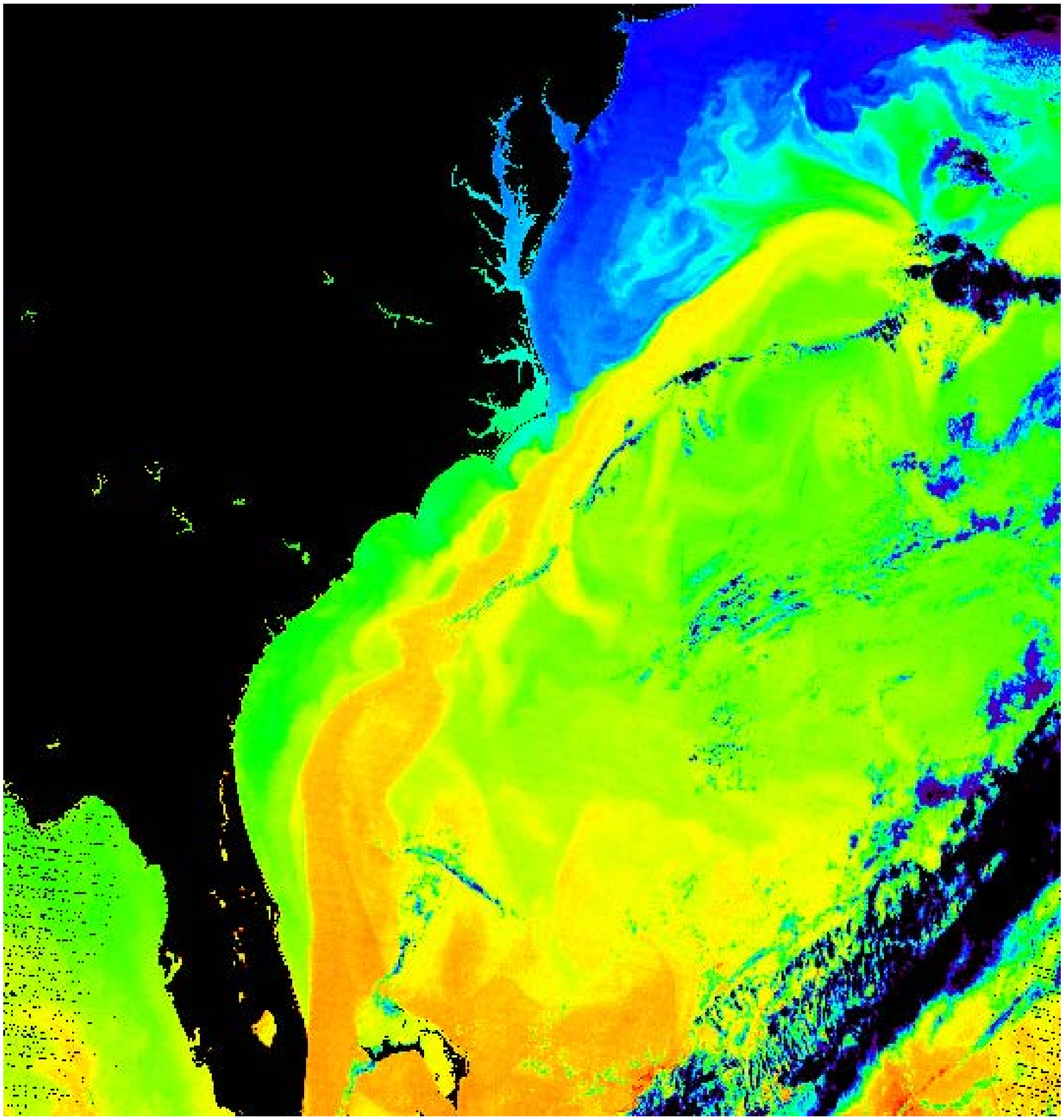
Prof. Bowles: An air mass which reaches the pole will descend there, creating a high pressure upon descent and feeding the polar equivalent of the Trade Winds, i.e., an easterly wind which is heading obliquely toward the equator. A Ferrel cell is the poleward half of the air which descends onto the twenty-to-thirty-degree zone. Repeating the analogy of dumping a bucket of water, the equatorward half becomes the Trade Winds and the poleward half becomes the westerlies. The westerlies appear to be coming from the west because they carry more eastward rotational velocity than the air at any poleward latitude that they enter. The westerlies appear to race eastward when, in reality, the polar regions are just being slow about heading eastward compared to that airmass.

Jenna: That was a long explanation for the Trade Winds, the wind that pushes water into the Gulf of Mexico to initiate the Gulf Stream. I suppose that there would be no Gulf Stream if Caribbean water could get through Central America into the Pacific instead of becoming stacked up against that narrow strip of land. The east-west elevation difference across the Atlantic amounts to a couple of meters (2 yards).

Jordan: It's no wonder the Gulf Stream is going so fast past my aunt's condo on Key Biscayne. It is being squeezed like a mustard bottle.

Prof. Bowles: We have a lot more to learn about the atmosphere, given the severe storms that mariners face. However, we will go back to marine currents for a while, now that we have an overview of the atmospheric currents that help to drive marine currents. The immediate question is, "Where is your rubber ducky now?"

Jordan: Ducky was last seen heading northeast off Cape Hatteras.

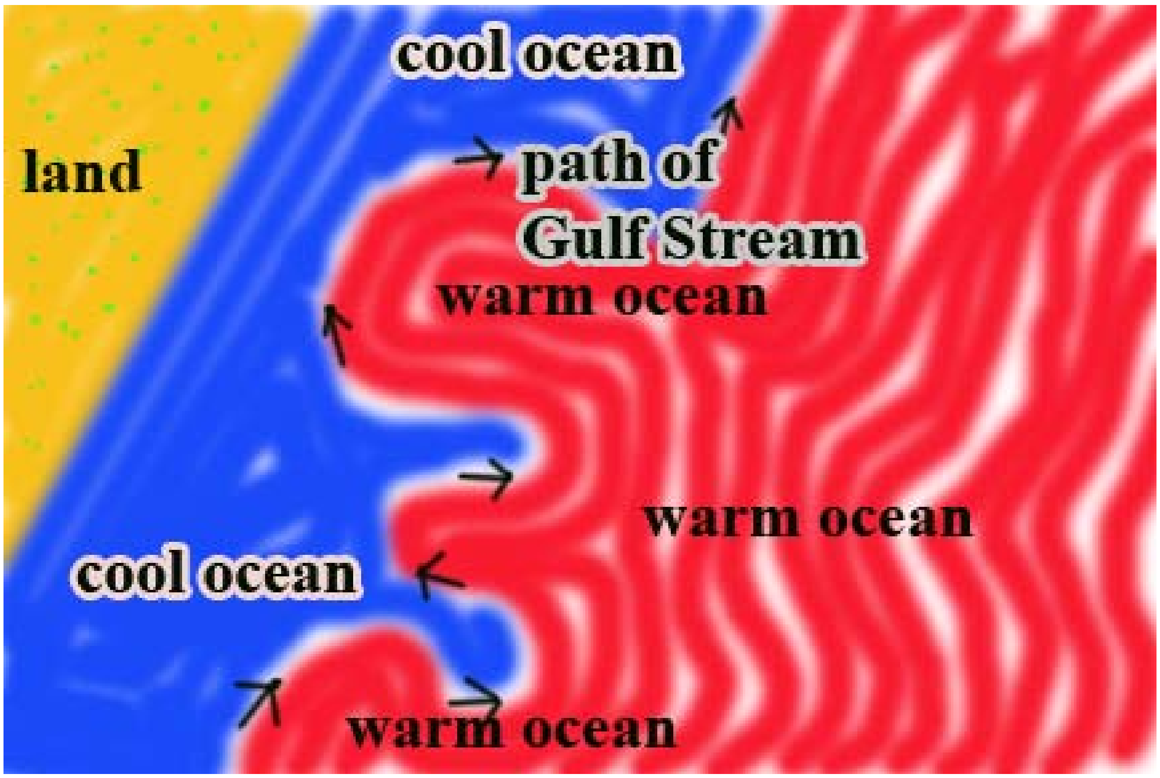


Prof. Bowles: This is an image of sea-surface temperature. It shows that the Gulf Stream is within pebble-skipping distance of Key Biscayne but diverges offshore as it heads northward to coastal Georgia. Further northward, the Gulf Stream gets a little closer to shore until it reaches Cape Hatteras where it says "Good-bye" to America and takes our warmth to the needy Europeans.

Jordan: Of course, this image is a composite of a series of satellite passes taken over a short interval. It is effectively a snapshot, and the Gulf Stream does not always look like this.

Prof. Bowles: You **are** smart, Jordan. Now I can see how your father got to be so rich with computers. Of course, one has to be a little cold-hearted to become that rich, so let's look at cold-cored gyres associated with the Gulf Stream. In the foregoing satellite composite, you can see three examples along the landward edge of the Gulf Stream, just off the Georgia-Carolinas coast. They have not separated from the Gulf Stream but have colder centers because of their counter-clockwise rotation.

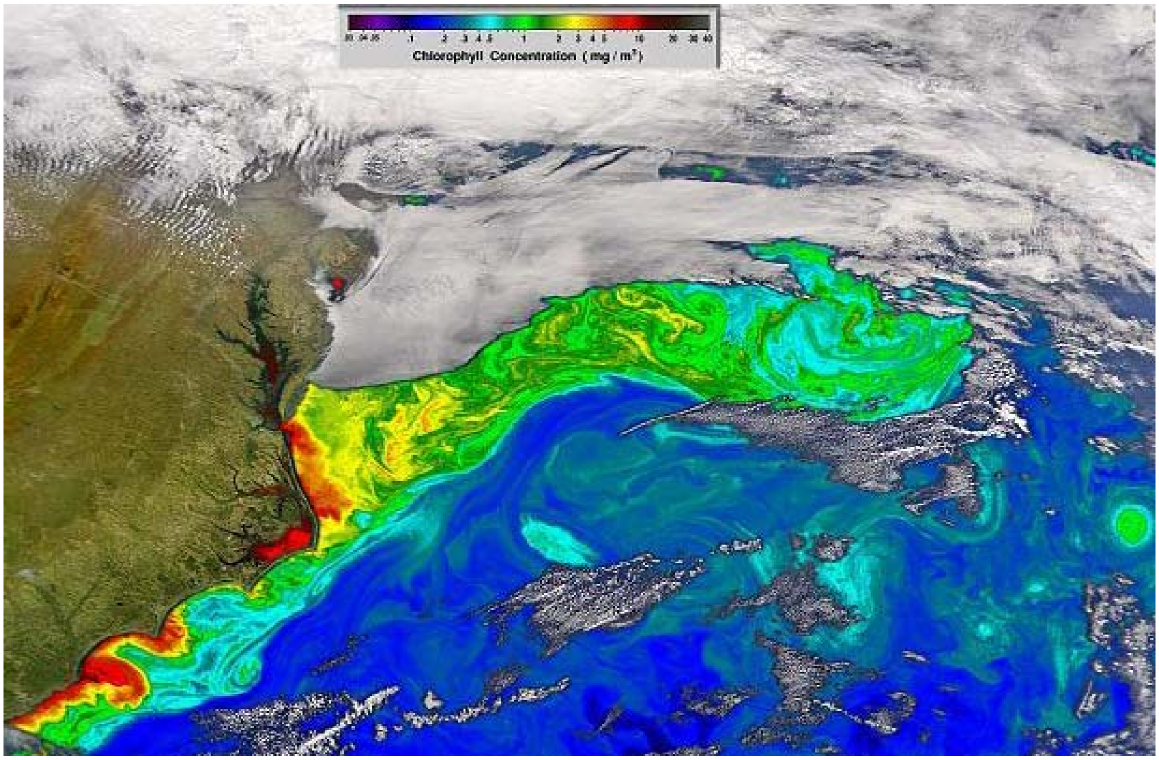
Janna: I prefer cartoon sketches to demonstrate spatial relationships. Here is a cartoon that shows a couple of cold-cored gyres within counter-clockwise loops of the Gulf Stream. They look like a couple of cold fingers pointing from the landward side into the warm ocean.



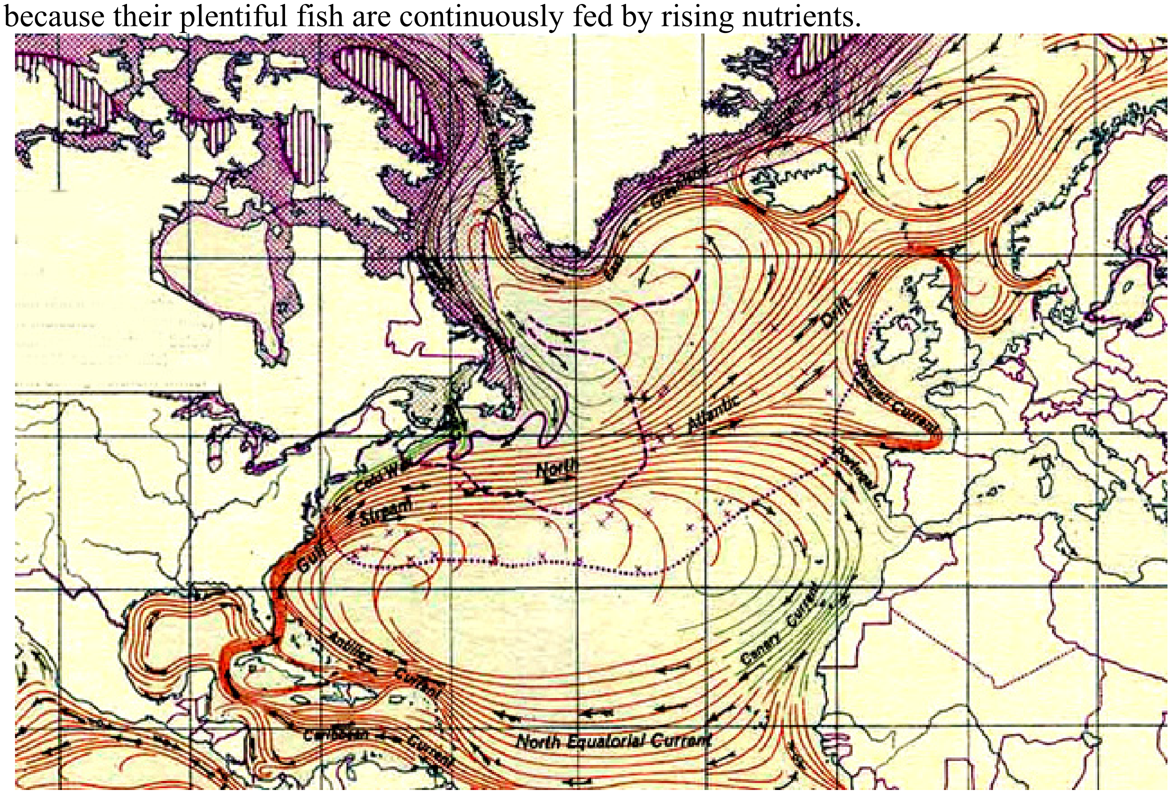
Jordan: In the northern hemisphere, everything veers to the right, just as we learned for the Trade Winds, so a counter-clockwise rotation is going to push water away from the center of the rotating gyre. That would bring up deep water to replace the surface water which is being pushed away.

Jenna: Deep water is always cold, so it is not surprising that a counter-clockwise-rotating gyre will have cold water. However, the Sun will soon warm that water, so it may be difficult to detect cold-water rings just by their surface temperature. Is there another detectable feature?

Prof. Bowles: Fortunately, the concentration of chlorophyll's green color tracks cold, nutrient-rich water. In the following satellite scan, a chlorophyll-rich gyre has migrated far to the east.



Cold-cored rings like this have diameters of about 300 kilometers (180 miles) and may extend downward about 1000 meters (yards) deep. The rings migrate at about five-to-six kilometers per day and survive for an average of a year-and-a-half. Fishermen like to find these rings because their plentiful fish are continuously fed by rising nutrients.



Warm-cored rings rotate in the opposite direction, clockwise, and therefore keep pushing the warm water toward the center of the gyre. The center thereby becomes higher than the edges of the eddy. The resulting gravitational push away from the center balances the rotational tendency that pushes toward the center. Warm-cored rings are readily distinguishable by a combination of high temperature and low chlorophyll content. They tend to spin off from the landward side of the Gulf Stream but they cannot ride up onto the adjacent continental shelf because the shelf is no more than 200 meters deep whereas the warm-cored rings tend to be 1500 meters deep. Nonetheless, tropical fish from a warm-cored ring might migrate onto the shelf and surprise some fishermen. The North Carolina Museum of Natural Sciences displays photos of fishermen with exotic tropical fish bigger than the fishermen. Let's track your rubber ducky offshore from Cape Hatteras and see where the Gulf Stream is headed.

Jordan: It seems to be headed for a split, with half the current veering north to Iceland while the other half heads south to Morocco. The northward water will become cold and sink whereas the southward water may loop back toward the Gulf of Mexico.

Prof. Bowles: The southbound lane does indeed loop back, and when it goes through the Gulf of Mexico it is even called the Loop Current.

Jenna: That's bizarre. On the one part of its journey when it's actually in the Gulf of Mexico, it's not called the Gulf Stream.

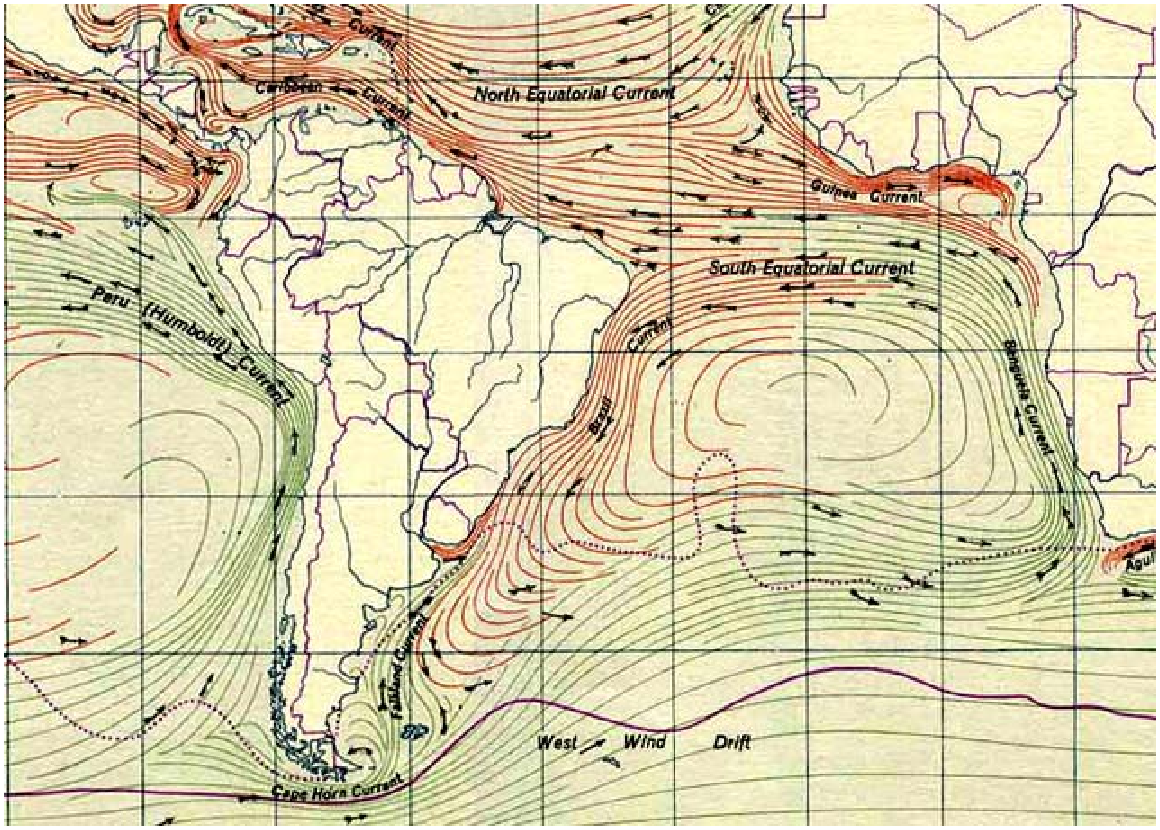
Prof. Bowles: Bizarre indeed. Westward-drifting rings in the Gulf may disrupt offshore oil-drilling operations because they have rotational velocities of up to 7 kilometers per hour. Can you imagine what the Gulf Stream does for its other extremity, Iceland?

Jordan: One of my friends spent a semester in Iceland with our Study Abroad Program. She had horrific stories about bad weather, so our Gulf Stream must not be turning that volcanic island into its geologic twin, Hawaii.

Jenna: She told me that they did not bother to measure precipitation in the wintertime because the wind was so strong that everything was moving sideways rather than downward. Her dorm was right across the street from her lecture hall but they would occasionally bar anyone from stepping foot outside the dorm. They must have had visions of Mary Poppins flying away with her umbrella.

Jordan: Despite her tall tales, the Gulf Stream still must be doing some good because she did say that Iceland's population exceeds 300,000. In contrast, a much bigger island at about the same latitude in northern Canada, Baffin Island, has fewer than 10,000 people.

Prof. Bowles: This North Atlantic stuff reminds me of ditties about the North Atlantic Squadron, but you definitely do not want to hear those ribald songs, so let's move south. Here we see that almost all the currents around the equator head westward, both the North Equatorial and South Equatorial Currents.



Jordan: Of course, that is partly an illusion because the Earth is actually spinning toward the east and the ocean is not perfectly bolted to the solid Earth.

Prof. Bowles: Yes, but much of life is just an illusion, so we will go with the flow and follow this water as it splits when it hits Brazil. The northern branch eventually joins the Gulf Stream and the southern branch, the weaker Brazil Current, heads for Antarctica.

Jenna: My Brazilian friends tell me that they are heading for Antarctica whenever they open the refrigerator because Antarctica has been Brazil's favorite brand of beer for 120 years.

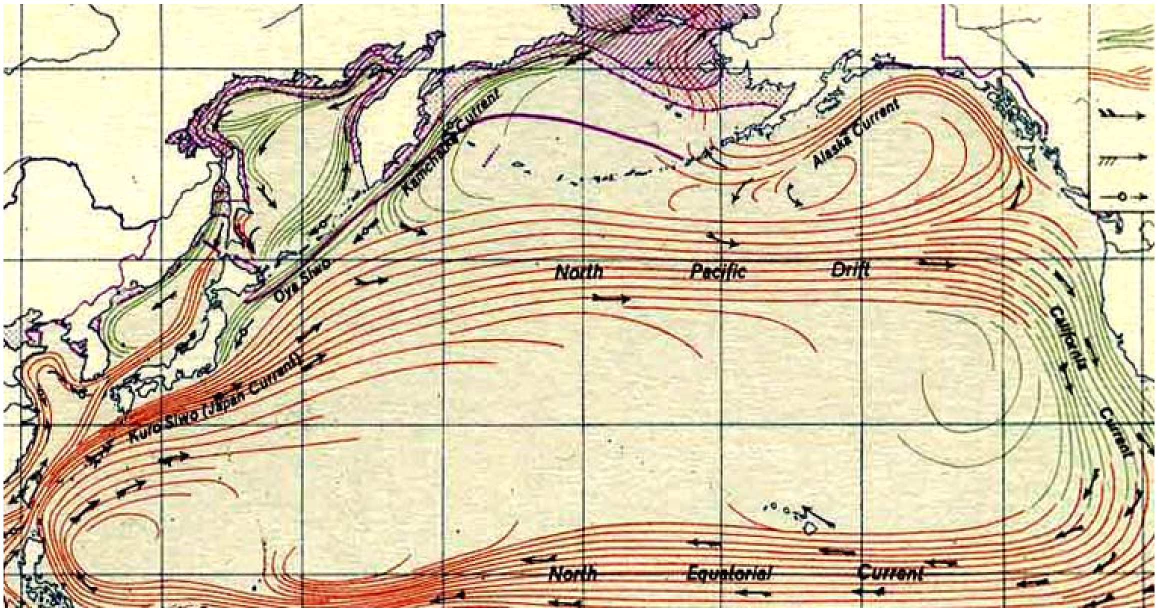
Jordan: What is this fixation with cool beer names? The most popular beer in Venezuela is called Polar. Taverns there display polar bears whereas Brazilian taverns display penguins.

Jenna: Yes, but in frigid Scotland, a hot toddy is a favorite alcoholic beverage.

Prof. Bowles: The south-bound Brazil Current does not make it to Antarctica because it encounters the West Wind Drift, a current that is propelled by a persistent west wind. This is the only current that is able to circumnavigate the world without interruption. Its power becomes augmented until the waves are huge. The west-wind direction comes from the global atmospheric cells that we previously illustrated. Air that drops from the upper atmosphere to the land surface around 30 degrees of latitude will come from the west as it heads poleward, due to the Earth's rotation. Both the wind and ocean currents continuously circumnavigate Antarctica, so the West Wind Drift is also called the Antarctic Circumpolar Current.

Jordan: In the previous diagram, I saw a northward current along the western coast of South America, called the Peru-Humboldt Current. Do we have a comparable southward cold current along the California coast?

Prof. Bowles: Indeed we do. Both the California Current and the Peru-Humboldt Current are comparable to the cold current that we previously described from coastal Morocco, the Canary Current. Just as the warm Gulf Stream generates the cold Canary Current, the warm Kuroshio of Japan generates the cold California Current, as seen here. Kuroshio means "black tide" in Japanese because the warm core of the current contains little life, just as the warm core of the Gulf Stream contains little life.



Jordan: My dad had to learn Japanese for his computer business and loved their picture words, called kanji. His most memorable word was "black" because that kanji is a picture of a village on fire, reducing it to black charcoal. Here I will fade to black … 黒.

Prof. Bowles: That kanji also looks like a pot of missionaries being blackened. Although the kanji tell interesting stories and can be beautiful, few kanji have come across to America with the North Pacific Drift. Meanwhile, the North Equatorial Current has carried lots of English to both the Philippines and Japan. American English has metamorphosed along the way, even where you know that the local author has been well-educated in American English. A Japanese train is officially listed as going "for" someplace rather than "to" someplace. Multimillion-dollar apartments bear translated names that are different from anything seen in America. The differences are so systematic and annoying that somebody must want Americans to feel a little uncomfortable whenever they read anything in these countries.

Jenna: Talking about feeling uncomfortable, the California Current certainly accomplishes that for Californian swimmers. According to the Guinness World Book of Records, the most-watched TV show of all time has been Baywatch, with its scantily-clad beauties sunbathing on a California beach. Having tried to swim in California myself, I know why they were sunbathing instead of swimming. The California Current makes the water too cold to swim for very long. I doubt if the bobbing heads of swimmers would have attracted over a billion viewers worldwide, no matter how much cosmetic surgery they had endured.

Prof. Bowles: Bobbing what? It seems strange that a hot show came from a cold current. Let's review the cold currents of the Southern Hemisphere. We have already mentioned the Peru-Humboldt Current of western South America. The foregoing maps also show the

Benguela Current of southwestern Africa and the West Australian Current. All of these cold currents create arid conditions on the adjacent land because they fail to provide much water vapor through evaporation.

Jordan: Cold currents are not all bad. They help California, Portugal, Southern Africa, and Chile grow excellent wine-making grapes.

Prof. Bowles: I do indeed enjoy those products of cold currents. The Pacific constitutes 46% of the Earth's water cover. That is 32% of the planetary surface. These high percentages are not immediately apparent on most maps, however, because most maps are drawn with the Mercator projection, a distortion that under-represents equatorial areas. Given the great extent of the Pacific, it exhibits significant east-west variation. The Earth spins quickly eastward in equatorial regions and this makes it appear that both the water and the air are traveling westward.

After traveling such a great distance close to the equator, both the water and air become warmer. The moisture content of the air increases correspondingly. Consequently, the mountains of Indonesia, along the western edge of the Pacific, get drenched in rainfall when they force the incoming air masses to rise and cool. After rising to the upper troposphere, the air returns eastward to the eastern rim of the Pacific. There it descends, warms, and evaporates moisture, forming a cool, dry, high-pressure region. This east-west circulation has long been known as Walker Circulation and more recently has become called La Niña. If this Walker Circulation breaks down, global weather patterns become disrupted. The period of disruption is called El Niño, the Spanish name for the Christ Child.

Jordan: I hear that El Niño got its name because disruption of the Walker Circulation in coastal Peru usually occurs around Christmas.

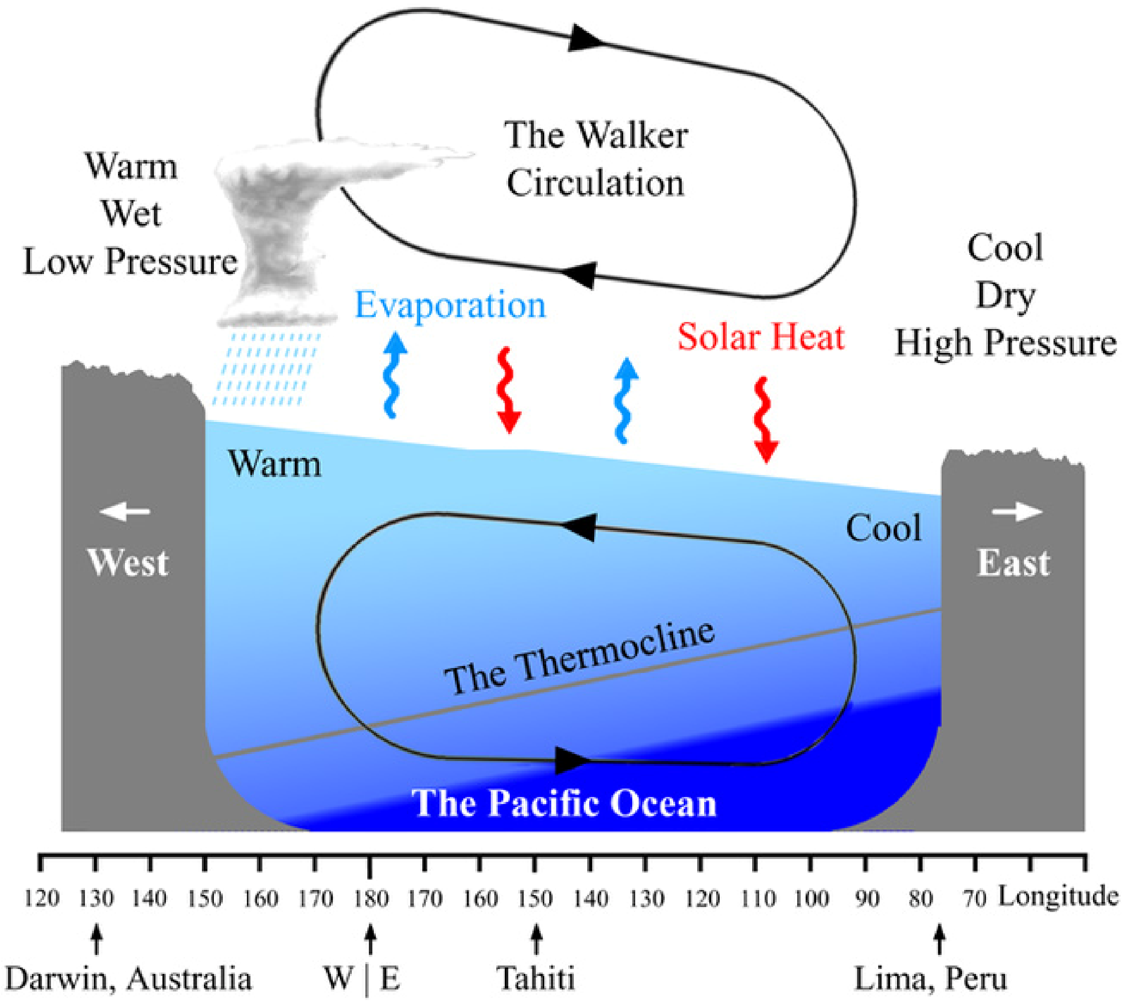
Prof. Bowles: Here we see a sketch of La Niña, the normal air-sea coupling for the Pacific. However, this sketch is exaggerated. Look at the westward dip on La Niña's thermocline. That would be a difference of a couple of kilometers from east-to-west if it were drawn to scale. However, you would not detect much of an inclination if it were drawn accurately, so you have to expect some exaggeration within any textbook.

Jordan: El Niño has become such a popular story, all over the world, that one should expect some embellishment, just as the morality tales of the Middle Ages embellished actual events. It is very convenient to have a bogeyman who can be blamed for anything about the weather that you dislike. It does seem ironic, however, that the Christ Child has become a bogeyman. I have heard some radio evangelists claim that this is just another subtle plot by agnostic scientists.

Prof. Bowles: It is indeed strange that the long-standing term of Walker Circulation is all but ignored and that El Niño has descended upon us.

Jenna: I hear that Sir Walker was an impressive dude in his day. In 1889, he was named Senior Wrangler at the University of Cambridge.

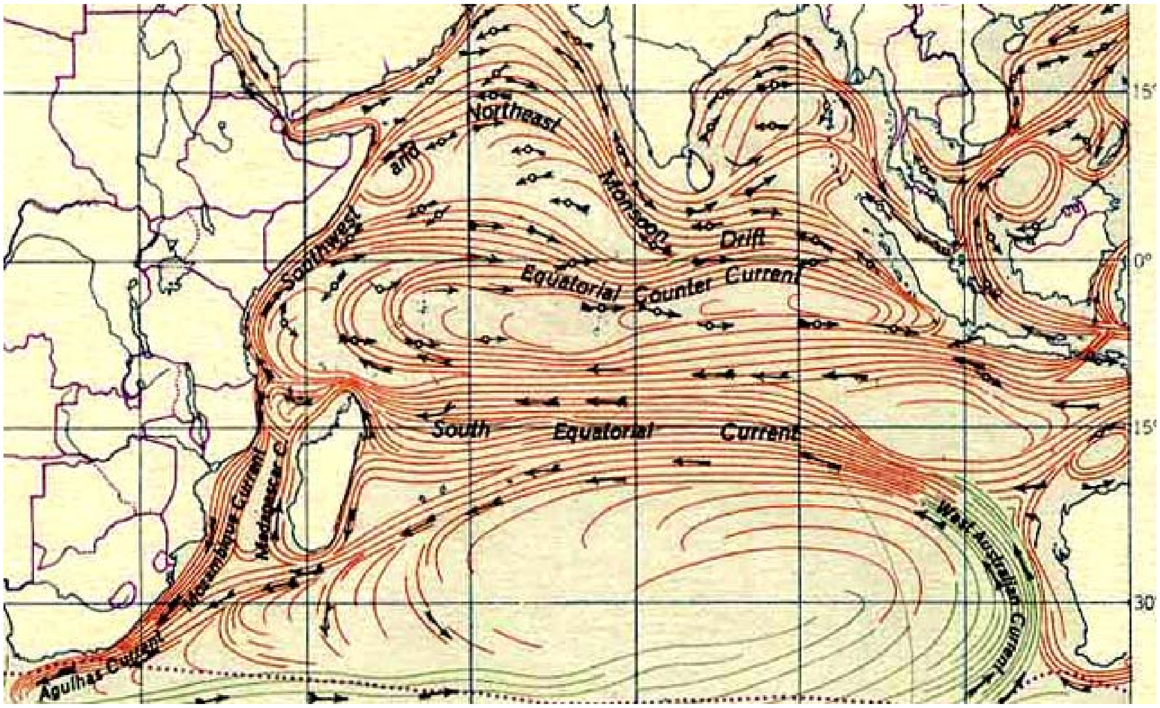
Prof. Bowles: Despite the title, Walker was not an early version of the Marlboro Man. The Senior Wrangler was the top mathematics student at Cambridge, typically anything but a dude. Walker spent most of his career as director-general of the meteorological observatories in India. He assumed that post a few years after a lack of monsoon rain had caused widespread famine across India, killing at least three million people.



Given that so many lives depend upon monsoon rains, let's see why the monsoons are attributed to the Indian Ocean whereas we do not hear about monsoons around the bigger Pacific and Atlantic Oceans. Everyone knows that the monsoon is distinctly seasonal, with onshore summer wind bringing rain and offshore winter wind causing drought, so we expect the marine currents in the Indian Ocean to change seasonally as well. The arrows with circles on them in the underlying map are currents that only flow in the monsoon winter.

Jordan: I see that between Mozambique and the island of Madagascar, there is a counterclockwise current that is reminiscent of the counterclockwise current between South America and Africa. Both counterclockwise currents must be driven by Earth's rotation, but obviously operate at different scales. How far down can you scale this Coriolis effect?

Prof. Bowles: Certainly not to the scale of a toilet bowl, as some claim. In the underlying map, you may notice the Agulhas Current that warms Durban, the second-largest city in the Republic of South Africa. Durban is the busiest port city in all of Africa and is famous for its subtropical beaches. It would be worth a visit. The Portuguese counterpart of Columbus, Vasco da Gama, headed east instead of west and landed here in Christmas of 1497. He gave the province its current name of Natal, Portuguese for Christmas.



Jordan: Along most of the coast of India, the wind-driven current seems to go in opposite directions seasonally, heading westward in the dry wintertime and eastward in the damp summertime. Why does India have this seasonal (monsoonal) difference?

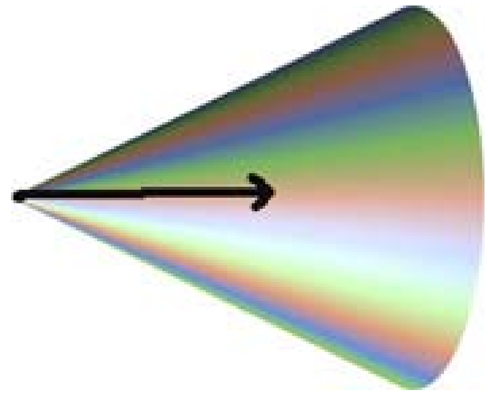
Prof. Bowles: A Canadian Prime Minister once pointed out that his sparsely-populated country sleeps beside an elephant, the United States. One has to be ever watchful in case the elephant rolls over in his sleep. Among continents, Eurasia is the Earth's elephant. This elephant rolls over twice a year, rather quickly, during the few days that could be called Spring or Fall. During the long and hot summer, air is pulled in from the Indian Ocean and elsewhere to replace the rising hot air. During the long and cold winter, air descends onto the land and pushes outward toward the oceans, barring the entry of moist air.

Jenna: I see that northeastern Africa also has seasonally-opposite coastal currents due to the monsoon effect. I suppose that we hear more about India because of its higher population. Off of equatorial Africa, I see the Equatorial Counter Current. I saw the same label in the Pacific. This sounds like a good name for a counter-culture rock band.

Prof. Bowles: I thought of that too when I was your age. The Equatorial Counter Current is a great name for a rock group, but your sponsor, Bill Bates, is far ahead of us and has already copyrighted it.

Jordan: If Earth's rotational velocity is greatest at the equator, how could there be an equatorial current which is heading the wrong way, eastward?

Prof. Bowles: In all three major oceans, the Pacific, Atlantic, and Indian, you can see that the Trade Winds and corresponding ocean currents converge like a cone on the western edge of the respective ocean basin. From there, the water mostly squirts north and south, but some of it is trapped at the tip of the cone and shoots straight back.



Jenna: Rubber ducky could go for quite a ride if he got to the equatorward edge of the Trade Wind belt and then migrated back-and-forth between the Trade-Wind-driven westward current and the eastward Equatorial Counter Current.

Prof. Bowles: Some early sailing ships were caught like that. Ducky similarly could get lost if he reached the poleward edge of the Trade Wind belt because there he would encounter descending air between the Hadley and Ferrel cells. The descending air bounces off the sea, making it choppy, but fails to provide propulsion in any consistent direction. Early Atlantic adventurers who mistakenly sailed into this region had to ditch their horses to lighten their load. The sight of bobbing horses gave rise to the name, Horse Latitudes, for this high-pressure region that lacks consistent currents.

Jordan: Does the Atlantic experience anything like the Niño-Niña oscillation of the Pacific?

Prof. Bowles: Yes. In fact, it was deduced by the same senior wrangler, Walker. He noted that Iceland always has low pressure while the Azores islands always have high pressure.

Jenna: If Walker deduced oscillations in the Indian, Pacific, and Atlantic oceans, then he definitely was a man in circulation. If Iceland and the Azores always have opposing atmospheric pressures that steer Atlantic circulation, why does the Atlantic oscillate?

Prof. Bowles: The difference between these two pressure extremes oscillates in magnitude and the resulting winds correspondingly vary in strength. At maximum contrast, strong west winds bring rainfall that warms northern European winters and cools their summers. At minimum pressure contrast, northern Europeans suffer cold winters, summer heat waves, and drought. When the northern Europeans experience drought, the southern Europeans and north Africans get the moisture that normally falls in northern Europe.

Jenna: I suppose that the higher pressure of the Azores is related to its latitude, about 38 degrees north, near the boundary between the Hadley and Ferrel cells. Iceland is warmed by the Gulf Stream, which must resemble the propane torch that is used to lift hot-air balloons.

Jordan: Air masses and surface currents are all that sailors need to know, but submariners surely must think more deeply. What about deep-sea currents?

Prof. Bowles: The deep ocean has water masses just as the atmosphere has air masses. However, the oceanic masses tend to be isopycnal. That is a fancy way of saying that the density tends to be uniform. If the density were not uniform, the oddball water would rise or sink out of the laterally-moving mass. Water masses mostly move laterally despite our common reference to sinking and upwelling. If one thinks about oceanic dimensions, upwelling from a maximum of 5 kilometers of water depth is trivial compared to potential lateral migration of 20,000 kilometers across the Pacific.

We have talked about some Gulf Stream water sinking in the North Atlantic after it migrated past Iceland toward Scotland. The crystallization of ice from this Gulf Stream water excludes solutes, making the remaining water denser because of its higher salinity. Simple cooling of other seawater north of Scotland increases its density without increasing salinity. These two types of descending waters eventually mix, but they remain distinguishable from adjacent water masses because of their elevated salinity.

Jenna: Where does that descending water go?

Prof. Bowles: Descending water from all the high-latitude regions becomes the North Atlantic Deep Water. Besides high-salinity water from the northeastern Atlantic, the North Atlantic Deep water mass also is fed by lower-salinity water that comes from the west, from north of Iceland. Like the Scotland water, this water has become dense due to simple cooling. This cold deep water breaks into the North Atlantic by passing through the straits between Iceland and Greenland, as seen on the overlying map.

Dr. Bubah reminds me that this southward path between Iceland and Greenland was made famous by the most fabled battleship of the Second World War, the Bismarck of Germany. It too was trying to break into the North Atlantic, but with the purpose of sinking cargo ships. In the straits between Iceland and Greenland, the Bismarck immediately sank a comparably large British battleship. However, its subsequent southward journey lasted just three more days. The British peppered it with every peashooter in their arsenal. The least likely British weapon proved to be decisive, a torpedo into the Bismarck's rudder from an obsolete biplane with a top speed of your family car. Unable to steer or go very fast, the Bismarck became a sitting duck. Fearful that it would be boarded as in the days of pirates, the Germans scuttled the pride of their navy. The Woods Hole Oceanographic Institute has found Bismarck intact on the seafloor. None of the British shells had penetrated its foot-thick (30-cm-thick) hull, but they did make a mess of the upper decks.

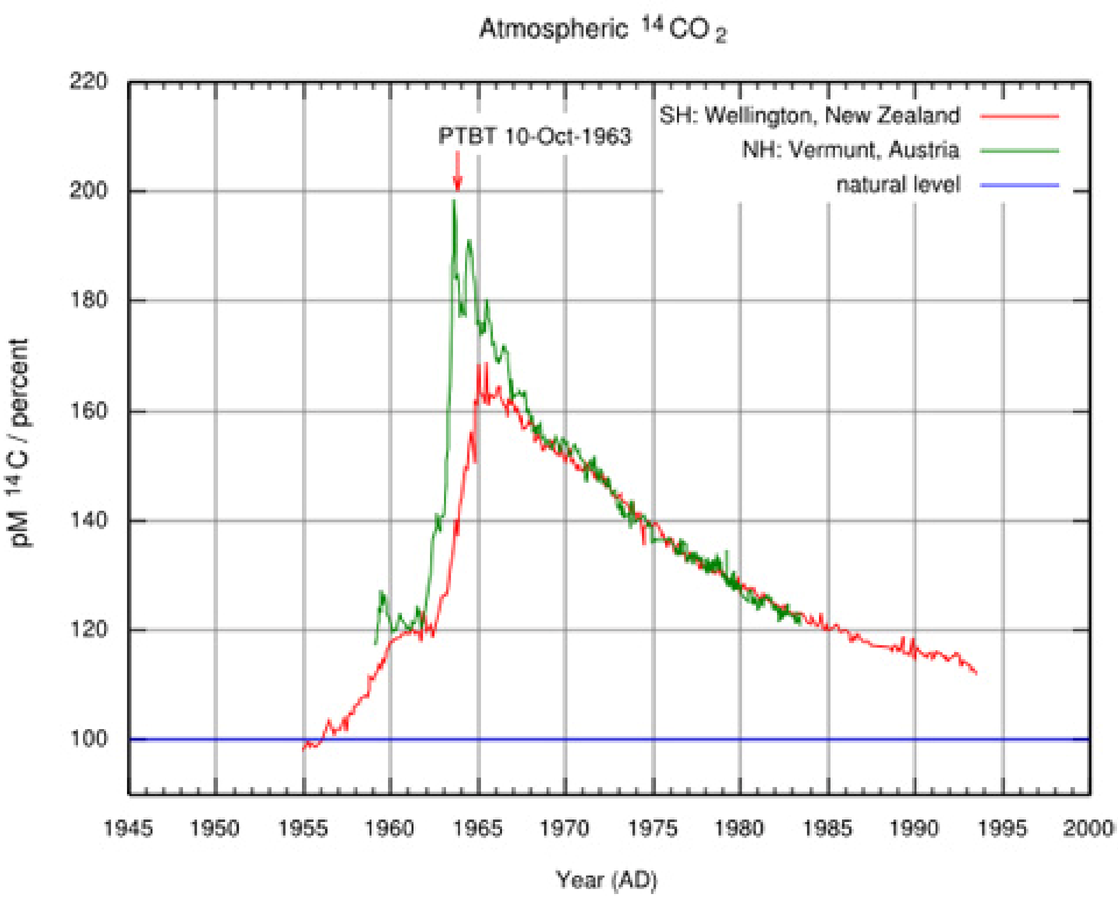
Jordan: That reminds me. Where's my own flagship, rubber ducky, these days?

Jenna: I bet that he stuffed himself full of plankton and sank in the North Atlantic.

Prof. Bowles: Perhaps. The North Atlantic Deep Water heads southward from Greenland and reaches a flow rate of 10 sverdrups, ten million cubic meters per second.

Jordan: That's not bad. That's a third of the Gulf Stream's flow in the opposite direction past Key Biscayne, where I first launched rubber ducky.

Prof. Bowles: The measurement of flow rates in deep water is more difficult than clocking a rubber ducky on the surface. One technique involves the decay of tritium, a radioactive isotope of hydrogen that has a half-life of a little more than a dozen years. Tritium has two neutrons whereas normal hydrogen has none. Given the mass of hydrogen's sole proton, a tritium atom weighs about three times that of a regular hydrogen atom, hence its name. Tritium is continuously produced by cosmic-ray bombardment of nitrogen in the upper atmosphere and was a product of atmospheric nuclear testing in the 1950's and early 1960's. The bomb-derived tritium spike is now largely decayed away. After five half-lives, only about 3% would remain.



However, the atmospheric bombs also produced a spike in carbon-fourteen and this has a half-life that is nearly five hundred times longer, so there has not been much decay since bomb production. Sinking seawater that incorporated this carbon would be identifiable forever if carbon were a conservative component of seawater like calcium. However, carbon becomes transformed among solute phases, a dissolved gas phase, organic matter, and animal shells that settle to the seafloor. Consequently, tritium has proved to be more reliable for tracing water masses. Nonetheless, the overlying graph of the carbon-fourteen spike shows when all the bomb-produced radioactive isotopes peaked in the environment, all over the world.

Jenna: I presume that the decay of tritium could help one estimate the velocity of deep-sea flow. How fast is it?

Prof. Bowles: The velocity varies a lot but a typical velocity would be on the order of a centimeter per second. Let's convert that to something more familiar, kilometers per hour or miles per hour. An hour has sixty times sixty seconds. That's 3600 seconds, so a centimeter per second would be 3600 centimeters, 36 meters, per hour. At that rate, it would take the entire duration of a football game for a slow-moving punt returner to score on the first kick-off. A meter has a hundred centimeters and a kilometer has a thousand meters, so a kilometer has a hundred times a thousand centimeters, 100,000 centimeters. Consequently, a flow rate of one centimeter per second is about one-thirtieth of a kilometer per hour or one-fortififth of a mile per hour.

Jenna: That does not sound very fast, but if one considers the huge volume of moving water, this type of system must have enormous momentum, mass times velocity.

Jordan: We have the North Atlantic Deep Water heading south toward Antarctica. Is there any lateral inflow? Does it pick up any hitchhikers along the way?

Prof. Bowles: After hearing about all these frigid inputs of deep water from the north, you may be relieved to learn that the Mediterranean offers a warm contribution, through its tiny nozzle at Gibraltar. The Mediterranean is a net evaporative basin and has evaporated completely in the past, whenever the tiny Gibraltar nozzle has been closed by mountain-building. Every day, the Mediterranean receives Atlantic seawater to compensate for evaporation of its own water. Whenever Gibraltar has been closed in the distant past, rivers like the Nile have become smaller and smaller as they entered the basin, due to evaporation. Even today, evaporation in the eastern Mediterranean makes the water dense enough to sink and become a warm plume that heads back toward Gibraltar, finally squirting out into the middle of the Atlantic's vertical profile. The Mediterranean plume may be traced across most the Atlantic, riding between colder layers of greater and lesser density.

Jordan: I suppose that the Mediterranean water mass is more of a novelty than a major contributor to Atlantic dynamics. What happens when the North Atlantic Deep Water approaches Antarctica?

Prof. Bowles: Given the configuration of land, major surface currents can get closer to the South Pole than they can to the North Pole, so the seasonal formation of ice is more voluminous in the southern hemisphere than in the northern hemisphere. The ice tends to expel seawater solutes as it forms, annually making a larger volume of dense brine in the southern hemisphere than in the northern hemisphere. Some of this cold salty water becomes Antarctic Bottom Water which heads northward beyond the equator in both the Atlantic and the Pacific basins. The North Atlantic Deep Water rides over it as it heads southward. When North Atlantic Deep Water travels south of South America, it runs into the Antarctic Circumpolar Water and gets carried south of Africa into the Pacific. Summertime melting of Antarctic ice creates low-density water that mixes with some of the North Atlantic Deep Water and creates Antarctic Intermediate Water that sinks and flows away from Antarctica.

Jenna: If Antarctic Bottom Water is the densest large water mass, just how dense is it?

Prof. Bowles: The density is usually listed as 27.88 but that is an abbreviation from 1.02788, the number of grams per cubic centimeter. This density is not much greater than the density of typical surface water, so we see that just tiny differences in density may control the location of water masses within the profile of an ocean.

Jordan: This water must be very cold if it comes from the edge of Antarctica.

Prof. Bowles: Yes. Antarctic Bottom Water is all at or below the freezing point of fresh water. Given that seawater freezes at minus 1.8 degrees Celsius, the temperature of this frigid water lies between zero and minus 1.8 degrees, typically a shade warmer than minus 0.8 degrees.

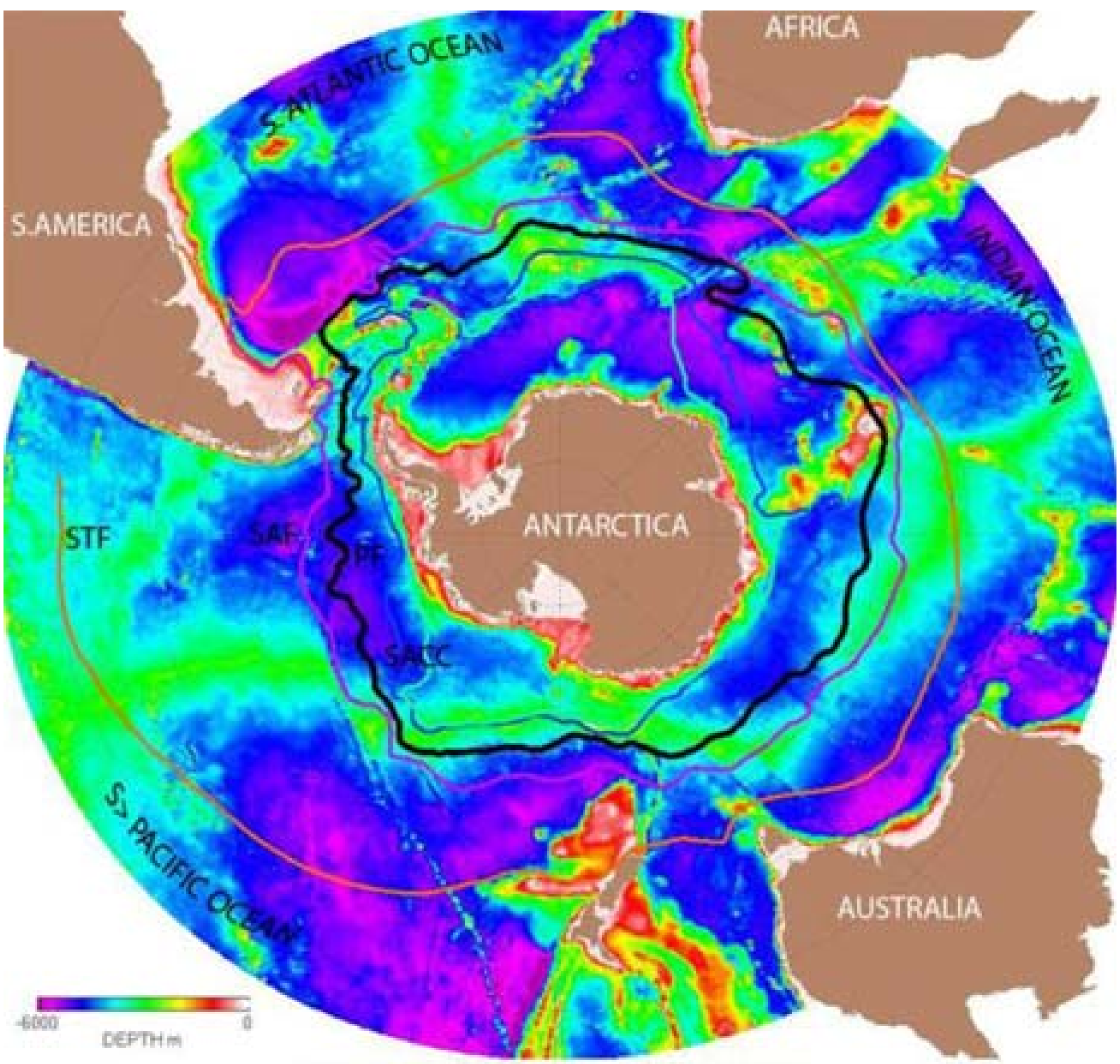
Jenna: When I convert my own body temperature of 98.6 degrees Fahrenheit to Celsius, I get 37 degrees, so these cold temperatures of high-latitude regions must be hard on local sailors.

Prof. Bowles: Sailors do not survive long if dumped into cold water. All Titanic passengers were issued life-jackets, but only those in life-rafts survived. Fortunately, they only had to wait a couple of hours for their rescue or they too would have succumbed to the cold. The 1500 with just life-jackets lost consciousness within a couple of minutes in the water and died. The Bismarck was a bigger ship than the Titanic and it lost more people, a total of 2100. When the Bismarck scuttled itself, its upper-deck crew jumped into life-rafts, but only five of those sailors survived the full day on the North Atlantic before German rescue arrived. A German submarine came because it heard the characteristic sound of a distant sinking ship.

Jordan: Naval bombardments and torpedoes have sent so many sailors into frigid water that it makes me shiver. The ship which saved 700 Titanic passengers was torpedoed and sunk by the Germans six years later.

Prof. Bowles: Let's follow the Antarctic Circumpolar Water that is traversing the South Atlantic from west to east. Like the Gulf Stream off the southeastern USA, this water mass occupies essentially the entire water column in places, so it is equivalent to the surface current that is similarly called the Antarctic Circumpolar Current, or the West Wind Drift. Acronyms abound in the study of water masses but we have resisted acronyms up to this point because somebody might conclude that we work for the world's greatest source of acronyms, the federal government. Nonetheless, it is hard for anyone teaching in North Carolina to resist the acronym for the Antarctic Circumpolar Current, the ACC.

The ACC squeezes itself through the passage between South America and Antarctica, through the so-called Drake Passage. The famous Elizabethan pirate, Francis Drake, was not tough enough to play in the ACC. He avoided the rough seas of the Drake Passage and settled for the calmer waters of the Straits of Magellan, between the island of Tierra del Fuego and mainland South America. The flow in the ACC is 135 sverdrups, higher than anywhere else in the Atlantic. The highest flow of any oceanic current is on the opposite side of the world, where the ACC passes south of Tasmania, the island that is shown here to lie south of southeastern Australia.



The highly irregular path of the ACC all around Antarctica is controlled by local topography. For example, a thick volcanic pile that resembles Iceland blocks the ACC's path in the southern Indian Ocean and forces it to split around it. However, we only show the dominant path here. This volcanic pile is called the Kerguelen Islands after their French discoverer. He was a contemporary of the more famous British explorer, James Cook, who discovered several other islands in the Southern Ocean in the 1770's.

Jordan: Eventually, Cook took a break from exploring frigid islands and sailed north to discover Hawaii. He was not accustomed to lush, populated islands and got himself killed when he reacted too strongly to somebody stealing a rowboat. Many tourists have subsequently made the same type of fatal mistake in third-world countries. Missionaries eventually followed Cook all across the Pacific and some of those missionaries shared Cook's fate of being killed by the indigenous people. Like Cook himself, a few of those were then ritually cooked by cannibals.

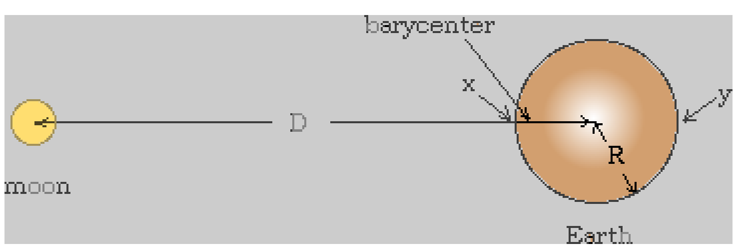
Prof. Bowles: Before becoming a Southern Ocean scientist, Cook helped the English capture Canada in 1759 by surveying the narrow channel around Quebec City. That allowed the English to sneak behind the entrenched French forces and surprise them from the rear. Of course, the English did not always win at oceanography. The movie, Das Boot, tells how a German submarine got into the Mediterranean despite the English defenses at Gibraltar during World War II. The English assumed that the dense bottom current from the Mediterranean continuously flowed outward into the Atlantic, so they only guarded the upper half of the water column. They knew that no submarine could power its way against the outflowing current without them hearing it. In contrast, the Germans correctly assumed that Mother Nature is a little fickle and occasionally sends the bottom current in the opposite direction, into the Mediterranean. They waited outside Gibraltar until there was a break in the outflow and they let the submarine be carried noiselessly past the unsuspecting English.

Jordan: Das Boot is one of the few major movies set inside a submarine, and also one of the few which was filmed in the projected sequence. I gather that Bill Bates is hoping to repeat that commercial success with another submarine venture filmed in sequence.

Prof. Bowles: Perhaps we can move on to a couple of other topics in physical oceanography, upwelling and tides. You may not like my tidal story because it is probably not like the one you learned in high school.

Jenna: What else is new? Are you going to tell us that the Moon does not have much pull any more?

Prof. Bowles: We are 81 times more massive than the Moon, so the Moon never has had much pull, compared to the Earth's gravitational pull. Here we see a typical Earth-Moon sketch, designed to illustrate tides. As usual, the Moon is drawn far too close to the Earth, or else you could not see them both at once.



The usual tidal story is that we experience tides at point **x** because of the Moon's pull on the water. However, the Earth's pull at point **x** in the opposite direction is about ten million times greater than that of the dinky distant Moon. If the usual high-school story were the whole story, we would not notice any tides. However, we would notice something more sinister. The Moon would keep getting closer until it collided with the Earth.

Perhaps you recall the asteroid-collision explanation for dinosaur extinction. The asteroid in that story was just 10 kilometers (6 miles) in diameter and it killed 45% of all species on Earth. The Moon is three hundred and fifty times greater in diameter than that. Its collision would vaporize every creature instantly. Fortunately, the Moon is actually moving slightly away from the Earth, so there must be something that counteracts gravity.

Jordan: I see a label that locates a barycenter, a center of mass. I know that the Swiss engineers wanted me to label the barycenter on the plans for my submarine. I suppose that they would then know how to lift it onto a flatbed railcar once it is finished.

Prof. Bowles: The illustrated location of the barycenter is just below the Earth's surface, so this must be the center of mass for the Earth-Moon system. The system rotates slowly around that barycenter, once in about 28 days.

Jenna: I presume that that is the origin of months, given that the Moon is going to wax and wane through that cycle. However, most months are assigned more than 28 days so that we can have twelve months in the year, given that 12 times 28 equals only 336 days.

Prof. Bowles: Another complication is that the lunar cycle itself varies up and down from 28 days because the Moon's orbit is elliptical and is subject to several perturbations. Moreover, the Earth-Moon system is orbiting the Sun, so our time reference of days is variable. Fortunately, for the purpose of understanding tides, we can ignore all this and pretend that the Earth-Moon rotation is a simple 28-day cycle.

Jordan: If the Moon keeps a constant distance from the Earth, what difference does it make if the Earth-Moon system is rotating? Gravitational attraction will remain the same.

Prof. Bowles: Gravitational attraction will indeed remain the same at the same distance, but something else will come into play due to rotation. This involves inertia, the tendency to keep doing whatever you are doing. Think of someone who is spinning while holding a ball on a string. If the string happens to break, the ball will fly away along a path that is tangential to its spinning orbit. At any instant of time, the ball obviously considers itself to be traveling tangentially, and it is only the pull of the string which keeps the ball from pursuing that tangential path. In the case of Earth-Moon rotation, both the Earth and the Moon would travel away from the barycenter if they were not constantly pulled toward it by gravity. The tangential tendency is often incorrectly called centrifugal force but it is not really a type of force because there is no acceleration, so we will call it the centrifugal effect.

Jenna: If gravity is balanced by the centrifugal effect, then why do we have tides at all?

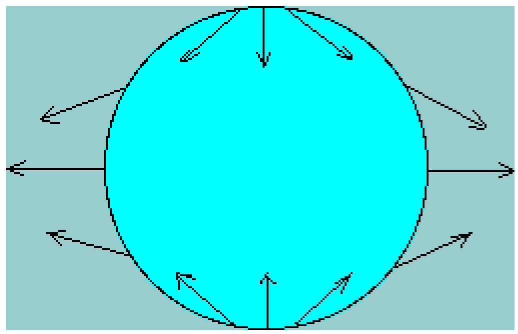
Prof. Bowles: The centrifugal effect balances gravity at the centers of both the Earth and the Moon, keeping those centers at a fixed distance apart. However, those are the only two points at which there is balance. Everywhere else, either gravity or the centrifugal effect dominates.

Jordan: If I had to guess where gravity dominates, it would be at the two points on the surfaces of the Earth and Moon which are closest to each other. The Moon's closest point to Earth must be affected by tidal forces, even though my high-school teacher ignored any effects of Earth on our Moon. After all, Earth is 81 times more massive than the Moon.

Prof. Bowles: You are right. Just because the Moon has no water, this does not mean that it lacks tidal effects. Even a waterless Earth would display tidal effects because the solid surface rises and falls daily by a few tens of centimeters, about a foot. Water deforms much more readily than does solid crust, so the tidal range at a beach is closer to a meter (a yard).

Jenna: The centrifugal effect must dominate where gravity is weakest, at the farthest extremities of the Earth-Moon system.

Prof. Bowles: Indeed, so the gravity and centrifugal vectors point away from each other on the Earth's surface, as shown here. Both sets of vectors form a focused bulge because the Moon is much smaller than the Earth.



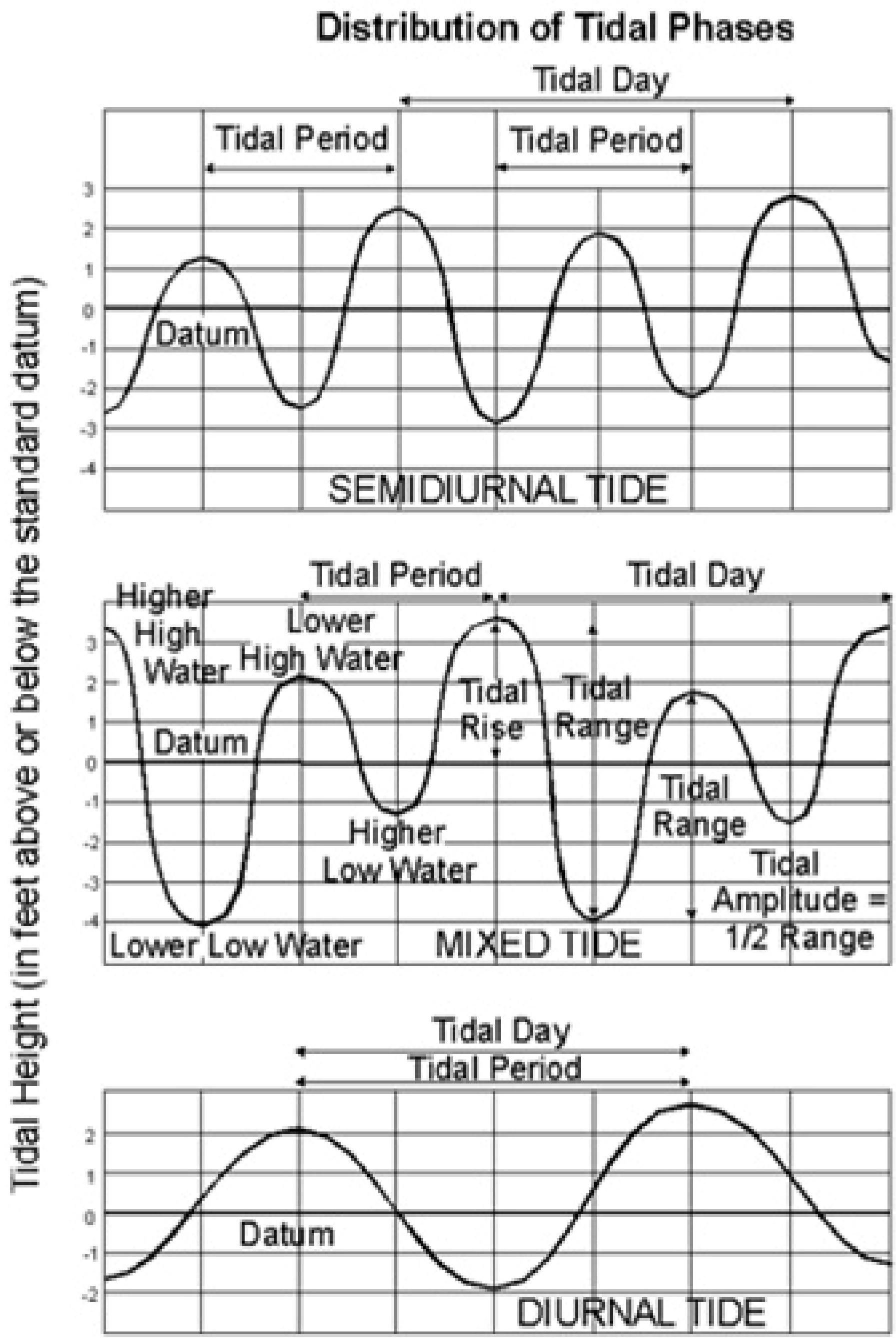
Although one could draw an infinite number of relevant vectors, most high-school teachers just draw the vector that is perpendicular to the Earth's surface. This is misleading because we have already seen that that vector is effectively eliminated by the opposing gravitational vector toward Earth's center. The other vectors are not completely eliminated by Earth's gravity. It is those vectors which constitute a tidal bulge.

Jordan: I suppose that my first hint about the inadequacy of the simplistic lunar-gravitation concept should have come from my personal observation that we experience two high tides in a full day. By itself, lunar gravity should just give us one high tide, as the Earth spins underneath the bulge of seawater held by the Moon.

Prof. Bowles: I like your image of a bulge of water with Earth spinning underneath it. The Earth rotates 28 times faster than the Earth-Moon system, so the Earth effectively spins under the bulge. The centrifugal bulge on the far side of Earth is the mirror image of the gravitational bulge toward the Moon. Within the centrifugal bulge, water is effectively being thrown skyward due to the Earth-Moon rotation. You could create a similar effect by tying together a pair of plastic containers that were half-full of water. If you spin the containers about a point at the middle of the string, the water will fly to the outside in both containers.

Jenna: You have noted that we should experience two high tides per day but I have found that the high tide keeps advancing a half-hour with each tidal cycle here in the Southeastern US.

Jordan: My jet-setting family vacations at beaches all over the world and we encounter such a variety of tidal cycles that I have googled the graph shown here for comparison.



Prof. Bowles: OK. You guys are correct. I was over-simplifying. The effect of the 28-day lunar cycle is to add 24 minutes to the 12-hour periodicity from Earth's spin on its axis. Moreover, the orbit of the Moon around the Earth oscillates between about 28^o N latitude and 28^o S latitude. When the Moon is passing over the southern hemisphere, lower tides occur in the northern hemisphere, resulting in the unequal tides shown here.

Jordan: As the Earth spins, the tidal bulge must keep running into land or topographic features on the seafloor, making the tidal cycles rather complicated.

Prof. Bowles: Indeed. When Isaac Newton tried to demonstrate his new formula for calculating gravity, back in 1687, he estimated the height of tides. To do that, he had to assume that the Earth had no topography or else the calculation became too difficult. Even with modern supercomputers, we find it difficult to calculate tides on a topographically complex planet. By the way, Newton calculated that the tidal range should be 55 cm (2 feet) at the equator. In fact, this is what we actually observe in the rising and falling of the solid Earth there. Is this half-meter range what you usually see at the beach?

Jenna: I would say that the range is closer to a full meter (yard).

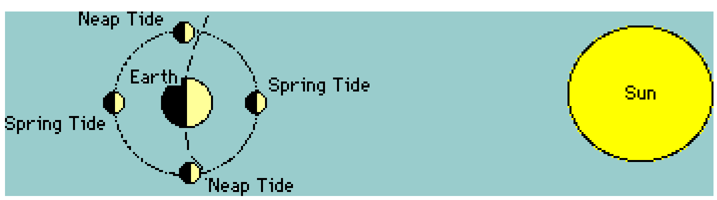
Prof. Bowles: The range varies seasonally but I would agree that it is usually closer to a meter.

Jordan: Why does the tidal range vary seasonally? I do not see any seasonal component in your gravitational-centrifugal imbalance explanation.

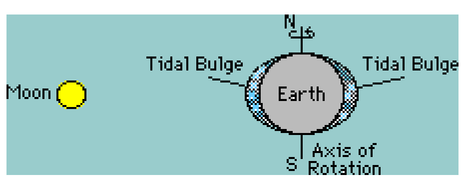
Prof. Bowles: You are right. There is none. However, there is yet another aspect to the tidal story that you may have missed in high school. Do you remember the sleeping elephant metaphor? In this case, the sleeping elephant is the Sun. The Earth has virtually the same tidal relationship with the Sun that it has with the Moon. Our distance from the Sun remains virtually constant for the same reason that the Earth-Moon distance remains virtually constant. That is a balance between gravitational and centrifugal effects at the centers of the two objects. Elsewhere, the same imbalance vectors apply.

Jenna: If the massive Sun is creating tides on Earth, then why are those tides not vastly bigger than the lunar tides?

Prof. Bowles: If you recall Newton's famous equation for gravity, the distance between the objects is squared but the mass of each object is not squared. Consequently, when the large distance between the Earth and Sun becomes squared, that significantly diminishes the Sun's effect. Nonetheless, the Sun is so massive that its contribution to tides amounts to about 46% of the lunar contribution. Spring tides, the highest tidal range of the year, occur when the Sun and Moon are aligned, as shown here. This will coincide with either a full moon or a new moon. Neap tides, the lowest tides, occur when the Sun opposes the Moon. This will coincide with a first-quarter moon or a last-quarter moon.



Here's a typical sketch of tides. What's wrong with this sketch?



Jordan: As in your previous sketch, the Moon is too close to the Earth.

Jenna: I see another problem. The illustrated tidal bulge is about one-third of Earth's radius. That would be about 2000 km. The tallest mountain on Earth, Everest, reaches just 9 km above sea-level, so everyone would be under water with each high tide.

Prof. Bowles: You have caught me sketching another absurd exaggeration. Of course, you would not see any tidal bulge if I drew it accurately. Let's move on to upwelling. What do you guys know about upwelling?

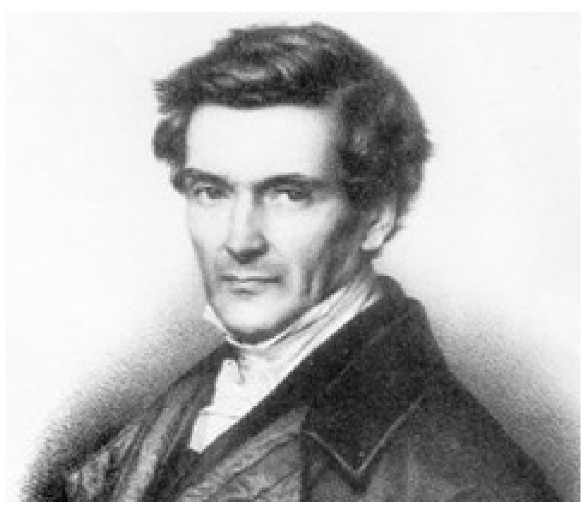
Jordan: Upwelling? Last February, my dad took me out on a research vessel that he was equipping with special computers and we got caught in a nor'easter. The ship was Duke University's R/V Cape Hatteras. The ship weighs about 300 tons and is 41 meters long (135 feet). I learned that this is the worst possible size in a storm because the ship is too long to move gracefully like a yacht and too short to gain stability from its mass, as a cruise ship does. Moreover, intersecting wave trains create an irregular sequence of wave crests, so you cannot predict how the ship will roll from one second to the next. Consequently, landlubber tummies like mine did a whole lot of upwelling.

Prof. Bowles: Been there, done that. Even oceanographers can get embarrassed by rough weather if they have not been to sea for a while. Actually, it's even more embarrassing to be land-sick after a long research voyage. For the first couple days of shore leave, you stagger around as if you were still ship-board. Let's consider another type of upwelling. Why does upwelling of deep water garner so much attention from oceanographers?

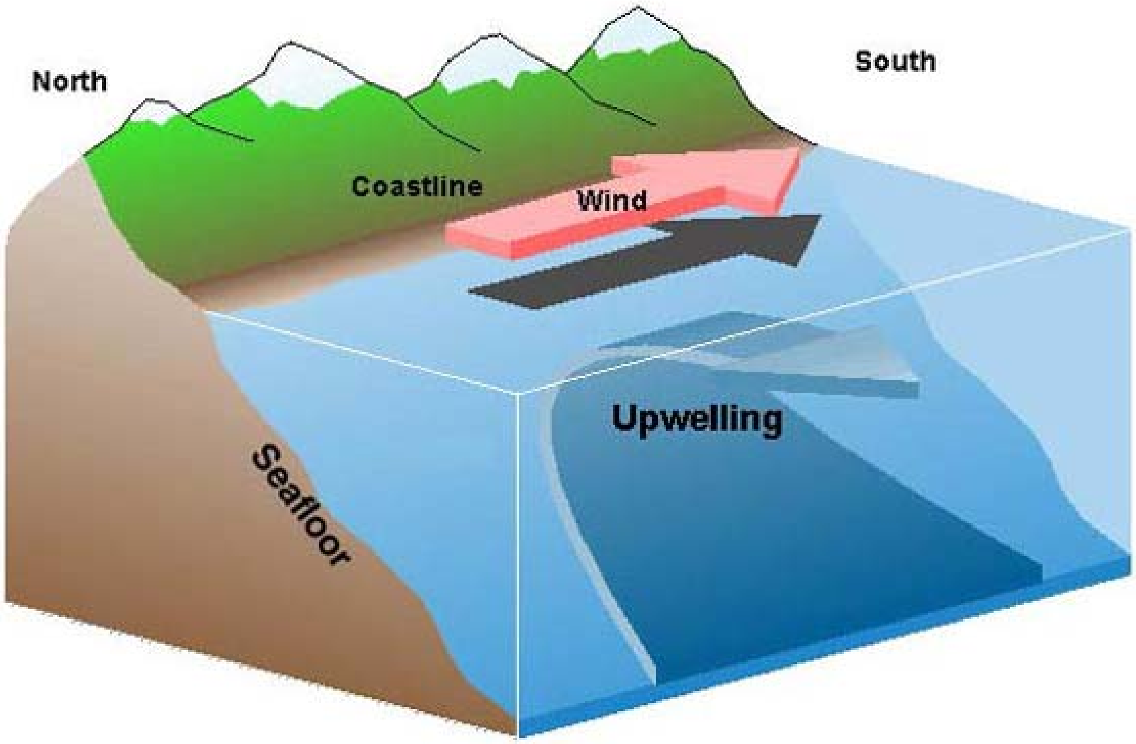
Jenna: I suppose that a lot of oceanographers work to support the fishing industry and upwelling supplies nutrients for the plankton that the fish eat.

Prof. Bowles: Bingo. We will consider plankton and other marine life in a subsequent discussion but we should remember the importance of upwelling to fishing as we take a rather lifeless view of the topic initially. The best way to induce upwelling is to move the surface water away from the deeper water because the deeper water will then rise to replace that void. There are several ways to accomplish this. We have already mentioned upwelling associated with cold-core eddies of the Gulf Stream. To bring up cold water, these eddies must be spinning counter-clockwise, like a hurricane, because that pushes water away from the center, due to the Coriolis effect. Have you guys researched Gustave de Coriolis?

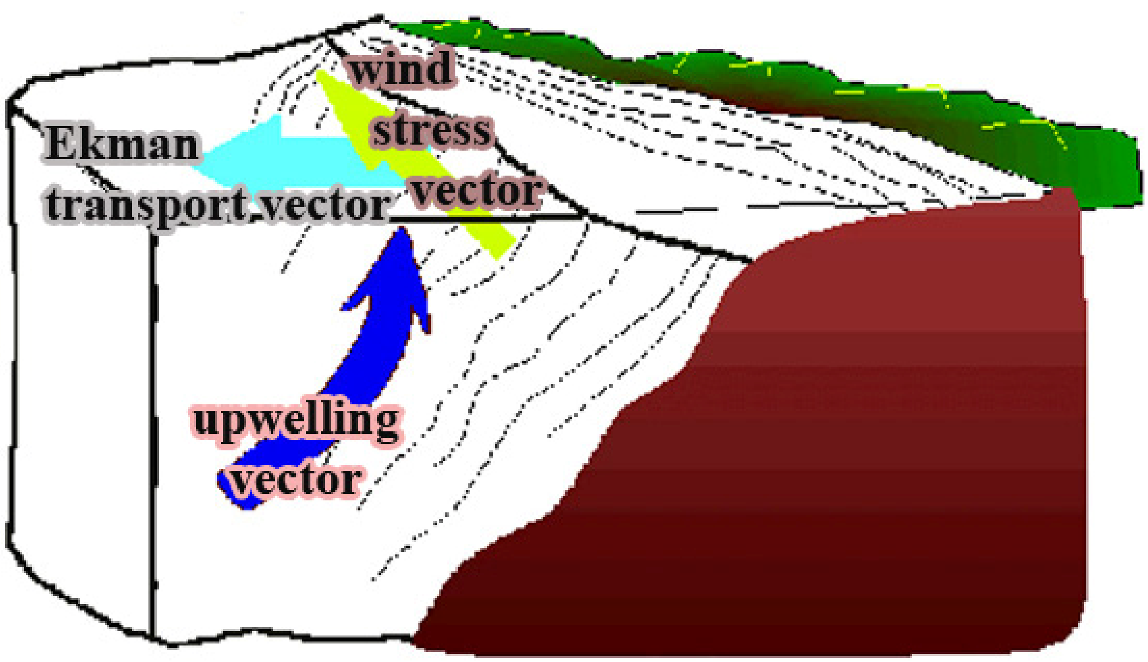
Jordan: I always judge a man by his looks so I went and found this portrait of Gustave.



Prof. Bowles: I hope that Gustave is a keeper. His Coriolis effect helps to induce upwelling of coastal water. Here is a sketch of the notoriously cold California coast. You surf instead of swim there because the dominant current comes from the north. Moreover, a north wind induces upwelling of the deep water that is always cold.

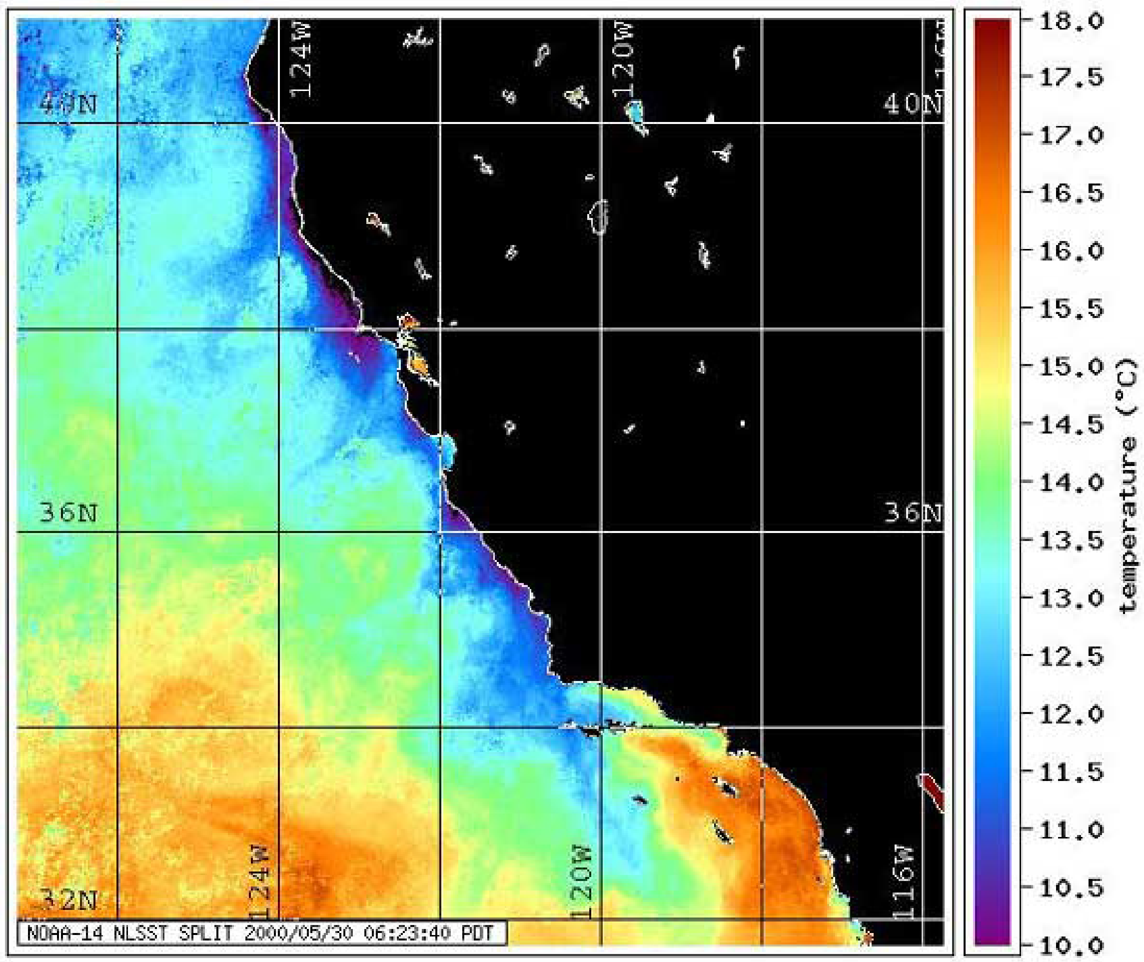


Jordan: In the southern hemisphere, the Coriolis effect is reversed, so I suppose that it would take a south wind to induce coastal upwelling along the Chilean coast. Offshore transport is labeled the "Ekman transport vector", at right angles to the wind in this sketch. I presume that we will hear an explanation of that right-angled relationship later.



Jenna: Given that upwelling is a coastal phenomenon in California, the temperature variation offshore is commonly the opposite of what we find in most places around the world. Most coasts have broad shallow continental shelves that are fairly warm, compared to deeper-water areas that lie farther offshore.

Prof. Bowles: California is certainly different. Here we see that the California coast north of Santa Barbara is much colder than the offshore areas. A difference of five Celsius degrees (10 Fahrenheit degrees) could be detected by simply immersing one's big toe.



Jordan: What about offshore winds that descend from a coastal mountain range? Would they not cause upwelling too?

Prof. Bowles: Persistent offshore winds that descend from a mountain range do indeed induce upwelling because they displace the surface water in such a way that it cannot be replaced by other surface water. In places like Chile and Peru, there are high mountains near the coast and persistent descending air may push surface water offshore, inducing the upwelling that supplies your pizza toppings.

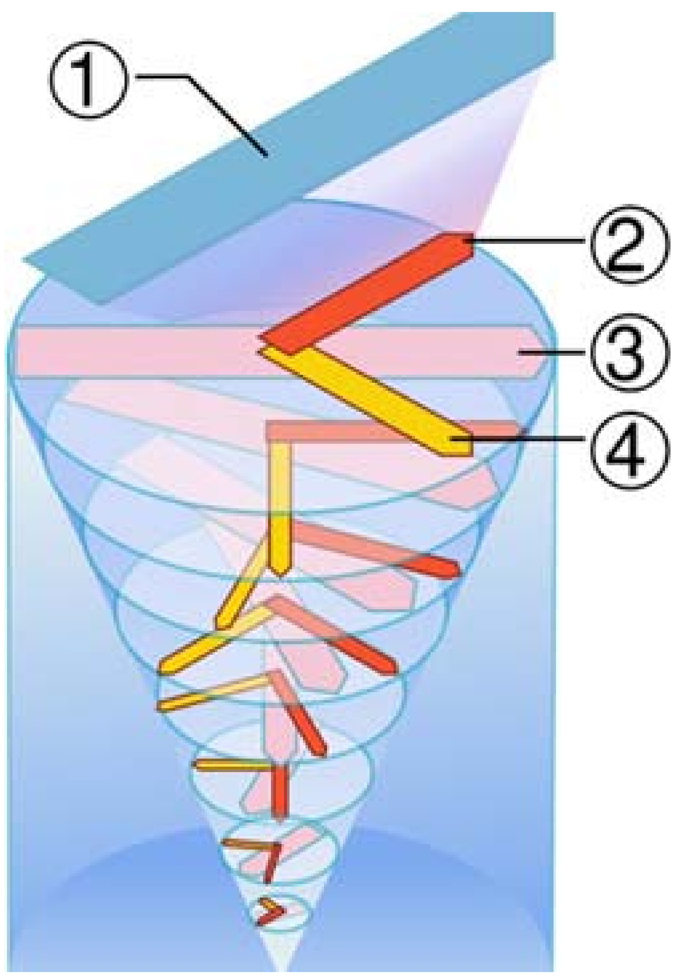
Jenna: Maybe it supplies **your** pizza toppings. I tend to pass on sardines and anchovies.

Jordan: That works out fine for me. I **do** like anchovies, so she always scrapes them onto my portion of the pizza.

Prof. Bowles: The Norwegian oceanographer, Nansen, probably never had the chance to sample pizza, but he had lots of time to study the effect of wind on surface water while his vessel was trapped in Arctic ice for more than three years. Nansen found that icebergs do not move in the direction of the wind but veer to the right, due to the Coriolis effect.

Jordan: Coriolis. Coriolis. All the textbooks imply that he is the father of physical oceanography, but when I dug up his portrait, I found that he never studied any aspect of oceanography. He never even studied the Earth's rotation. He was into the transfer of energy among waterwheels.

Prof. Bowles: Perhaps we live on one big waterwheel, or is it a merry-do-round? In any case, a friend of Nansen, named Ekman, used the mathematics of Coriolis to explain the wind-induced drifting of icebergs. Ekman calculated that wind-driven marine currents should spiral downward, as shown here. In the underlying Ekman spiral, (1) labels the wind direction and (2) is the corresponding force. (3) labels the resulting flow at the very surface, due to the Coriolis effect. The immediately subjacent water does not sense the wind direction. It only senses the motion of the surface water, so it veers to the right of the wind-induced surface motion. The next layer down responds accordingly, twisting the spiral. (4) shows the net flow, an integration of all the Coriolis-induced twisted flows downward through the near-surface water column. The spiral becomes smaller downward because friction progressively diminishes the effect of the wind with depth through the water column.



Jenna: Now I can see why a wind parallel to shore may cause the nearshore water to move offshore and allow for deeper water to rise.

Prof. Bowles: Yes. In the northern hemisphere, Ekman would predict upwelling if there is a north wind along a north-south-oriented shoreline, as we have already seen for California. If coming from the north, the net effect of the wind would be to push the surface water perpendicularly away from the shore, to the right. This displaced surface water would be replaced by upwelling deeper water. In the southern hemisphere, the wind would have to be a south wind to have the same effect, given that everything in the southern hemisphere veers to the left, as we have seen for the Peru-Chile coast.

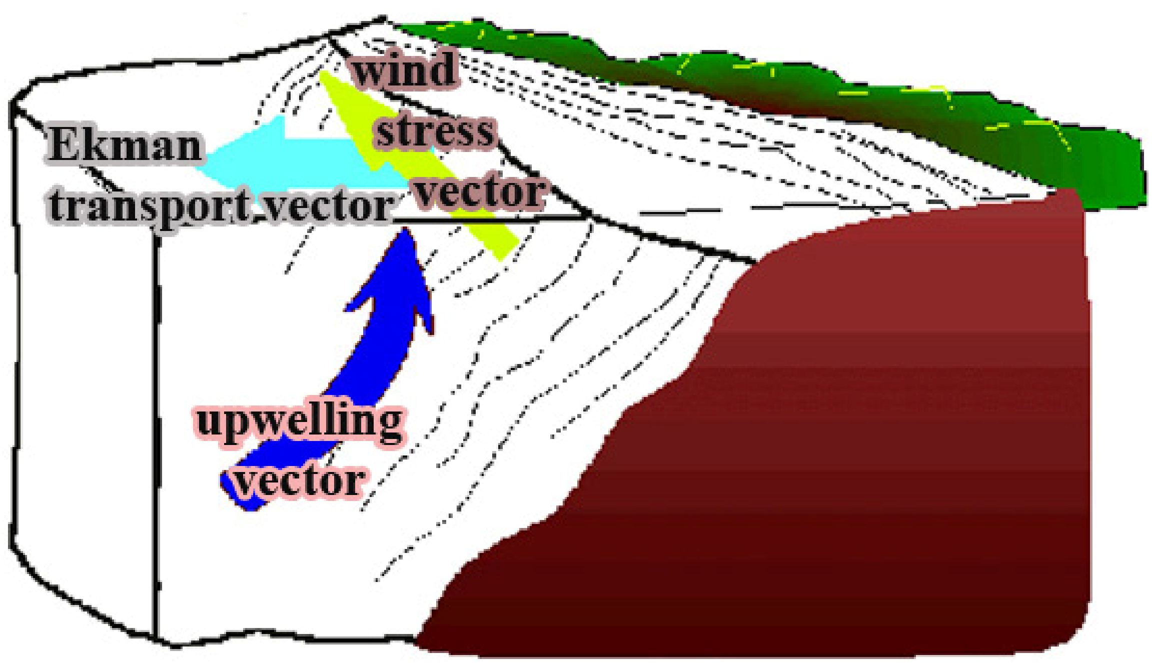
Jordan: That's a cute theory but do we actually observe Ekman spirals all over the ocean?

Prof. Bowles: No. They appear in coastal regions as illustrated here, but diurnal cycles in the open ocean create so much turbulence that the Ekman spirals generally become disrupted. Solar heating typically makes daytime winds stronger than nighttime winds. Moreover, waves that come from distant storms commonly dominate the surface waters.

Although absent from the open ocean where you might expect them, Ekman spirals have been found in unexpected places such as under ice floes and within the atmosphere. Even the force of the wind on the sea-surface is twisted nearly ten degrees from the direction of the wind itself. However, that small angular difference is not apparent in the overlying sketch.

Jordan: Let's go back to El Niño upwelling off Peru. You have noted that some talk-show participants relate global climatic changes to that upwelling. However, I personally doubt if that tiny Peruvian tail wags the global dog. Nonetheless, I would like to learn more about Peruvian upwelling.

Prof. Bowles: OK. Here we see that an equatorward wind parallel to the coastline causes upwelling because Ekman transport is then offshore.



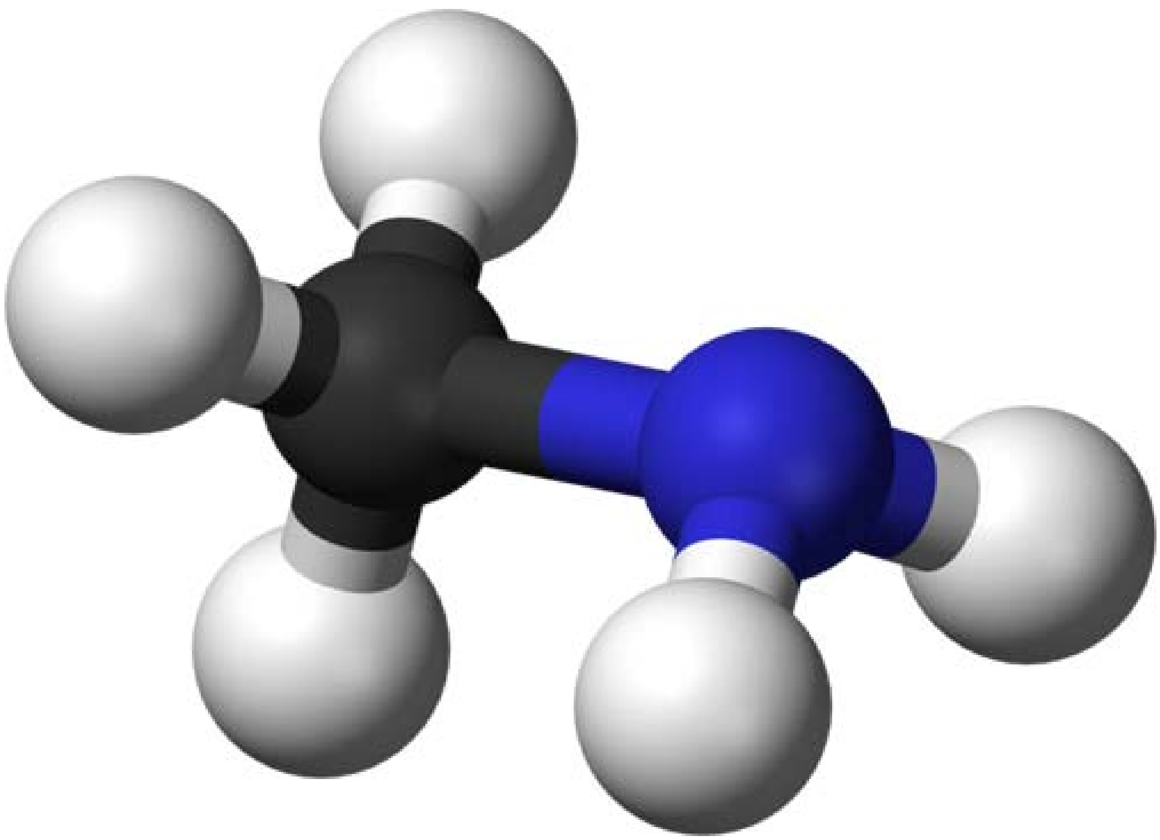
This image comes from the US Naval Oceanographic and Atmospheric Administration, better known as NOAA. NOAA reports similar upwelling along the coasts of California, Morocco, and south-western Africa. Fish blooms are commonly followed by mass mortality that can make adjacent coastal areas rather pungent.

Jenna: Pungent? I hear that fishing villages in Peru can smell so bad that you expect the paint to start peeling. Why does upwelling cause the paint to come down?

Prof. Bowles: The mass mortality of fish leads to the decay of the amino acids which are an essential component of all organisms. We discussed amino acids in the preceding chapter on marine chemistry. All amino acids contain amines. Amines are related to ammonia, NH_3. As you know, ammonia itself has a pungent odor.

Jenna: Yes, but not as pungent as rotting fish.

Prof. Bowles: I will grant you that. As a teenager, I worked in a drafting office where ammonia was continuously used as a solvent. It was unpleasant but bearable. However, the odor of rotting fish can be truly unbearable. Here is one of the amines that can make you gasp. This is methylamine. You can make methylamine out of ammonia by replacing one of the hydrogen atoms in NH_3 with a methyl group, CH_3. In the underlying sketch, the CH_3 group is on the left and the remaining NH_2 is on the right.

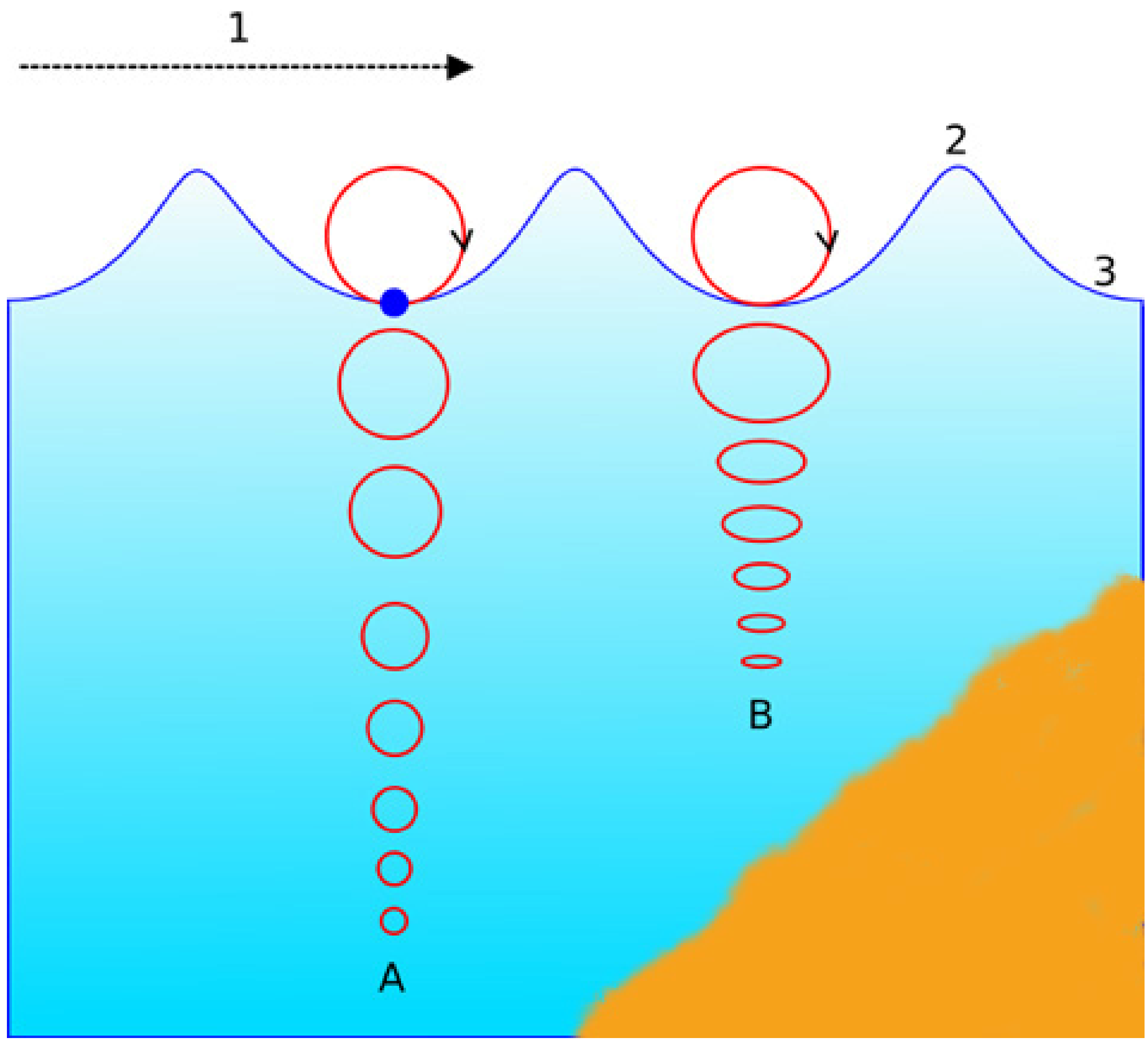


I should warn you that some cockroaches go one step further and replace a second hydrogen with a methyl group, producing dimethylamine. The roaches may then communicate with each other by scent across large distances. This amine is a type of pheromone. Lots of animals, including humans, emit chemicals that trigger a behavioral response in other members of the species. For humans, the pheromones trigger a sexual response.

Jordan: There's a guy in my class whose body odor triggers an anti-sexual response.

Jenna: I know him. His odor is not a "fair-ole-mahn" but a "nasty ole mahn".

Prof. Bowles: It seems that upwelling has brought more to the surface than we expected so I will close this discussion of currents with a few words about the most commonly observed motion in the sea, a wave train. Every textbook presents a sketch of both an open-ocean wave and a wave approaching shore, like the ones shown here. You may notice the circular path of water droplets in the open-ocean wave and the elliptical path that results from interference with the shallowing seafloor.



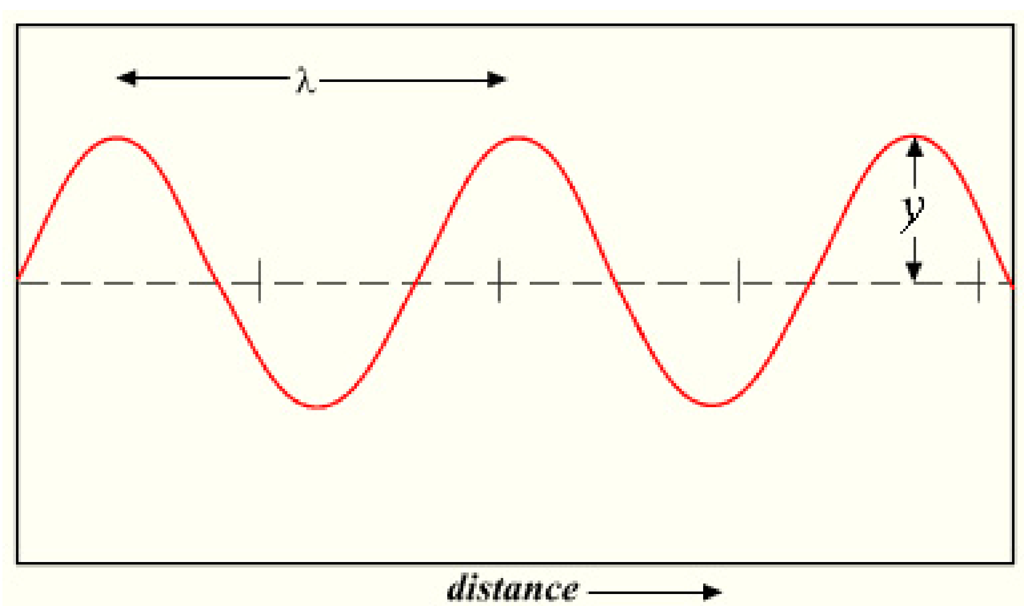
The direction of wave propagation is labeled (1) whereas (2) and (3) respectively represent a wave crest and a wave trough. If you recall the story of tangential motion associated with tides, a similar story applies here. At any instant of time, a water droplet is traveling tangentially to the illustrated circle or ellipse. If interference with the seafloor eliminates the landward portion of a circle or ellipse, the seaward portion may continue and produce crashing surf.

Jordan: I love surfing. Jenna thinks that our submarine trip will just be an expensive way to reach Hawaii's surfing beaches. Why is the northern coast the best for winter surfing?

Prof. Bowles: Big waves come from big storms and the northern Pacific is stormier in the wintertime than the summertime. Moreover, Hawaii is our most southerly State and the only one in which the Northeast Trade Winds predominate. Coming from the northeast, the winds push waves onto Hawaii's northern shores. Those shores are steep, so the seafloor does not cause the waves to break until they are close to shore, as seen in the overlying sketch.

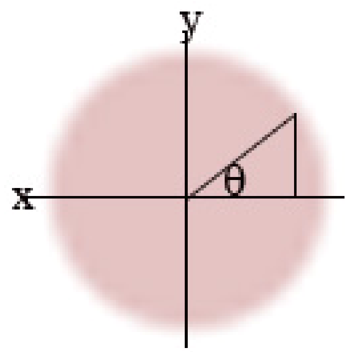
Jenna: Here is the north coast of Oahu with its famous pipeline surfing. Surfers travel sideways along the face of the breaking wave while the curl hangs over their head. In a sense, the surfers are traveling along a pipe. The waves exceed four meters in height, making this type of surfing so dangerous that the pipe connotation probably has more than one meaning.

Prof. Bowles: Let's review the basic math of waves. Here we define wavelength (λ=lambda) and amplitude (γ=gamma). When surfing, these would be the most obvious wave properties. The waveform shown here could be either a sine wave or a cosine wave, depending on how we scale the **x** axis. If we scale it so that **x** equals zero when **y** equals zero, then this would be a sine curve. A sine curve is a type of circular function, as is a cosine curve. As you may have guessed by now, we could declare this sketch to be a cosine curve by making **x** equals zero when **y** is at its maximum value. As you can see, sine curves and cosine curves are equally good at representing waves, but we tend to use the sine curve because it is a little simpler. The origin for its coordinate system is (0,0); that is, **x** equals zero, **y** equals zero.



Jordan: The curl that hangs over a surfer's head looks like an arc of a circle but I do not see anything circular in this sine wave. Nonetheless, you claim that both the sine function and cosine function are members of a big family of circular functions. Is that just another example of circular reasoning?

Prof. Bowles: There is plenty of circular reasoning in science, I must admit. Most of it involves "truth by definition". However, a sine curve is truly related to a circle. Allow me to show you how it works. Imagine a circle with a radius of one unit. By that, I mean that you could choose any unit of measure, whether metric or non-metric, and draw the circle so that its radius has a distance of one unit. Now, imagine that a radial line is sweeping counter-clockwise around the circle. At any instant in time, its angle above the horizontal, the **x**-axis, is theta, as shown here.



Wherever that radial line reaches the circumference, there will be an **x,y** location of intersection. When the radial line is lying flat, coincidental with the positive **x**-axis, theta will be zero and the **y**-coordinate value will also be zero. Of course, **x** will be one.

The sine function is the value of the **y**-coordinate as theta sweeps counterclockwise. You can see that the sine function is zero when theta is zero. When the radial line swings counterclockwise a quarter of the full circle, **x** decreases to zero and the sine function reaches its maximum value of one. When the radial line continues sweeping, the **y**-value will come back to zero as theta progresses through another quarter-turn, where **x** becomes equal to minus one. This pattern continues as the radial line keeps rotating counterclockwise.

Jenna: I always measure angles like theta in degrees but I gather that you scientists have some other scheme when dealing with circular functions like the sine function.

Prof. Bowles: Yes, we use radians instead of degrees. However, I do not want to pretend that degrees are some hillbilly unit of measure that will soon disappear. Why do you think that the vast majority of the world's population continues to use degrees for angular measure, even though most people outside the USA have switched to metric units for nearly every other type of measurement?

Jordan: A complete revolution is 360 degrees on a compass and 60 minutes on a clock. Mental arithmetic can readily divide both 360 and 60 in many ways. Both numbers easily may be divided into a host of fractions such as halves, thirds, quarters, and tenths. I bet that that is not true for radians.

Prof. Bowles: Very good. Like π, the value of a radian in degrees is an unending string of digits, starting with 57.2958. A high-school nerd typically can recite π to some absurd number of decimal places whereas a college-level nerd is someone who can recite the value of a radian to a comparable number of decimal places. In fact, it is a radian's relationship to π that makes it so useful. A complete revolution, 360 degrees, equals two π radians.

Jenna: You have noted that the value of the sine function becomes zero at every half-turn of theta. If expressing this in radian measure, I suppose that you could say that sine returns to zero whenever theta progresses through π radians. Sine oscillates between its extreme values whenever theta progresses through one-half of π radians.

Prof. Bowles: Indeed. Radian-based calculations are more straightforward, once you learn how to use them. Every scientific hand calculator has a button for π, and the calculator always gives you the option of calculating in radian measure instead of degrees. Now that we understand the shape of a sine wave, we should examine a few other properties of waves. Where would you like to start?

Jordan: If I were watching waves splash against my submarine's periscope, I would like to know the wave frequency so that I could predict the time interval between wave crests that would come to obstruct my view.

Prof. Bowles: Wave frequency (f) is a fundamental property that is related to several other wave properties. For example, we have shown that a sine wave is generated by a counterclockwise rotation of a circle's radius. That rotation would have an angular velocity. Angular velocity is normally designed by the Greek letter, omega (ω), and is always measured in radians by scientists. We have just noted that one complete revolution, 360 degrees, equals 2π radians and constitutes one wavelength. Consequently, the frequency equals the angular velocity divided by 2π. If the angular velocity happens to be 2π radians per second, then 2π divided by 2π equals one and the frequency is one cycle per second. Your periscope would then be hit by a wave crest every second.

Jenna: Let's say that we surfaced with our submarine and wanted to compare the wavelength to the length of our submarine. What would be the relevant wave property?

Prof. Bowles: That would be the wavenumber. The wavenumber is the number of wavelengths in a given distance. It is the inverse of the wavelength so it has units of one over distance. If you multiple the wavenumber times the speed of propagation of a wave, then the distance units cancel and you are left with units of one over time. Specifically, you are left with frequency because it has units of one over time.

Jordan: I have heard that oceanic waves may be classified as surface gravity waves. What does that mean?

Prof. Bowles: There are many kinds of waves that follow the basic math which we have reviewed here. Waves on the ocean are gravity waves because they are generated along the interface between two media of contrasting density, air and seawater. Given the difference in density, gravity acts to counteract any vertical displacement away from a flat interface. This attempted restoration sets up the oscillation that we observe as waves.

Surface waves are generally generated by wind acting over an extensive fetch. However, other disturbances can also generate gravity waves, such as the disturbances that produce tsunamis. In addition to surface waves, oceans also have subsurface gravity waves that propagate along interfaces of contrasting density. These are called internal waves. Submariners have to watch for those waves because they can be quite powerful.

Jenna: I have heard that wave energy can be used to generate electricity. Some books include sketches of devices that flap up and down in the waves, generating a little current.

Prof. Bowles: Those devices generate some federal funding for eloquent researchers, but you must realize that waves are like wind in that you would need a vast array of mechanical devices. Generally, it costs more to maintain those devices than you gain in electricity.

Jordan: My dad would probably kill me for telling you this but I know that he has gotten involved in a marine-power-generating scheme that involves the Gulf Stream. The State of Florida has invested five million dollars in a group of researchers at Florida Atlantic

University who use my dad as a consultant. They claim that one-third of Florida's power consumption could come from the Gulf Stream. After all, both coal and nuclear plants are designed to do nothing more than turn a turbine. Here is a steady flow that could do a good job of spinning a turbine.

Prof. Bowles: I agree that the Gulf Stream holds more promise than waves or wind, but seawater is a corrosive agent which would make maintenance even more difficult than for wind turbines. What does not corrode away in seawater gets covered quickly with coralline algae and animals such as barnacles. Perhaps you recall the pitiful fate of the Russian Navy that become so encrusted with barnacles in 1905 that the ships could not outmaneuver the Japanese and ended up as scrap metal on the seafloor.

Jordan: Given that my dad is making a lot of money with this scheme, he would not want to know that I am paying a tutor to explain its potential shortcomings, so we should end this discussion about oceanic waves and currents.

Jenna: I did like learning about places where we could turn off our submarine engine and just "go with the flow", like gliding along in a yacht. Talking about yachts, how is your French friend, Florence, doing on her cruise around the world, sailing her family's yacht? That sounds like the French equivalent of our scheme.

Jordan: Florence and I were constantly competing for the same boyfriends in Paris. Whenever she found a beautiful and expensive outfit, I had to find one that was even more beautiful and more expensive. I must admit that I dreamed up this submarine excursion partly to outdo her circumnavigation of the world on her family's yacht. Even though Florence's family has the most expensive private yacht in France, it still cost them just one-tenth of our submarine budget.

Jenna: Maybe I'm going on the wrong vessel. Her yacht must move with all the grace of a ballerina whereas our submarine will plough through the ocean like a dump truck. I would even bet that she has a handsome French chef on board. I hope that you are not planning to smuggle a French chef onto our sub. I don't want to be marooned on Easter Island when you two decide that three's a crowd. I think that you had better resign yourself to watching soaps on our trip rather than living them.

Jordan: Just to remind Florence about who is richer, I have hired her to produce an interactive video of the coastal areas that she is visiting. I will get my dad to set up the satellite links so that we can communicate during her little exposés on hot sand and cool surf. She will probably discover some secluded beaches where we can park our dump truck and frolic in that waves. When we get there, remind me to slip into something not too revealing in case I get completely wet.

Jenna: Like, who cares, or perhaps my premonition of Pierre the pastry pounder portends a passionate pastime of playing like porpoises.

Jordan: Hey. Park it. My dad should have us connected to Florence in just a few minutes.

Chapter 6: Where the Blue of the Night Meets the Gold of the Day, Someone Waits for Me

Jordan: It's so good to see you again, Florence, or should I say, "Bonjour des Etats-Unis" (*Bohnjure days ay-tahs-eu-knee)*

Florence: La dernière fois que je vous ai vu, vous compreniez le francais bien mieux que vous ne le parliez. Ainsi je vais parler français pour voir si c'est encore le cas.

Janna: What was that?

Jordan: Florence said that she is going to talk to me in French because she knows that I can understand better than I can speak.

Janna: I wish that somebody would do that for me in Spanish. My high-school Spanish teacher did not sound anything like the tapes she played in class, so I am struggling with college Spanish.

Florence: Yo sé también como hablar en español. Pues, yo hablaré con usted en español mientras que hablaré con Jordan en francés. ¿Usted me entiende?

Janna: I understand you perfectly. It would be great if you would respond to me in Spanish. However, like Jordan, I will have to speak in English. I hear that you have just returned from sailing around the world in your family yacht. Jordan and I are thinking about doing something like that and we cannot wait to see the photos from your trip.

Florence: Bueno. Tengo millares. ¿Qué tipo de paisaje le interesa más?

Jordan: We are mostly interested in coastal scenes, where the blue of the sea meets the gold of the land. That's what we're waiting to see. Knowing your dad, he must have given you an excellent telephoto lens that could capture details with your 12 megapixel Nikon™.

Florence: Effectivement, mais mon frère Pierre m'a empreinté certaines photos à haute résolution de plages qu'il a trouvé particulièrement enchantresses.

Jordan: I can imagine that your brother would be interested in a few of your photos. I gather that Pierre is still studying what he calls marine biology, specializing in certain beaches where the *Homo sapiens* species wears as much as any other animal frolicking on the beach.

Janna: I'm just as glad that you lost those photos to Pierre because the frolicking beaches that I have visited contain some rather ugly specimens of *Homo sapiens*. I have often been tempted to hand out towels to improve the landscape. Where are you going to start your picture show?

Florence: Comme vous êtes américains, je commencerai par Hawaï.

Jordan: Hawaii is a spectacular place to start. I am sure that Captain Cook was surprised to stumble upon that extensive island chain, stretching across an uncharted portion of the Pacific. Mauna Kea on the big island rises to 4200 m, nearly half the height of Mount Everest.

Janna: For all its topographic variability, there are not many rock types in Hawaii, given its monotonous sequence of basaltic lava flows. Many of the coastal cliffs are so steep that they lack vegetation, so the bedding must be obvious to anyone sailing along in their yacht, right?

Florence: Oui. Les lits basaltiques sont tout à fait flagrants.

Jordan: After we settle down and join the business world, we are likely to return to Hawaii for some conventions. Conventions are mostly held in Honolulu, so let's look at Honolulu's beach, the world-famous Waikiki beach. Here we are looking from Waikiki up to the basaltic promontory of Diamond Head. We can see that the beds are almost flat-lying and that the uppermost beds of Diamond Head are much darker than the lower ones. I am glad that this is a public beach, so this photo did not become lost to Pierre's collection.

Florence: J'ai été vraiment étonnée par les plages de sable blanc alors que toute la roche est basalte noire.

Janna: I too was surprised by all the quartz in Waikiki's beach sand because basalt is not supposed to have any quartz in it. I found that the quartz had been imported in barges towed from a beach in Los Angeles County back in the 1920's and 1930's.

Jordan: Waikiki's sand looks nicely rippled, so the tide must cover all of the area shown here. That would bring high tide close to a lot of very expensive real estate. Land values in Honolulu are among the priciest in the world. Let's climb Diamond Head and take a look back toward Honolulu and its beach, Waikiki.

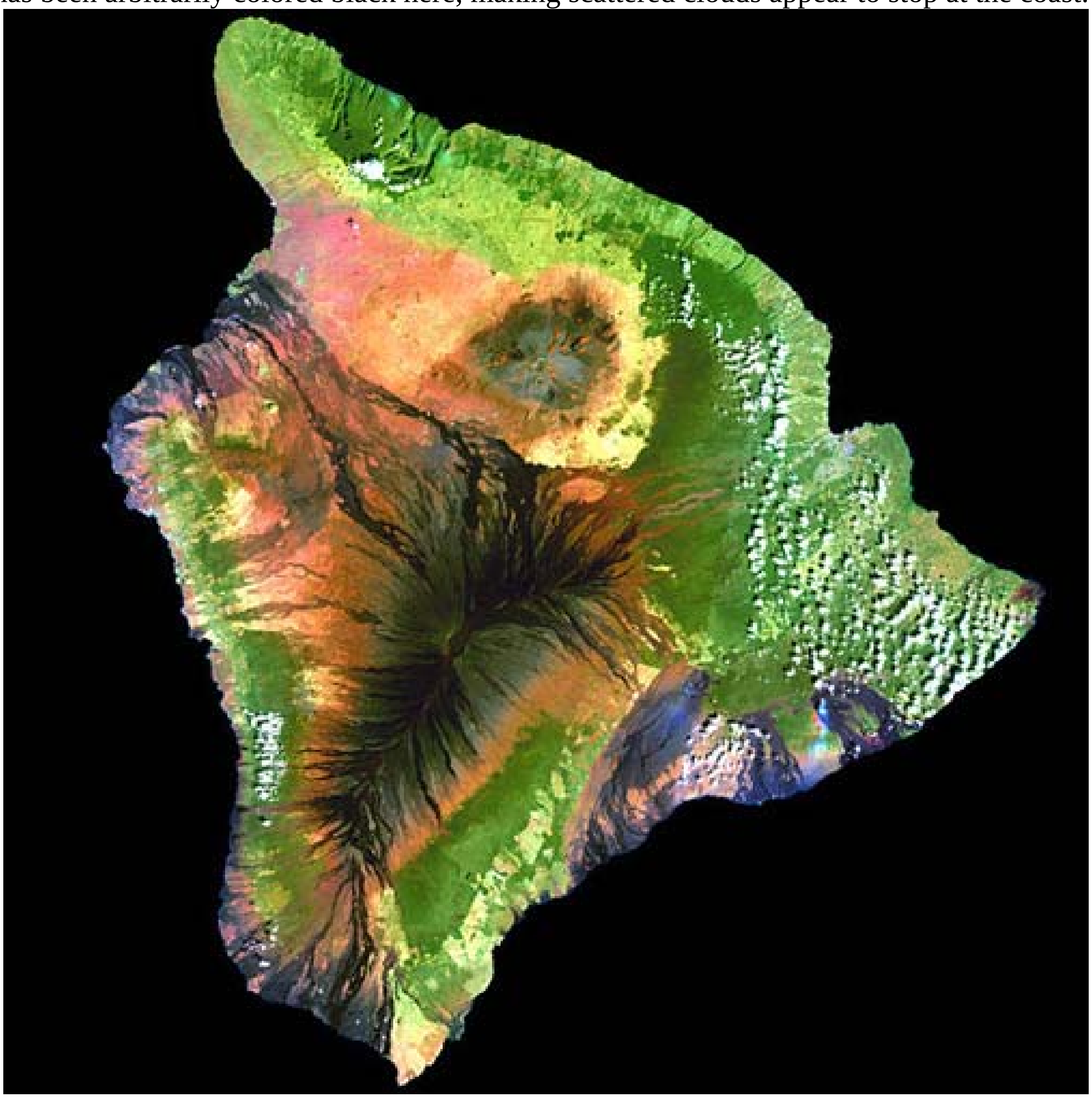
Florence: Oh la la, j'étais hors de souffle quand je suis grimpée au sommet pour prendre cette photo.

Jordan: I too would have been out of breath by the time I had climbed high enough to take that photo. Looking back from that vantage point, I can see why they were hauling all that sand from California to extend the beach. The surf zone almost reaches the seaside entrances for some of those skyscrapers. Hawaiians had better hope that Al Gore is as accurate in his prediction of sea-level rise as he was about winning the presidential election.

Janna: Didn't Charles Darwin predict that all volcanic islands tend to subside because the Earth is not strong enough to hold up isolated peaks like Hawaii?

Florence: Si, asi es. El hundimiento de un volcan produce un atolón.

Janna: That's right. The volcano subsides and erodes until all that is left is an atoll. I have a feeling that we are going to see some other expensive but endangered beachfront property as we tour the Pacific rim. I see that Florence has added a satellite photo to her collection. The lava flows from Mauna Kea make Hawaii look as if it is having a bad-hair day. The ocean has been arbitrarily colored black here, making scattered clouds appear to stop at the coast.

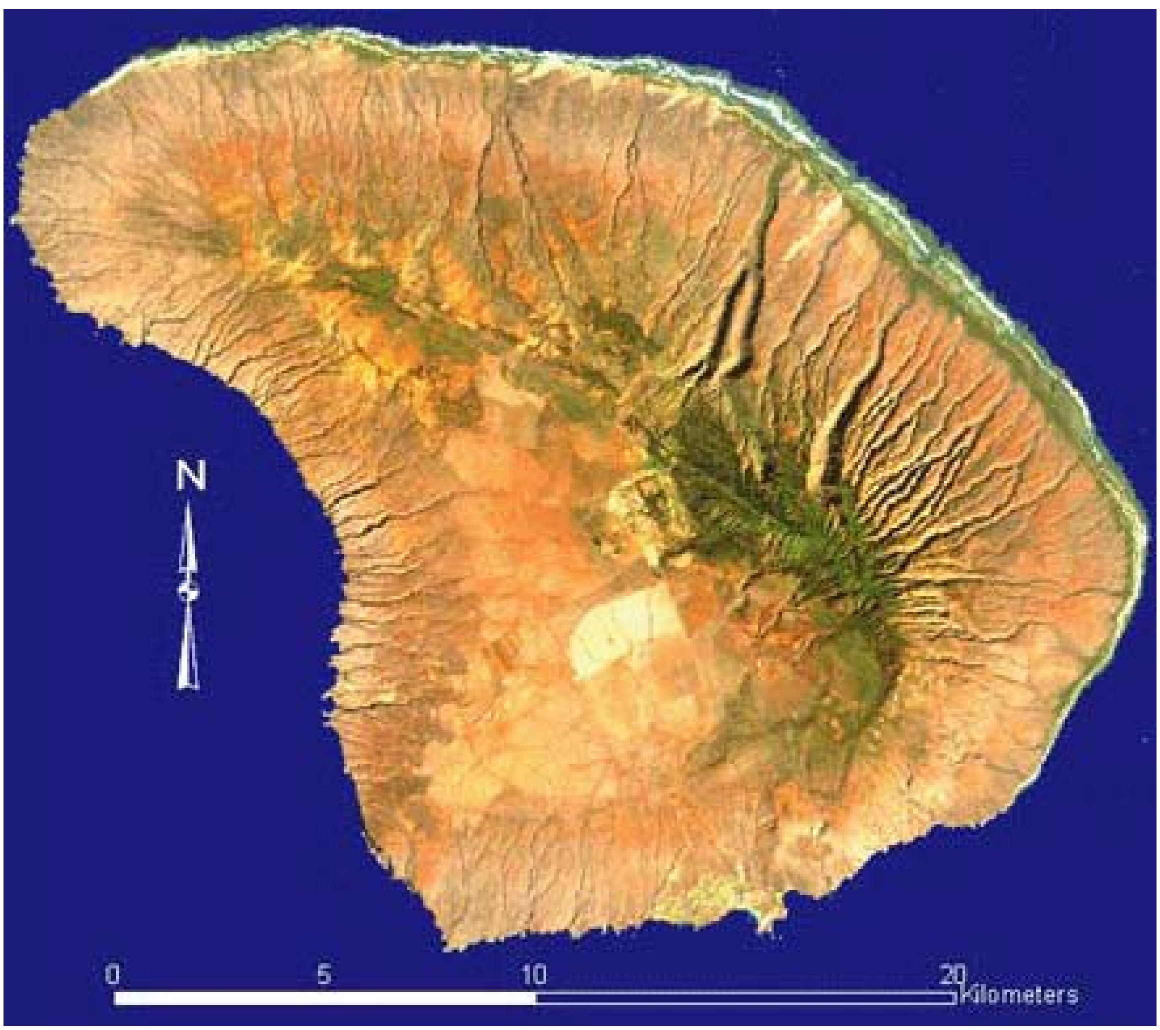


Jordan: The recent lava flows have been toward the south, through the Royal Gardens subdivision. Apparently, Mother Nature does not pay much attention to stop signs here.

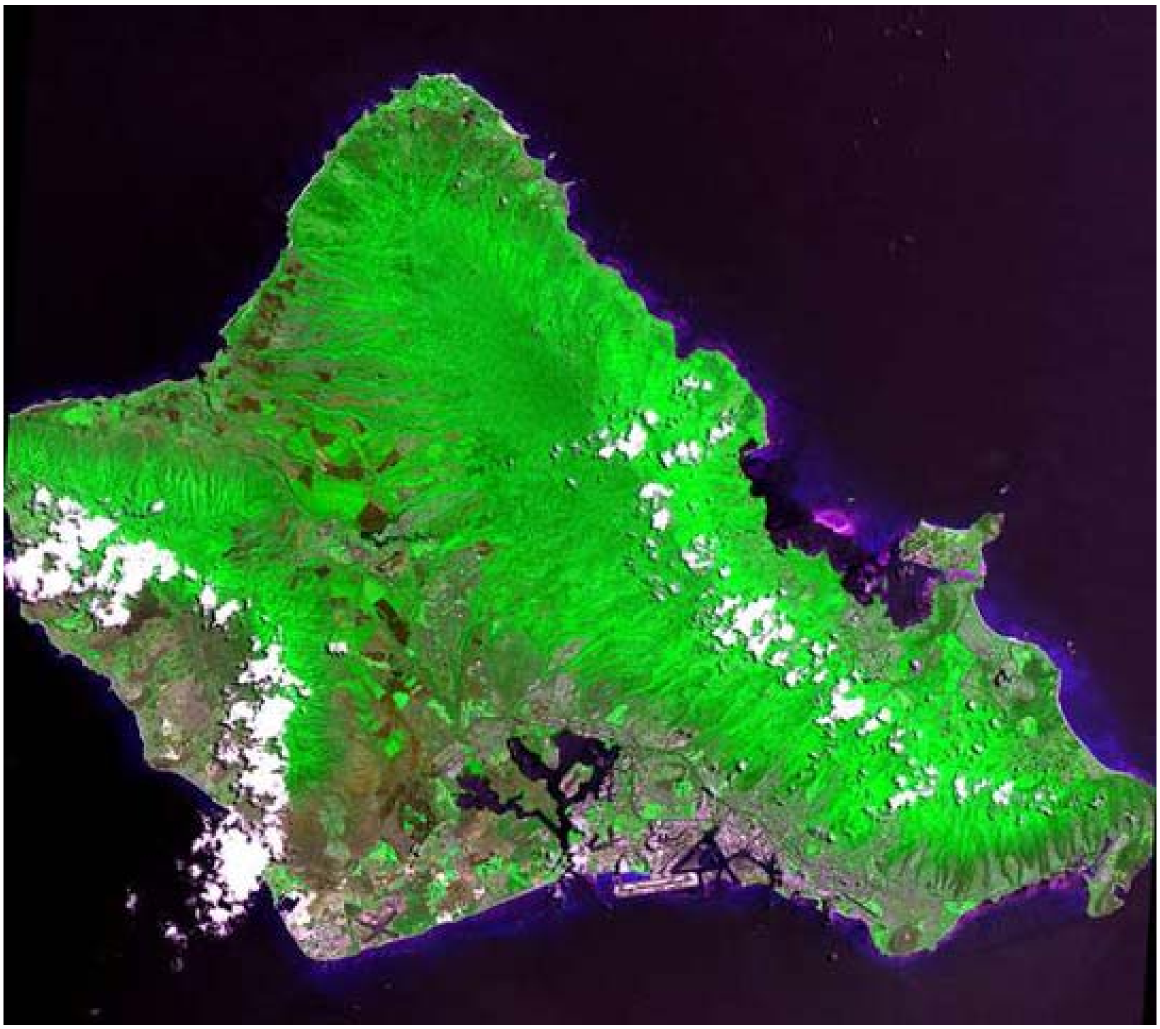
Florence: Pouvez-vous voir le port de Hilo sur l'image satellite d'Hawaï ?
Jordan: Yes. I can see Hilo Harbor, opening toward the northeast. Here is a photo.

Janna: Hilo has been tsunami central for the United States, given its northeastern orientation. Hilo Harbor points toward tsunamis that are generated by Alaskan earthquakes. I wonder if the breakwater would help to protect the citizens of Hilo.

Florence: Desafortunadamente, no pararía un tsunami.
Jordan: That's too bad. I guess that breakwater would have as much effect as sticking up a stop sign. I do not see any other natural harbor around the big island, so I guess that they are stuck with Hilo. What did you see while sailing along the coast, other than tourist activities?
Florence: J'ai remarqué qu'il y a un bon nombre de fermes côtières, tout spécialement le long des côtes nordiques et du sud-est.
Janna: Ah, yes. I can see that the northern and southeastern coasts of Hawaii are subdivided into farmland, as well as other portions of the coastline. Are those pineapple plantations? Are Jordan and I going to see pineapples growing along the coast of the big island?
Florence: Para ver las piñas, hay que viajar alrededor de la isla de Lanai.
Jordan: Lanai. That's the Hawaiian island which was purchased in 1922 by James Dole and converted from a cactus-strewn wasteland into the supplier of 75% of the world's pineapples. We should load up on those pineapples when we motor past Lanai because they will have a long shelf life in our vessel.
Janna: I must say that Lanai still looks pretty dry. I wonder if Dole has been mining groundwater, pulling irrigation water out of the ground at a faster rate than rainfall replenishes it. If so, the island will eventually revert to cactus. In fact, I hear that agricultural production is already declining on Lanai.



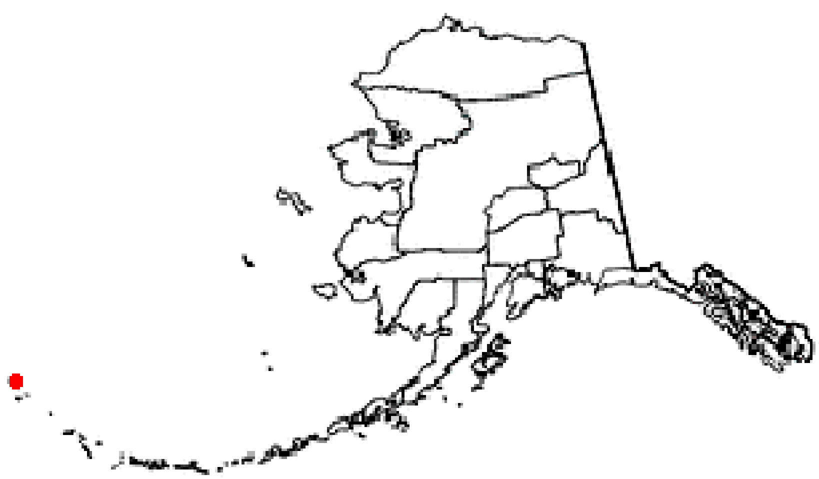
Florence: Et voici l'île d'Oahu, avec Pearl Harbor à l'extrémité méridionale.
Jordan: Sure enough. That's Pearl Harbor at the southern end of Oahu. Now I understand the movie sequence where the radar operators on the island's northern tip got buzzed by the incoming Japanese warplanes.
Janna: Yes, and those planes slipped down the central valley with its ethnic Japanese farm workers, on their way to bomb American warships in the southern harbor. Pearl Harbor does look like one of the Pacific's very best harbors.



Florence: Je vous ai suffisamment gaté avec la beauté tropicale d'Hawaï. Dirigeons-vous à présent vers le nord aux Aléoutes.
Jordan: Not the Aleutian Islands of Alaska!! I was just starting to enjoy Hawaii.
Florence: Examinons tout d'abord la partie de l'Alaska qui fût envahie par les Japonais.
Jordan: The Japanese invaded the Aleutians? That sounds as dumb as Napoleon declaring war on the Russian winter.
Janna: It was just as dumb. When the Japanese ran out of food, eight hundred of them charged straight into the well-fortified American lines, committing mass suicide. If the Japanese had had their Alaskan warships at the Battle of Midway, they might have avoided

that disaster. Let's look at the worthless real estate that the Japanese held for a year in the Aleutian Islands. This is frosty Attu Island where the only occupants today are twenty guys who man an observation station.

Jordan: I see that Attu lies at the far western end of the Aleutian Chain, making it closer to Russian towns than American towns. The Russians were our allies in World War Two, so the Japanese must have been trying to keep us apart.



Janna: Their scheme worked for a while, but then the US Navy cut off their food supply and the Japanese found that Attu itself can only supply snow cones. Americans sent to fight on Attu faced more hardships from the weather than from the Japanese, suffering 4000 casualties altogether. Here they climb through Attu's snow in May of 1943. Notice the shovel for digging a foxhole.

Jordan: That's rather gruesome. Are there no cheery sights in the Aleutians?
Florence: Mais oui, bien-sûr. D'ailleurs, voici une belle reproduction d'un chèque de 7.2 millions de dollars! Comme vous devez le savoir, l'Amérique a acquis l'Alaska des Russes en 1867.
Jordan: You have a copy of the 7.2 million-dollar check that we used to buy Alaska?

Janna: Any check for 7.2 million dollars looks pretty to me. I don't care what was bought with it.
Jordan: Actually, there must be some pretty places in Alaska or else the cruise business out of Seattle would not rival the Caribbean cruises.
Florence: Tout à fait. Voici par exemple une jolie église orthodoxe russe abandonnée par les propriétaires précédents.
Jordan: Yes. This church has classic Russian Orthodox architecture, and the landscape looks ideal for a Sunday stroll if you are physically fit. I bet that the winter winds can blow down any tree that tries to grow on that hillside.
Janna: Florence. I presume that you did stroll up those hills. What kind of rocks did you find there?

Florence: Encontré rocas basálticas, apenas como ésos en Hawaii.
Janna: Basaltic rocks like those on Hawaii? Dr. Bowles has been telling us that the Aleutians overlie a subduction zone and the volcanic rocks are therefore richer in silica, sodium, and potassium, making them andesitic instead of basaltic.
Florence: Non. Les roches sont basaltiques, riches en fer et en magnésium. Le géologue local m'a même démontré par le biais des données séismiques que les roches restent riches en fer et en magnésium vers le bas, vers le manteau.
Jordan: If the earthquake waves (seismic waves) cannot find any andesite down to the mantle, then you are not likely to find much strolling around the hills. Dr. Bowles wanted to make continental crust out of magmatic arcs like the Aleutians, but the Aleutians obviously

do not have the right chemical composition for that to happen. It's amazing the things that you learn when you travel to some place instead of simply watch a documentary.

Janna: It's a big world and I think that the Aleutians have had their share of attention, so let's head past Attu into the Kamchatka Peninsula of Russia. Here the east-west Aleutian arc intersects the northeast-southwest Kamchatka arc. A third arc joins the point of intersection, coming north from the western end of the Hawaiian chain. The Kamchatka arc curves down to the northernmost Japanese island, Hokkaido. I presume that Florence will take us to Japan after showing us Kamchatka.

Florence: Por supuesto, seré su guía turístico para Japón. Sin embargo, debemos primero mirar la ciudad portuaria en Kamchatka adonde los tres arcos vienen juntos. ¿Qué espera encontrar allí?

Janna: What do I expect to find where the three arcs converge on Kamchatka? I expect something geologically dramatic, like a towering volcano.

Jordan: I must admit that I would be worried about that volcano blowing its top off every time I sailed into the harbor to top off my diesel fuel tanks.

Janna: I have found a map that shows the Kamchatka volcano in this photo. The volcano must be very active or else its cone would not be so smooth. Deposition of volcanic ash must be outpacing erosion here.

Florence: Vayamos a Japón. Me costó $10.000 para comprar un kimono tradicional allí.

Janna: Ten thousand dollars for a kimono? I am going to get Jordan to buy me a couple so that I can learn how to make them. Even though there is a vast amount of silk in a kimono, I am sure that a little bit of American ingenuity will help me find a way to make a fat profit on assembling kimonos.

Jordan: I will invest in a couple kimonos if Florence and I get a stake in your company.

Janna: What's this? I thought that you and I were best friends and now you are siding with the French?

Jordan: You might want to reread the War of Independence. Without French explosives, French weapons, French field officers, and the French Navy, independence would have been impossible. However, Florence and I are not going to gang up on you as the British descendents in America did against their motherland. We are going to be like the post-independence French, and just ask for a small percentage of your American profits, in exchange for helping you get started.

Janna: You are just like your dad. No wonder he got to be so rich.

Jordan: My dad brought some kimonos back from Japan for my mom. He said that "kimono" means "tree thing" and that a kimono should hang from a wooden stand that makes it look like a tree. Here is a photo of a wedding kimono.

Janna: I must admit that even when smiling in wedding photos, Japanese ladies look a little wooden to me. I can never guess what they might be thinking.

Jordan: I would not worry about that. You are not likely to end up in a poker game with a Japanese lady, especially one wearing a kimono.

Florence: Regardez les sculptures de neige du Hokkaido, Japon.

Jordan: They carved all that out of snow? Maybe some Japanese ladies really do need all those layers of silk, just to stay warm. If it is that cold in Hokkaido, I cannot imagine how cold it gets in the northern end of that volcanic arc, back in Kamchatka. I have heard that the snow festival in Hokkaido, Japan, draws two million tourists every year. What do they do there?

Florence: Quand Pierre est venu au festival de neige, il a prélevé l'exportation principale de la ville capitale du Hokkaido.

Jordan: So what does the capital of Hokkaido have to do with having a good time?

Janna: I can answer that one. Hokkaido's capital is Sapporo, a world-famous beer. Here is Sapporo, with a central park like that in New York City.

Florence: Cuando dije a una senora en Tokio que viniera de Hokkaido, ella reaccionó como si viniera de un diverso país.

Janna: I too have heard that Japan is not as monolithic as is portrayed in the movies. Outside the US, everyone seems to think that there is only one kind of American. We always get portrayed the same way in foreign movies. I can imagine that some people in Tokyo consider Hokkaido to be weird. I certainly bet that Florence found it weird.

Florence: Como ustedes dicen en América, yo realicé que no estaba más en Kansas.

Janna: So you realized that you were no longer in Kansas. I bet that you have never been in Kansas and never will be in Kansas, even though you might wear ruby red slippers some day.

Jordan: Hey. The French did not become the world's most famous writers without using a few metaphors here and there. What was the weirdest aspect of Japan for you? I know that you learned enough Japanese before leaving Paris that you were conversant.

Florence: Les coutumes sociales sont respectées à la lettre et je n'ai cessé de faire des maladresses.

Jordan: So the Japanese would wince every time you did or said anything because you did not know the correct social customs. That must have been continually painful for both you and the Japanese. Given America's history as a melting pot, we have avoided that pitfall.

Florence: Au premier abord, Tokyo ressemble beaucoup à une ville américaine.

Jordan: At first glance, that did look like New York City to me, but now I can see that it is an imitation. We devastated them in World War Two and then they erect a Statue of Liberty? The atom bombs that we dropped on Hiroshima and Nagasaki were less destructive than the napalm that we used to fire-bomb their cities. It would take a major earthquake or volcanic eruption to come close to the carnage that resulted from our bombing raids. Talking about volcanoes, did you get a close look at Fuji, the volcano that threatens Tokyo?

Florence: Voici Fuji, côté sud.

Jordan: Fuji looks as smooth as that dangerous volcano in Kamchatka, so I would not want to be holding mortgages on some of the world's most expensive real estate in downtown Tokyo. Fuji has about the same latitude and climate as Raleigh, North Carolina, so there is plenty of potential for erosion. Fuji's smooth surface indicates that the addition of volcanic ash has kept ahead of erosion.

Janna: Fuji is the tallest and most voluminous volcano in Japan, and highly variable in its emanations. Volcanic ash, lava, and mudflows have all destroyed surrounding areas.

Jordan: Fuji has not erupted for 300 years, but prior to that it erupted roughly every thirty years through most of a millennium.

Florence: On a pris tellement de photos du Mont Fuji, que le nom Fuji est devenue une marque de pellicule photo.

Jordan: I remember Fuji film. I want to become so famous that some photographic medium becomes named after me.

Florence: J'ai essayé d'escalader la montagne de Hotaka au sud-ouest du Japon mais la blocaille était tellement instable que je ne pouvais obtenir aucune traction.

Jordan: I can see why you had trouble climbing Mount Hotaka in southwestern Japan. The talus appears to be at the angle of repose, so it would slide downhill with every step. Did you find that Japan is mostly rugged like this, outside of the major cities?

Florence: Oui, presque 130 millions de japonnais sont entassés dans juste un peu de terrain plat.

Jordan: It seems that flat areas tend to be under water in Japan, so the nearly 130 million Japanese must have trouble finding somewhere to live. I must say that camping looks good.

Florence: J'ai vu quelques campeurs mais aucun d'eux n'étaient japonais.
Jordan: You mean that all the campers you saw in Japan were foreigners? There must be a social taboo against disturbing some Buddhist deity.
Janna: Why do they keep believing in all those gods? The god of war obviously became their enemy in World War Two, so why keep worshiping him? The Japanese were on our side in World War One but foolishly switched to Hitler. How could they have put Hitler on their mantelpiece? Being a lean vegetarian, Hitler obviously lacked the contented belly of Buddha. Nonetheless, I see that the Japanese are back at it again, building destroyers.
Jordan: Maybe they plan to take on Neptune, the Roman Greek god of the sea.

Florence: J'ai découvert que trois religions coexistent au Japon: le Shintoism, le bouddhisme, et le christianisme.
Jordan: Yes. I have heard that religion in Japan is more complicated than anywhere else because they all want to be born into Shintoism, the native Japanese religion, get married as Christians, and die as Buddhists.
Janna: Let me guess why. Shintoism emphasizes ancestor worship, so that would establish the new-born's place in society. The pictures that I have seen of Christian weddings in Japan looked like a lot more fun than those of traditional weddings. As a Christian, you could spend your ten thousand dollars on a party instead of buying a kimono party-dress, so all your friends would vote for a Christian ceremony. The Buddhists believe in a tangible afterlife, if only as a butterfly, and that seems more reassuring than a hypothetical afterlife, so I can understand that appeal too. I guess that they are ShintoChristiBuddhists.
Jordan: Don't get any ideas about encouraging Christian weddings if you want to retain your piece of my upcoming business in ten-thousand-dollar kimonos.
Florence: Avant que nous n'entamions une autre guerre religieuse, allons donc aux Philippines.
Jordan: OK. Let's go south to the Philippines. I hear that it is becoming an inexpensive retirement community for the Japanese.
Janna: The most famous long-term Japanese resident in the Philippines was Hiroo Onoda. For 29 years, he and his fellow guerillas refused to believe that Japan had lost World War Two and kept harassing the locals. By the twenty-seventh year, Lieutenant Onoda was the only survivor and a Japanese college student set out to find him in the Philippine jungle.

After finding Onoda, the college student could not convince him to surrender until he brought Major Taniguchi from Japan, the superior officer who had sent Onoda on his guerilla mission back in 1944.

Florence: Encontré a algunos filipinos que dudan la historia de Onoda porque su uniforme estaba demasiado bien preservado para vivir 30 años en la selva.

Jordan: I must admit that wearing the same uniform for nearly 30 years is a tall tale. The Philippine jungle has prickly plants and sharp volcanic rocks. My mom has not worn the same dress for more than a day since she got married, and the roughest thing that she encounters is her leather car seat.

Janna: I bet that that college student found Onoda living comfortably in some town and dreamed up this story so that he could sell it to the news media. Besides, Lieutenant Onoda was an intelligence officer and those guys are trained to talk all day long without ever revealing truthful information.

Florence: Los fragmentos volcánicos en el primero plano aquí son enormes.

Janna: Fragments this big are called bombs and the rock which consists of bombs is called agglomerate. The bombs probably came from the volcano in the background. This volcano is as smooth as Fuji and must erupt just as frequently.

Florence: Éstos son volcanes de andesita, como en Japón, en vez de basalto.

Janna: If these are andesitic volcanoes, as in Japan, then they must be more explosive than the basaltic volcanoes of Hawaii.

Jordan: The Filipino volcano, Pinatubo, produced the second-biggest eruption of the twentieth century, in 1991. The world's biggest eruption in that century, Novarupta, occurred at the eastern end of the Aleutians in 1912.

Janna: The adjacent Alaskan valley became known as the Valley of Ten Thousand Smokes because of all the hydrothermal emanations that continued for years. It was a dangerous but rewarding valley to visit shortly after the eruption because precious metals precipitated around the rims of those ten thousand hydrothermal vents. Of course, some of the vented gases were toxic.

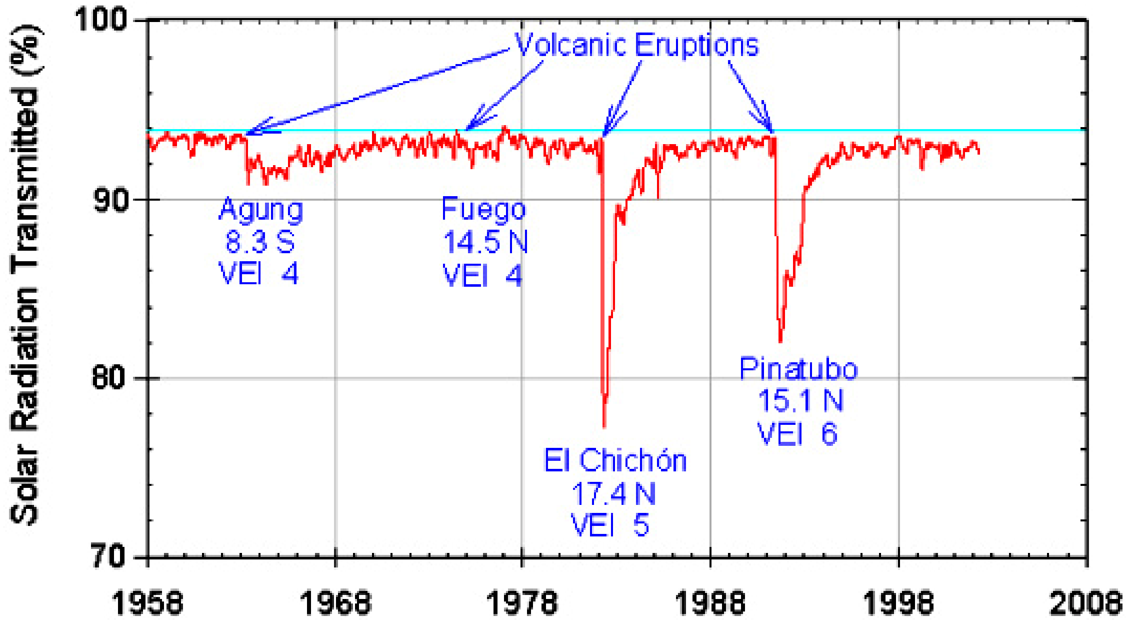
Florence: Solamente los indígenas vivieron cerca de Novarupta. Por eso, no tenemos ninguna fotografía de esa erupción. En contraste, tenemos muchas fotos de Pinatubo, tales como éste.

Janna: Here Pinatubo is sending ten billion tons of ash and twenty million tons of gaseous sulfur into the upper atmosphere, as high as 34 km. That is three times the average height of the troposphere, the turbulent portion of the Earth's atmosphere, the portion which generates Earth's weather systems.

Jordan: By injecting ash and gases to such a high altitude, Pinatubo managed to affect the whole world. Sulfur gas had the longer-lasting effect because the gas did not settle out gravitationally like ash particles. It took about five years for sunlight to get the sulfur to react and precipitate. In the meantime, sulfur decreased the global temperature by about 0.5^{o} Celsius.

Janna: The effect of the ash was much more immediate and direct because the particles blocked sunlight quite effectively. Here is a graph showing the diminished sunlight on Hawaii, 8500 kilometers away (5200 miles away).

Jordan: The Pinatubo ash blocked about 10% of incoming sunlight for roughly two years. The time-averaged effect of Pinatubo was comparable to that of the Mexican volcano, El Chichón, even though El Chichón had a more impressive maximum impact.



Florence: L'éruption principale du Pinatubo fut tellement puissante qu'on ne peut pas apercevoir l'écoulement pyroclastique sur la photo. Cette plus petite éruption montre les dispositifs un peu mieux.

Jordan: This smaller Filipino eruption does indeed show a basal surge of pyroclastics.
Florence: Aussi longtemps que nous resterons sur la jante Pacifique, vous allez continuer à voir des volcans.
Jordan: I suppose that we will indeed continue to see volcanoes as we keep sailing along Pacific coasts. Where are you taking us next, Indonesia?
Florence: Oui, mais d'abord regardons cette image satellite pour passer en revue notre croisière.

Jordan: We have made it from the Arctic Circle in Kamchatka down to the equator in Indonesia. Kamchatka's population is under four hundred thousand whereas Indonesia's population is nearly 600 times greater, about 235 million.
Janna: Is this supposed to teach us that global warming is a singularly bad thing?
Florence: Algunos de los fósiles más viejos que se asemejan a seres humanos se han encontrado en Indonesia. Se parecen haber gozado del calor.
Janna: I have heard about Java man and other fossil hominids. Humans and hominids have been enjoying the warmth of Indonesia for a couple million years. These were the oldest known hominid fossils until we discovered the famous sites in eastern Africa.

Jordan: It should not be too surprising that Indonesia has ancient hominid fossils because we humans are primates and Indonesia is famous for its wide variety of other living primates, especially the orangutan shown here.

Janna: I wonder if the orangutan was named for his orange color by the Dutch who ruled Indonesia until World War Two.

Jordan: Not even close. The Dutch word for orange is *sinaasappel*. Actually, the orangutan's name comes from a native phrase that means "man of the forest", *orang hutan*.

Florence: J'en ai apercu lors de mon voyage sur l'île indonésienne de Bornéo, et c'est vrai qu'on aurait dit un homme des forêts.

Jordan: Besides being home to the orangutan, Borneo boasts some of the world's greatest biodiversity in both plants and animals, including local varieties of leopard, elephant, and rhinoceros. There are about 15,000 species of flowering plants and 3000 types of trees. Here is a carnivorous pitcher plant. You know that it is a tough neighborhood when even the plants can trap and kill animals.

Florence: Ces petits animaux connaissent leur douleur quand ils plongent la tête la première dans ce soit-disant pichet de vin rouge! Bien que l'Indonésie possède l'une des jungles les plus primitives sur terre, sa population est très dense et son agriculture intensive.

Jordan: With the world's fourth-highest population, behind China, India, and the US, Indonesia cannot all be jungle. Intensive agriculture is necessary to sustain that population.

Janna: Agriculture is enhanced by a combination of tropical rainfall and frequent volcanic ashfalls. Indonesia extends for 5300 kilometers (3300 miles) along the equator, so it is drenched in the afternoon showers that result from the daily cycle of atmospheric convection.

Jordan: Indonesian volcanoes erupt even more frequently than in most other parts of the so-called Ring of Fire that surrounds the Pacific Ocean.

Janna: Despite being one of the world's greatest sources of petroleum, Indonesian agriculture is less mechanized than that of petroleum-poor places like Europe.

Jordan: The Indonesians export most of their petroleum and rely on cheap human labor along with even lower-paid water buffalos, as seen here.

Florence: Les Indonésiens ont été sous tutelle étrangère pour tellement longtemps qu'elle n'est pas évidente qui décide qu'elles devraient exporter leur pétrole et compter sur des buffles de l'eau.

Jordan: It is indeed true that there are few countries in the modern world that are truly independent, no matter what their constitution may say. It does seem unlikely that the Indonesians willingly export their voluminous petroleum production while relying upon water buffalos at home.

Janna: Ever since the Dutch East India Company became established in 1602, the Indonesians have been dancing to somebody else's music. However, they have remained mostly Muslim even though none of their foreign rulers have been Muslim.

Florence: Leur fidélité à l'Islam vient peut-être en réaction contre les chrétiens et Shintos japonais qui les ont dominé pendant si longtemps. Tenez, voici une mosquée que j'ai visitée.

Jordan: Their faithfulness to Islam may well be some type of protest against foreign rulers.

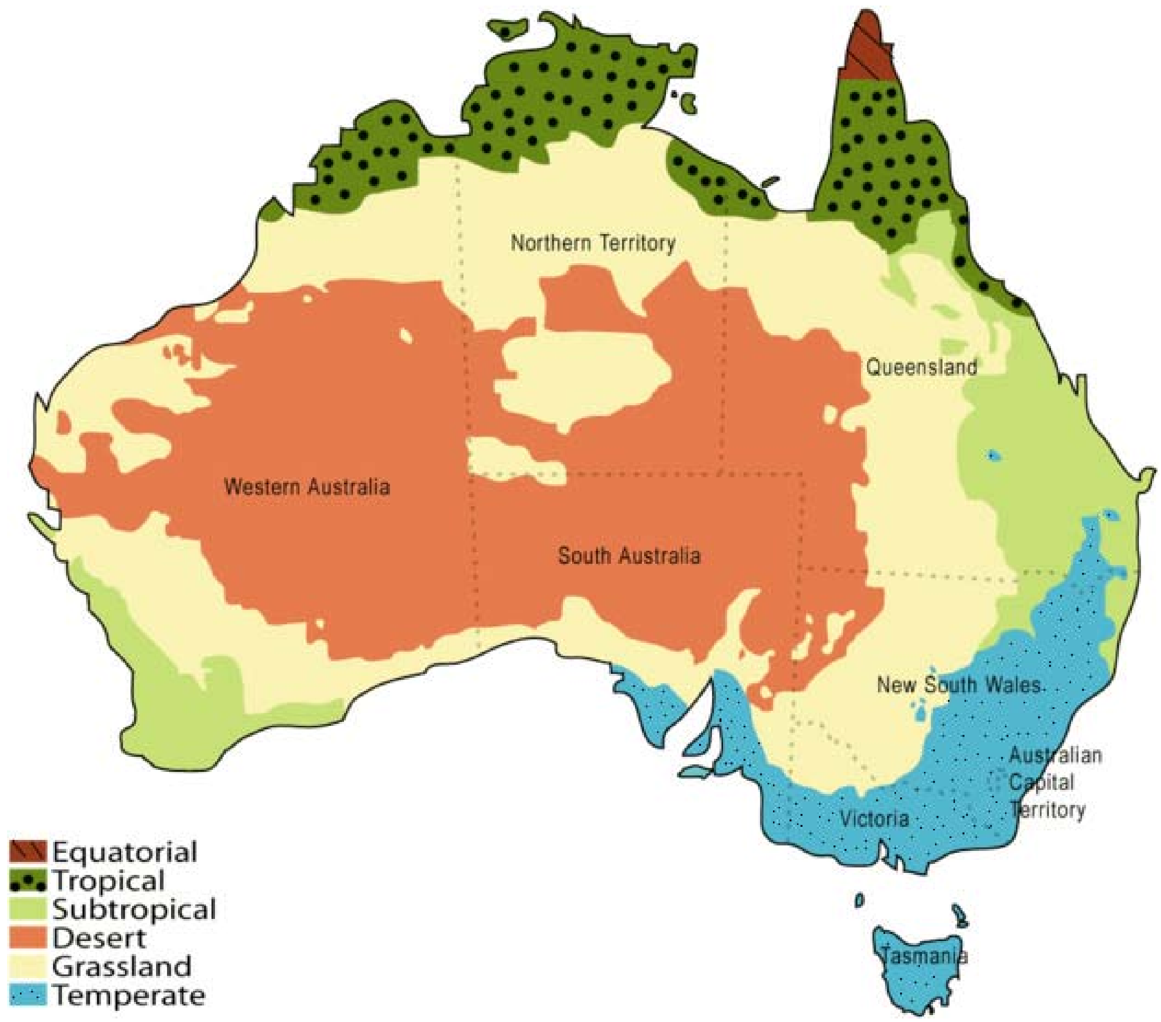
Janna: Before leaving Indonesia, please show us at least one volcano that you saw there.
Florence: Aquí están algunos volcanes que son tan activos que han matado a todas las plantas.

Janna: If those volcanoes can turn jungle into a wasteland, then they must be lethally active.
Jordan: Maybe it is time for us to head southeast to Australia.
Florence: Rendons-nous à présent en Australie, en commençant par l'Australie tropicale humide du nord. Voici une photo de nuit d'un orage d'été au dessus de la ville côtière nordique de Darwin.
Jordan: Darwin, Australia lies about 12.5 degrees south of the equator. That takes it out of the year-round humid zone and places it into the realm of summertime rainfall, as we see here in your photo of a nighttime storm.
Janna: Of course, summer in Australia occurs during America's winter months.

Jordan: It is difficult for me to imagine that being humid and tropical would mean being in the northern part of a country, but I guess that geography is different "down under". This climatic map looks like a bull's eye with a central desert.

Janna: Darwin lies in the middle of the northern coast, within the tropical zone, whereas the subtropical to temperate zone lies mostly along the eastern coast.

Jordan: Australia's largest cities lie along that eastern coast whereas desert stretches all the way to the western coast. This east-west difference must have something to do with marine currents.



Janna: Marine currents in the Pacific mimic those of the Atlantic because Earth's rotation and associated winds drive surface currents in both oceans.

Jordan: As the solid Earth rotates under both its water and wind in the tropical Pacific, Indonesia blocks further westward migration and forces the water to split into the northward-flowing Kuroshio and the southward-flowing Australian current.

Janna: The Australian current brings warmth and moisture to the cities along the eastern coast of Australia.

Florence: Capitán Cook era el primer para planear la costa del este de Australia y al circumnavigate Nueva Zelandia.

Janna: It seems that Captain Cook got everywhere, charting and claiming both Australia and New Zealand for the Brits. Tens of millions of people owe their homesteads to that early oceanographer. Sydney alone has nearly four-and-a-half million residents.

Jordan: That's bigger than most famous cities in America. A periscope view of Sydney's opera house is so distinctive that it could not possibly be confused with anywhere else.

Florence: Un périscope? Pourquoi regarderiez-vous Sydney par l'intermédiaire d'un périscope? Si vous avez vraiment l'intention de parcourir le grand système de récif de barrière de l'Australie du nord-est dans un sous-marin miniature, faites-bien attention à éviter les tortues vertes comme celle-ci.

Jordan: I suppose that someone in a tiny submarine might be concerned about running into one of these meter-long creatures in the Great Barrier Reef system of northeastern Australia. However, a green sea turtle would lose in an encounter with a larger vessel.

Janna: One-man and two-man submarines were commonplace during World War Two for spying on enemy harbors, but they are too dangerous to be a recreational vehicle. When we finally recaptured the western Aleutian Islands from the Japanese, we found the remains of some tiny submarines. We have even dredged them from Pearl Harbor. The mortality rate for those submariners must have approached that of kamikaze pilots.

Jordan: Of course, the objective of every military power on Earth was to hunt those spying submariners to extinction. Green sea turtles were the least of the submariners' problems.

Florence: Bon, soyons courageux. Naviguons en diagonale à travers l'océan pacifique, du sud-ouest au nord-est, en passant par la Nouvelle-Calédonie, le Fiji, et le Samoa avant d'atteindre la province de Colombie britannique au Canada.

Jordan: Sailing across the enormous Pacific Ocean all the way to Canada must have tested your courage but you did get to see New Caledonia, Fiji, and Samoa.

Janna: New Caledonia is best known for supplying a quarter of the world's nickel. With every fourth nickel that I spend, I think of this tropical paradise.

Jordan: It looks as if that rock is so poor in nutrients that plants are finding it difficult to survive, despite receiving a couple meters of rainfall each year.

Janna: Half of the rocks on New Caledonia are very poor in potassium, one of the essential elements for plant growth. The nickel is mined from soil that has developed on rock from the Earth's mantle. Mantle rock contains about one-quarter of one percent nickel, but this nickel becomes augmented to a couple percent when more-soluble elements wash away during weathering.

Florence: Nueva Caledonia es una isla bastante grande, con casi 20.000 kilómetros cuadrados, Pues, hay más a ver que suelo niquelífero. El filón de barrera está en segundo lugar solamente al filón australiano.

Janna: If New Caledonia has the world's second-longest barrier island system, then there should also be some nearshore islands that are undercut by wave erosion.

Jordan: We are not going to be swimming around those islands, so where are the pocket beaches?

Janna: New Caledonia is French Territory, so you never know what you might see on one of their beaches.

Jordan: Florence's brother, Pierre, snatched all the good snaps. Did he leave anything?

Florence: Voici la seule photographie de plage qu'il me reste.

Jordan: This little pocket beach certainly is inviting. I can see a sea arch on the side of the headland. That must have been weak rock that was easily eroded by the surf.

Florence: A chaque fois qu'un promontoire est coupé comme celui-ci, nous l'appelons "percé".

Jordan: I have found another “pierced rock” in your photo collection, officially named Percé. This is the Atlantic seaboard’s most famous example. Of course, it is in French Canada, north of Maine. When my parents took me to see Percé, I first thought it was a big ship.

Florence: Si on navigue vers le nord-est, on atteint la province canadienne de Colombie britannique.

Jordan: I bet that the Canadian province of British Columbia gave you a bit of a shock after leaving the paradise islands of the South Pacific.

Florence: Quand j'ai visité la ville touristique de Whistler, j'ai d'abord cru observer des marins polynésiens… C’est alors que je me suis rendu compte que ces Canadiens naviguaient en fait sur la glace.

Jordan: This guy may initially resemble a Polynesian wind-surfer in the South Pacific, but at the Whistler Resort in British Columbia, wind-surfing is done on ice.

Janna: The British Columbian coast offers spectacular scenery because its mountains have all recently had glaciers eroding away their sides, producing steep cliffs. I found this photo of Mount Robson, peaking above the clouds to four kilometers in elevation.

Florence: A pesar de ser un aventurero, no tenía ningún impulso de subir esa montaña.

Jordan: Perhaps mountain-climbing is indeed rather challenging in British Columbia but the waterfalls are truly beautiful, complete with a rainbow.

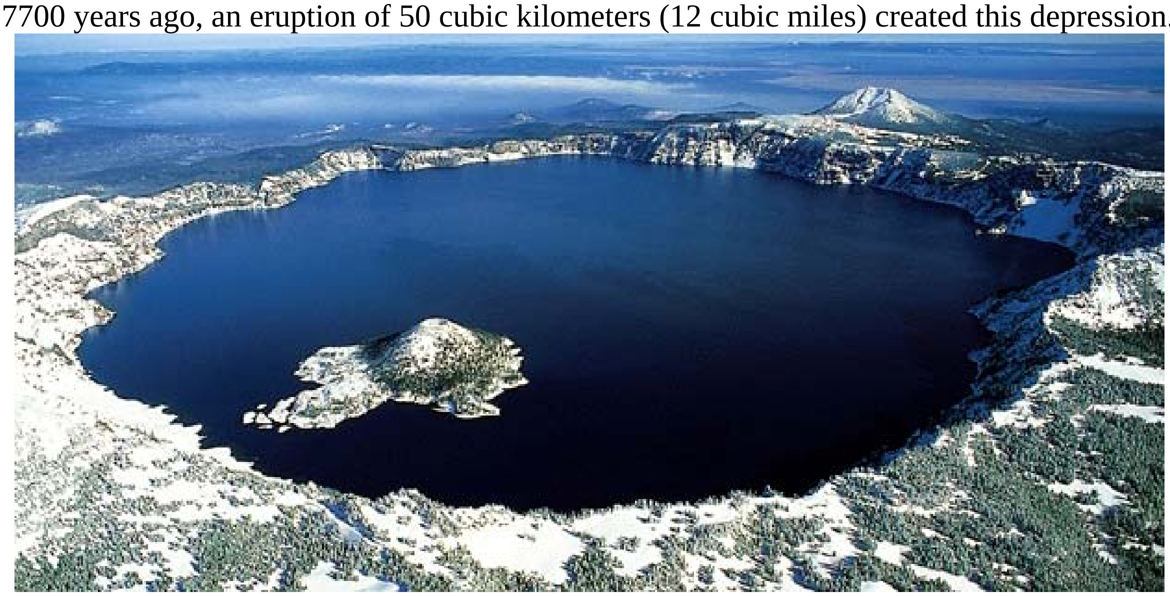
Florence: Finissons notre excursion Pacifique, en descendant tout au long de la côte américaine en direction de San Francisco. Voici comment la bougeoisie se promène le long de la côte occidentale des Amériques.

Jordan: That's a Seattle ferry. That's how the bourgeoisie get to see what you have gotten to see with your family yacht.

Janna: Washington State is famous for its active volcanoes. Did you take any photos of threatening volcanoes to compare with those of Japan?

Florence: Aquí está el Montaje Rainier, amenazando Tacoma.

Janna: If I were living in Tacoma, Washington and woke up to that view every morning, I would try to learn which Buddhist god appeases the evil spirits of volcanoes. Of course, living beside America's biggest caldera in nearby Oregon is similarly dangerous. About 7700 years ago, an eruption of 50 cubic kilometers (12 cubic miles) created this depression.



Florence: Finalmente llegué en San Francisco y vi todas las vistas clásicas allí.
Janna: Ay yes, the Golden Gate Bridge. You know, it looks more like red to me.

Florence: Usted está conjeturando bien las localizaciones de mis fotos. Veamos si usted puede conjeturar adonde éste fue tomado.

Janna: I must admit that it is not too tough to guess where that photo was taken. Why is it that every disaster movie set in Los Angeles has to show those letters swaying and then toppling?
Jordan: I suppose that it is easier to make miniatures of letters than of buildings.
Janna: There are nearly 18 million people living in metropolitan LA whereas back in 1820, there were only 650. At that time, Boston had about seventy times more people than LA. LA's growth spurt must make it the world's fastest-growing city outside of China and India.
Jordan: The local beaches must have taken a beating as this population exploded. To add insult to injury, they exported the beach sand that we saw earlier at Waikiki, Hawaii. Here is one of the most-impacted beaches, the Los Angeles suburb of Huntington.
Janna: Huntington sits on top of an oil-producing salt dome that once made LA the source for one-quarter of the world's oil supply.
Jordan: The city includes the delta of the Santa Ana River. Occasional flooding of that river spoils the beach.

Florence: Quittons la Californie à la région limitrophe mexicaine.
Jordan: As we keep heading south into Mexico, down the Baja California peninsula, the climate becomes increasingly arid.

Florence: Après que nous voyagions au sud de Baja, nous atteignons Acapulco, une halte de choix des bateaux de croisière.
Jordan: Cruise ships do like Acapulco so we should make a quick stop there to see why.

Jordan: Acapulco looks considerably more inviting than Baja, I must say.
Florence: Si vous aimez Acapulco, alors vous aimerez également le Costa Rica.
Jordan: For the past thirty years, American institutions have consistently favored Costa Rica as a tourist destination. In fact, a lot of Americans live there. Given its tropical volcanoes, Costa Rica does offer some spectacular scenery, such as this waterfall.

Janna: Next comes Panama. I wonder if anyone has managed to sneak a submarine through the locks.

Florence: ¿Usted desea hacer furtivamente un submarino a través del Canal de Panamá?

Janna: Just a thought. Let's move on to Colombia. Panama used to belong to Colombia until we helped to liberate it, about the time that we decided to take over the French canal project.

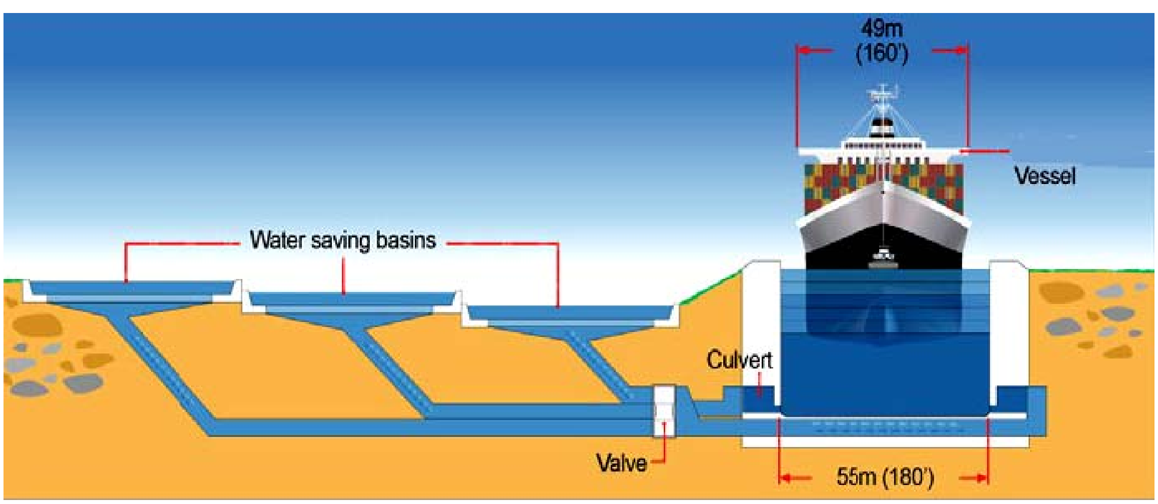
Jordan: I am sure that it was easier to negotiate canal-building with a few Panamanians than with several million Colombians.

Janna: Colombia was more powerful then than now. The Spanish in Colombia had large and sophisticated cities by the time the Mayflower dropped anchor at Cape Cod, Massachusetts, in 1620.

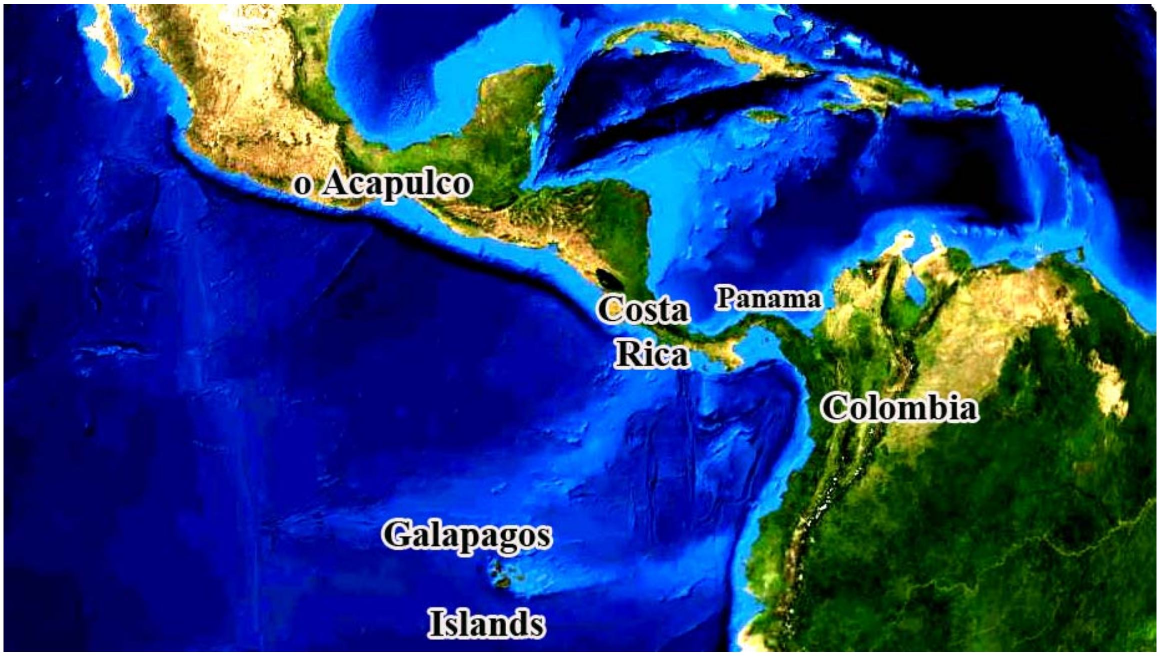
Jordan: About a decade before starting the Panama Canal in 1880, the French had completed the Suez Canal in Egypt. Each of those projects cost about 30,000 lives to complete.

Florence: Nous, les français, avons perdu presque autant d'hommes dans notre tentative de construction du canal que pendant la bataille de Waterloo, c'est à dire environ 22,000. Les américains en ont perdu encore 8000 après qu'ils aient repris le projet.

Jordan: Having been completed nearly a century ago, the canal is currently being upgraded with modern locks.



Florence: La Costa Rica n'est pas le seul endroit hispanique que les américains aiment visiter. Les américains aiment également se rendre dans l'endroit rendu célèbre par Darwin, les îles du Galapagos. Laissez-moi vous montrer sur une carte comment vous y rendre.



Jordan: The Galápagos made Darwin famous because he realized that the volcanic islands had grown above sea-level far from shore and were barren of life when they first emerged. It was difficult for any terrestrial life to reach the islands and become established.

Janna: Once established, they had essentially no competition, so they could evolve as if they were on a separate planet. The result became lots of species that are unique to the Galápagos.

Jordan: If you want some good reading on a long cruise, I would suggest Darwin's book about his five-year-long cruise around the world, Voyage of the Beagle. This was written a couple of decades before he became famous.

Janna: You do not have to spend money on this book because you may read it freely on the Web.

Florence: El éxito del libro de Darwin ha animado a otros autores que escriban sobre navegación alrededor del mundo.

Janna: I suppose that this record of your exploits with the family yacht is yet another example of somebody trying to imitate Darwin's masterful tale of circumnavigation.

Jordan: I hear that Darwin rewrote his book several times through the years, as he developed his concepts of evolution.

Janna: Is that like fudging your experimental results after you learn what the textbook result is supposed to be?

Jordan: I must admit that I started doing that in a laboratory course when I found that my lab partner was getting much higher grades by fudging his results. Was that unethical?

Janna: Of course it was unethical. It was also unethical for your teaching assistant to be grading you on your proximity to textbook results rather than actually checking your procedure.

Florence: Antes de que ustedes pierdan todos las consideraciones éticas les tomaré a lo largo de la costa de Suramérica, a Chile.
Janna: Before continuing on to Chile, I want to see the Galápagos iguana, the world's only swimming iguana. Iguanas are so ugly that they are beautiful.

Jordan: I suppose that if you on a barren Galápagos island, you had better learn how to swim if you are going to get enough to eat.
Janna: I see that he is perched on a dipping block of vesicular basalt. I recall that we found similar gas holes in some of the Hawaiian basalt.
Florence: Ya basta. Vamos a Chile. Aquí está un volcán en Chile norteño.

Janna: I must say that this smooth-surfaced volcano resembles all the other active andesitic volcanoes that we have seen around the Pacific rim. However, the animals are different. Are these llamas?
Florence: Si. Éstos son algunos animales muy inteligentes que aprenden rápidamente cómo ser animales útiles del paquete. Continuaremos yendo hacia el antártica.

Janna: A glacier in Latin America? We must have reached the part of Chile which lies closest to Antarctica.

Jordan: As they say in New York, we have **done** the Pacific, so now we need to slip through the Straits of Magellan into the Atlantic and explore Argentina. Before we leave Spanish America, we should pay our respects to the many cathedrals that were built in the 1600's. This is Argentina's cathedral in Cordoba, a city with 1.3 million residents.

Florence: Les conquérants ont dépensé autant dans la construction des cathédrales que nous dépensons aujourd'hui en faisant des films. Poursuivons vers le nord jusqu'au Brésil, qui est le seul pays de langue portugaise en Amérique du sud.

Jordan: Brazil is the world's fifth-most-populous country, with 190 million people.

Janna: As is evident in this photo, a lot of Brazilians live within a stone's throw of the ocean, making any rise in sea-level a serious economic threat. Recife lies in northeastern Brazil, where the Brazilian Current brings tropical warmth and 2 meters of rainfall annually. Recife means "reef" in Portuguese, as is evident in this photo.

Jordan: If we reach Rio de Janeiro, we will not be able to miss Christ the Redeemer as he gazes down upon the city and its harbor.

Janna: That Brazilian statue has become one of the seven modern wonders of the world.

Florence: Nous traverserons les Caraïbes sur notre chemin au littoral oriental des USA.

Jordan: Hey, that's the fort guarding Havana harbor, built thirty years before the Mayflower landed.
Janna: I thought that there was a travel ban on Cuba. How did you manage to get there?
Florence: Soy francés. Los franceses no excluyen a su gente de lugares interesantes.
Janna: I guess that only Americans face travel restrictions. Cuba must be a pretty place. Diego Columbus, son of Christopher, got the King of Spain to make him governor of Cuba.
Florence: A le no se permite estar en Cuba, así que debo tomarle de nuevo a Norteamérica.
Janna: Let's stop in Charleston, South Carolina, and check out their new bridge. I hear that it is the longest cable-supported bridge in the Western Hemisphere.

Jordan: I love walking around downtown Charleston and learning about the history of the South. The Civil War started there when General Beauregard opened fire on the federal fort in Charleston harbor, Fort Sumter. In 1864, an eight-ton Confederate submarine, the Hunley, sank an 1800-ton federal warship in Charleston harbor. This was the first warship ever sunk by a submarine.
Janna: Of course, the Hunley also sank, so it was not a complete victory. By the time federal troops entered Charleston in 1865, they had shelled much of the city into heaps of rubble.
Jordan: Twenty-one years later, Mother Nature created her own heaps of rubble when an earthquake measuring 7.5 on the Richter scale brought down 2000 buildings. Charleston had just barely recovered from the war damage when rebuilding had to start all over again.

Janna: Many buildings in downtown Charleston still display a smart engineering trick that they used for houses which had flopped open but not fallen. To cram as many houses as possible along Charleston's original streets, they kept the houses narrow and deep. After the earthquake turned those narrow houses into "flop houses" by pulling the walls apart, the engineers inserted steel rods and screwed the walls back together.

Jordan: You can still see the rods and washers holding the old houses together.

Florence: Après vous avoir montré une imitation de la statue de la liberté à Tokyo, je me dois de vous montrer la vraie statue à New York. Relativement peu d'américains réalisent que cette statue a été conçue, financée, et construite par les français.

Jordan: The Statue of Liberty was indeed a French project from start to finish. It is ironic that President Cleveland got to bask in the glory of its inaugural after vetoing a bill to finance just the pedestal while he was governor of New York.

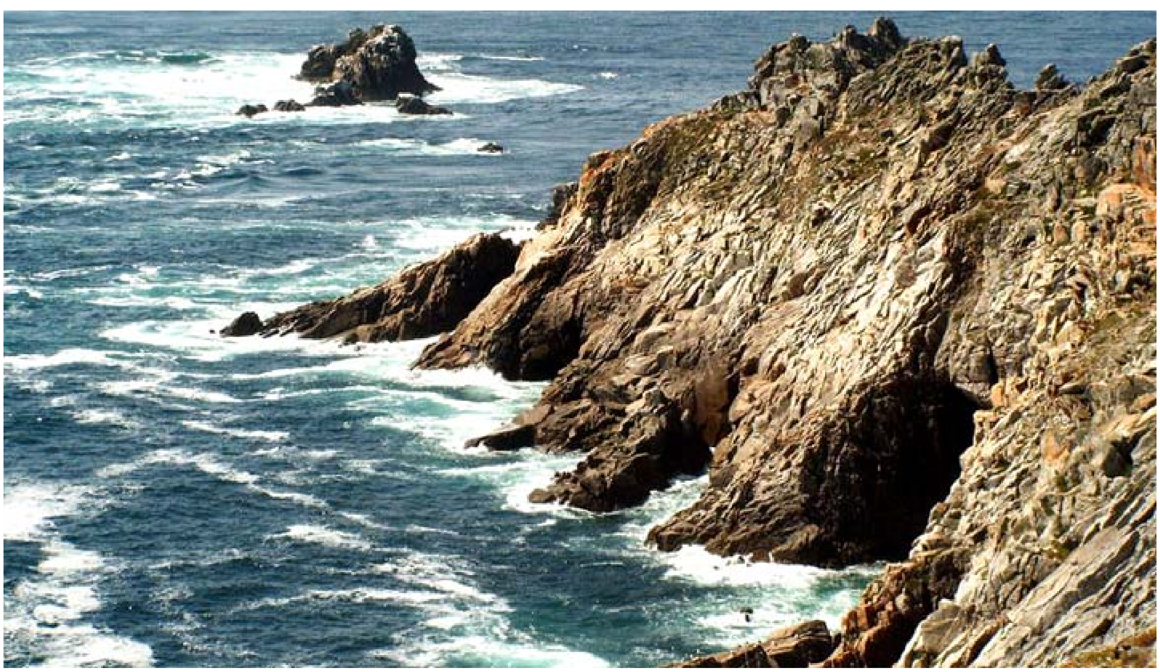
Janna: For all the French influence on America, from the War of Independence to the Statue of Liberty, not that many French came to live here. I guess that they were just too comfortable in France.

Jordan: Germany was the biggest source of Americans, even though those transplanted Germans ended up fighting their former countrymen in a couple of world wars.

Florence: J'ai hâte de vous montrer ma patrie, France. Voici la côte raboteuse de Bretagne où les roches métamorphiques résistent à la puissance érosive de l'Océan atlantique.

Jordan: I was wondering when you were going to show us your homeland. The peninsula of Brittany is populated by tough remnant rocks and tough remnant people. The remnant people are the Celts who were pushed to the fringes of Europe by invading Romans and Germans about 2300 years ago. These fringes include Ireland, Wales, and Scotland, as well as Brittany, the northwestern corner of France.

Janna: These remnant rocks are some of the oldest and most deformed in France. One has to be tough to face the storms of the North Atlantic Ocean.



Jordan: The Celts of Brittany have certainly faced the ravages of invasions by mainline French throughout the past millennium. A ban on speaking their Celtic language has resulted in a sharp decline in native Celtic speakers over the past fifty years.

Florence: Beaucoup de Britanniques riches ont des maisons d'été ici. Une amie a une maison qu'elle appelle la petite Grande-Bretagne pour la distinguer de Grande-Bretagne.

Jordan: I suppose that the name, Great Britain, dates from the time when England was largely Celtic and they had to distinguish between big Britain and little Brittany.

Janna: I always thought that "great" meant "great" and that we would soon be talking about the Great USA since we are the only remaining superpower.

Jordan: However, President Nixon kept warning us that superpowers do not last forever.

Florence: Oui, peut-être que vous devriez rebaptiser les Etats-Unis “les grands Etats-Unis” avant que les chinois ne vous surpassent. Déplaçons vers le sud, au bout méridional du Portugal, l'Algarve.

Jordan: The Algarve of Portugal makes a perfect next stop. I love these sea stacks, cut into flat-lying limestone that contains a high proportion of sand.

Janna: Sandy limestone is called marl and is quite common around continental coasts, as opposed to the pure limestone that one finds in an open-ocean region such as the Bahamas.

Jordan: I have learned that any word starting with “al” is likely to have an Arabic origin, such as algebra and almanac, so I suppose that the Moors used to control the Algarve.

Florence: Oui. Le Maroc se trouvent au travers du détroit de Gibraltar.

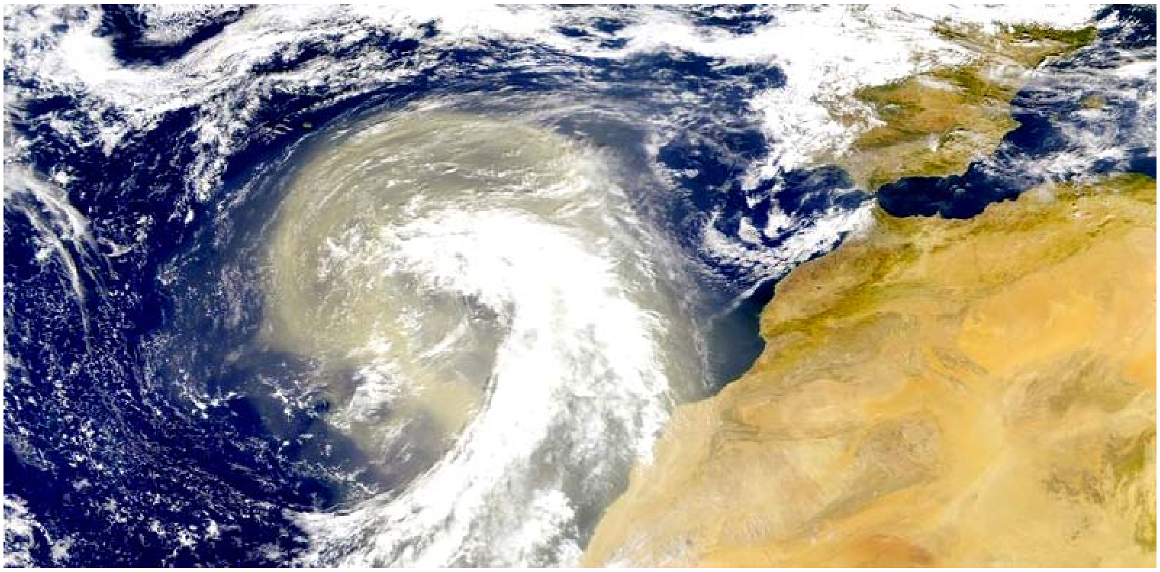
Jordan: By the time we reach Morocco, the semi-arid conditions of the Algarve have degraded to desert conditions.

Janna: The same, southward-moving cold current is to blame, the Canary Current, because its Icelandic water does not give rise to much evaporation, hence little rainfall.

Jordan: Morocco is one of those peculiar places where one can find desert dunes marching directly into the ocean.

Janna: Swirling updrafts of hot air from that desert continue across the Atlantic Ocean and appear on our shores as hurricanes. Did you encounter any turbulence as you sailed your yacht along the Moroccan Coast?

Florence: Sí. Yo busqué en el Internet hasta que encontré esta foto basada en los satélites.



Janna: That was a smart thing to do because you could then see where to sail your yacht away from the worst of the storm.

Jordan: I see that this dust storm is the size of a hurricane and has the same counter-clockwise rotation pattern that characterizes all northern-hemisphere hurricanes.

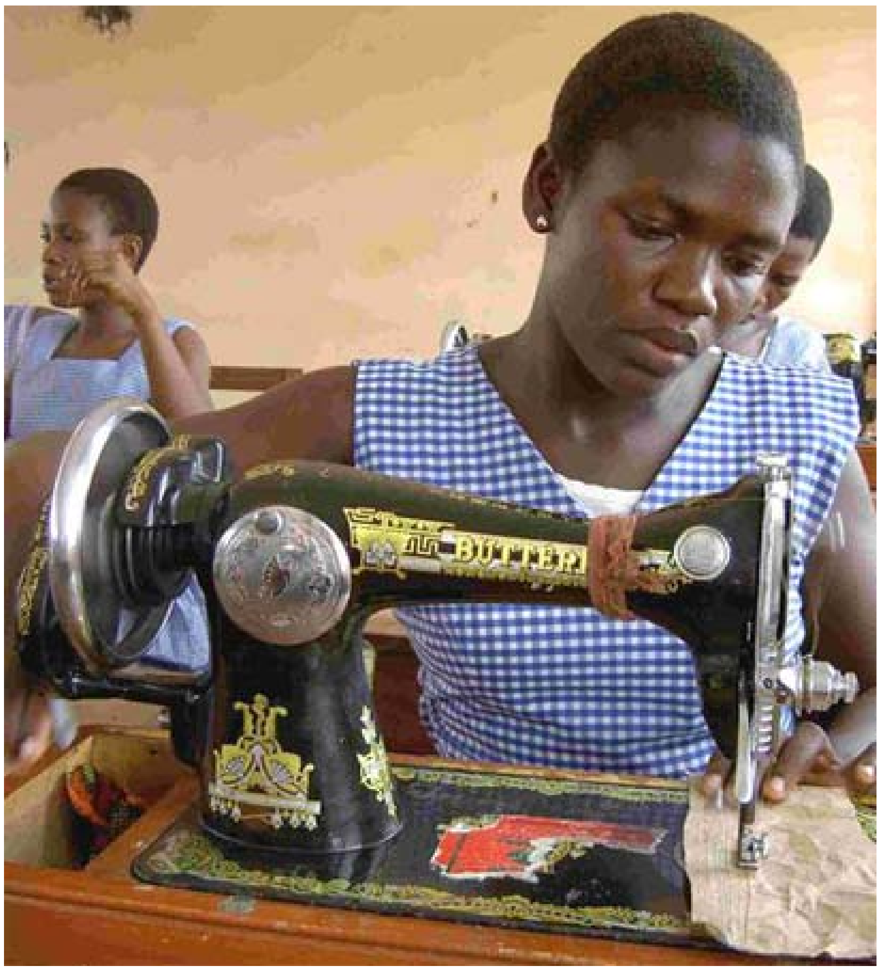
Florence: Laissez-moi vous amener le long de la côte africaine occidentale dans un pays qui a été longtemps sous l'influence americaine: le Libéria.

Jordan: Liberia has been essentially owned by America since 1822 when the American Colonization Society established Liberia as a place to send freed slaves. Lincoln himself supported this plan.

Janna: However, the past quarter-century has been rather turbulent as the locals have attempted to wrest control of the country from those who have ancestral ties to American immigrants.

Jordan: Liberia is not a prime destination for Americans these days but another country half way between Liberia and Nigeria receives a lot of Study Abroad students. That is Ghana.

Janna: Ghana's poverty is typical of Third World countries, so American students encounter crude conditions as they attempt to help the locals.



Jordan: Nigeria is the most populous country in Africa and the eighth-most populous country on Earth, given more than 140 million citizens.

Janna: In America, Nigeria is best known as being the apparent source of most email scams. However, even a cursory study of email patterns reveals that there must be an alternative source that masquerades as being Nigerian.

Jordan: If you are smart enough to send the majority of America's computer-based scams, then you must be smart enough to hide your true identity.

Florence: Même alors que j'étais sur mon yacht, j'ai reçu un bon nombre d'emails fraûduleux nigérians. J'ai quelques amis au Nigéria à qui j'ai demandé de ne plus m'envoyer d'emails parce que je supprime automatiquement tout email en provenance du Nigéria.
Jordan: I suppose that lots of legitimate emails from Nigeria get trashed these days because they are considered to be just more scam.
Janna: Let's continue to Africa's central country, the Congo, home to the world's second-most-voluminous river, also called the Congo.
Jordan: The Congo is a mirror image of the world's biggest river, the Amazon, on the opposite side of the South Atlantic. Besides coming in second in annual discharge, the Congo also comes second to the Amazon in total drainage area and in rainforest area.

Florence: Quand j'ai vu le fleuve du Congo, il m'a semblé si large que j'ai cru voir un lac.
Jordan: The Congo is so wide that it really does look more like a lake than a river.

Janna: Given its central location in the continent, the European powers gave Congo to the King of Belgium in 1885 in exchange for him becoming the arbitrator for disputes among the colonial forces that controlled the rest of Africa. One man owned the world's second-biggest drainage basin and exploited its local population mercilessly to harvest rubber from its trees.

Jordan: In 1905, Mark Twain wrote a stinging satire about that Belgian King, "King Leopold's Soliloquy", and that shamed the Belgian government into replacing their overzealous king with dispassionate bureaucrats to administrator the Congo.

Janna: As a result of Mark Twain's satire, the lives of millions of Africans improved dramatically.

Florence: Continuemos viajando al sur, a Angola.

Janna: The Portuguese established a colony at the mouth of the Congo nine years before Columbus found America and then moved a little south to Angola in 1575 with the purpose of exporting slaves, mostly to their colony in Brazil.

Jordan: The Portuguese in Angola were the world's prime slavers for nearly three hundred years. The demand for slaves was high because the mortality rate was so horrible in Brazilian mines and sugar cane plantations.

Janna: In contrast, the mortality rate for slaves in North America was low because they received much better care than in Brazil.

Jordan: In fact, African slaves in the US commonly received better treatment than did white indentured workers. Those workers had to serve for a given number of years to pay for their passage to America. Indentured European men tended to be worked to death because they would be of no value anyway after their term of indenture expired.

Florence: Voici Luanda en Angola, un port où des millions d'esclaves ont été traités.

Jordan: So this is Angola's infamous port of Luanda, from which millions of slaves were shipped to the Americas.

Janna: Somewhere between eleven and twenty million Africans were exported from all the ports, but this port was the busiest.

Jordan: I cannot imagine the anguish of families being separated forever as they were herded onto separate slave ships here in Luanda.

Janna: The image of a Coke™ bottle covering the entire wall of a Luandan skyscraper seems out-of-place here, given that Coke™ consistently presents itself as the purveyor of happiness and good times.

Jordan: The Luandan slave trade was nearly three hundred years of decidedly bad times for millions of innocent people.

Florence: Partons par Capetown dans la République de l'Afrique du sud.

Jordan: This is not what I expected to see in Cape Town, within the Republic of South Africa. This scene looks more like Europe than Africa, with American-style yachts and Dutch architecture. The famous Table Mountain forms the horizon.

Janna: Table Mountain is capped by an erosion-resistant unit of metamorphosed sandstone. Here we can see it from a different angle, showing the extent of South Africa's second-largest city.

Jordan: A satellite view provides a regional perspective. Here Table Mountain lies in the foreground, right next to the sea. Spread inland along the bay is Cape Town.

Janna: I can understand why the Dutch East India Company established a settlement here in 1652. It was a long way from the Netherlands to Indonesia and this provided a way station.

Besides, the climate in Cape Town is the coolest in Africa, making it most like the Netherlands.

Jordan: That similarity in climate attracted a lot of Dutch settlers whose descendants continue to dominate South Africa, despite giving the presidency to an African.

Florence: Il est temps de se rendre à Madagascar dans l'Océan Indien.

Jordan: I know why you want to sail to Madagascar. That's French territory, or at least it used to be French territory. The French attacked the capital city in 1895 and lost only 20 men in capturing it.

Janna: Nonetheless, the French lost 6000 to malaria and other diseases in the ensuing months.

Jordan: Madagascar figured in one of Hitler's crazy schemes. While he was capturing Paris, he was planning to exile all of Europe's Jews to Madagascar.

Janna: Come to think of it, that might have been better than concentration camps in frigid Poland, provided that they allowed the use of anti-malarial medicine.

Jordan: Hitler's plan for Madagascar was thwarted by a British invasion in the summer of 1942. Japanese submarines came to torpedo the British supply ships but the British survived to hold the island.

Janna: Madagascar is important on a global scale for its ecological diversity. Of its ten thousand plants, ninety percent are known only within Madagascar.

Jordan: Ecological diversity is enhanced by highly irregular karst landscape. Karst may form when the bedrock is limestone and that limestone has developed caverns through selective dissolution by groundwater. Collapse of cavern roofs leaves pillars between the collapsed caverns, as shown here from Madagascar.

Florence: A présent, dirigeons-nous vers nord pour atteindre la Somalie.

Jordan: OK. We move on to Somalia. US forces entered Somalia in 1992 in a humanitarian effort designed to alleviate the starvation that was resulting from civil war. Local warlords had effectively divided Somalia among themselves and were disrupting the food supply.

Janna: American troops found Somalia to be a strange place. Here in an arid open-air market, we see that umbrellas are used for protection from the sun rather than from the rain.

Florence: A medida que continuamos nuestro circuito a la derecha del Océano Índico, alcanzamos Paquistán.

Janna: Our clockwise tour of the Indian Ocean takes us to Pakistan, the world's sixth-largest country. However, I hope that our cruise to Pakistan will not bring us into the middle of a Pakistani naval exercise like the one you encountered.

Jordan: I see that each of those warships is equipped with a helicopter pad to hunt for submarines.

Florence: Faisons un detour pour éviter un conflit armé et ses consequences désastrueuses, et visitons une région où un désastre encore plus grand s'est produit en décembre 2004, ou plus précisemment un tsunami.

Jordan: The Indonesian earthquake right after Christmas in 2004 killed more than 230,000 people along the coasts of Indonesia, India, Sri Lanka (Ceylon), Myanmar (Burma), Thailand, and even eastern Africa.

Janna: This was one of the greatest natural disasters of all time. Only earthquakes within China, given its high population, have managed to kill more people.

Jordan: Epidemics such as the plague, cholera, and Spanish influenza have been the all-time champion killers throughout history. War has come next. However, I suppose that earthquakes and related tsunamis have come in third.

Janna: Earthquakes and tsunamis may soon rise to the top of that list because modern medicine seems to be controlling deadly epidemics and superpowers are not going to allow local wars to disrupt trade for very long.

Jordan: I have noticed that the flow of Iraqi oil has not been disrupted by squabbles in that country. As long as there are no stray bullets hitting oil pipelines, we do not seem to be particularly concerned about a few bullets flying around there.

Janna: Iraqis have had plenty of warning about increasing hostilities but the poor folk living around the Indian Ocean had no warning about an incoming tsunami.

Jordan: Earthquake-measuring devices, seismometers, must have been jumping off-scale all around the Indian Ocean for a couple hours before the tsunami reached India and Sri Lanka, where most people died.

Janna: Hundreds of Indian scientists must have realized that there was a high probability of a tsunami and they surely reported that concern to the relevant political leaders.

Jordan: Even though there was no system of sirens to alert coastal dwellers, the political leaders could have contacted TV and radio stations. This was a daytime disaster. It occurred when the vast majority of people would have had a radio playing in the background.

Janna: The total lack of any warning in any country was virtually criminal. One can only hope that such collective incompetence will not be seen again.

Jordan: We should get Florence to publish her travelogue in the hope that scenes like this one will never again prove to be so lethal.

Florence: C'est une photographie de l'Indonésie que nous avons déjà visité. Ainsi nous avons voyagé autour du monde entier.

Jordan: If all these drowned people are in Indonesia, a country that we previously visited, then we have indeed completed our world tour. I think that I can manage to enunciate one French word for Florence, "merci".

Janna: From me, it will have to be "muchas gracias".

Jordan: You must have fond memories from your trip.

Florence: Tout à fait. Merci de m'avoir laissé partager ces photos et le souvenir de toutes ces expériences.

Jordan: Perhaps Janna and I will attempt a tour that will be more technically challenging than sailing a yacht, but something tells me that you guys from France have a better appreciation for having a good time.

Janna: This travelogue has taught me a lot of coastal geology but I am still itching to learn something about the creatures that live in the sea, considering that we are planning to live within the ocean for a whole year ourselves.

Jordan: I have hired Dr. Fondah and some of her students to give us some lessons in marine biology. As soon as she has taped those lessons, we can watch them together.

Janna: I certainly hope that her first student is not studying under Dr. Bubah.

Jordan: He might be. I asked him what the first rule of the sea is. He replied that big fish eat little fish.
Janna: What's his name?
Jordan: Ben.
Janna: Is that Ben as in Big Ben, the clock on England's Parliament?
Jordan: Compared to Dr. Bubah, even Parliament's clock is just Little Ben.
Janna: OK. You go and try to find a French chef for us while I watch Ben eating fish.
Jordan: Perhaps Florence could help Dr. Fondah cook up some marine delicacies for her video.
Janna: I can already smell the lobster tails simmering.

Chapter 7: Small Fry

Dr. Fondah: Thanks for inviting me and my student, Ben, to your apartment here in New York and offering to help us with our video on marine biology. I can only dream of having an apartment some day in Paris. I hope that you are going to speak in English because French technical terms are beyond my comprehension.

Florence: Naturellement, je parlerai en anglais si c'est ce que vous préférez.

Ben: Daaaah….

Florence: I was just kidding, Ben. I said, "Of course, I will speak in English if that is what you prefer."

Dr. Fondah: Trust me. That is what Ben would prefer.

Florence: Well, Ben, have you ever been to Paris?

Ben: Only in my dreams.

Florence: I suppose that that is true for the vast majority of the world's population. Perhaps this video will make you so famous that Parisian movie directors will invite you to visit.

Ben: Hey, now **you** are dreaming.

Florence: More realistically, there might be room for you on my yacht when I return home in a week or two.

Ben: You **do** know how to get a guy to behave himself.

Dr. Fondah: If I could bribe **my** students with a Paris-bound yacht trip, I am sure that the whole class would behave like heavenly angels, instead of like Charlie's Angels.

Ben: French documentaries are what originally attracted me to marine exploration, especially the 120 documentaries by Jacques-Yves Cousteau. I have heard that Cousteau got his start by co-inventing SCUBA back in 1943. I **love** SCUBA diving.

Florence: I love SCUBA too. Perhaps we can try diving from my yacht.

Dr. Fondah: The French are famous for reducing complex relationships to a few memorable phrases. Can you help us explain the complexity of marine biology?

Florence: Not as well as Cousteau, but I should note that Cousteau himself had some complex personal relationships, as is common among famous Frenchmen, even French presidents. When Jacques-Yves Cousteau married Francine in 1991, he inherited a couple of children that he had sired with her a decade earlier. Then he sued his son by a previous marriage for using the name, Cousteau, on a Caribbean resort. His son's name obviously was Cousteau but Jacques-Yves convinced a court to bar his son from using that name. What did he think his son's name should be, Victor Hugo?

Ben: If Jacques-Yves Cousteau could explain all his complicated personal relationships to his confessor, then he must have found it simple to explain marine biology in his documentaries.

Dr. Fondah: Cousteau obviously was not monogamous but other terrestrial organisms do exhibit that tendency better than he did. Marine organisms, in contrast, are virtually never monogamous. Perhaps the well-publicized infidelities of Frenchmen make them ideally suited to study the ever-changing mating of marine animals.

Ben: Don't tell my girlfriend that. She will put even more pressure on me to transfer out of marine biology into the College of Management. She's already an expert in management.

Florence: Although courtship is an almost universal ritual among terrestrial animals, marine animals do not expect their potential mates to participate in such a protracted engagement before they get down to business. In particular, they never ask to meet any relatives.

Dr. Fondah: Few marine fathers seem to know who their children are, so the mothers of newborns have to protect them from their fathers as much as from any other predator.

Ben: Is this why marine biology is so popular among the ladies? Do they share some universal compulsion to protect newborns from the predatory males that stalk the planet?

Florence: To be honest, female animals in the ocean are about as voracious as their male counterparts. If some newborn is not theirs, it looks like sushi.

Ben: Life in the ocean must resemble those summer holidays when my parents were away, just snacking whenever I happened to hit a grocery store or wander under the golden arches.

Dr. Fondah: Of course, virtually everything in the ocean is eaten while it is fresher than what you find in the "fresh, never frozen" section of your grocery store. In fact, it is still alive.

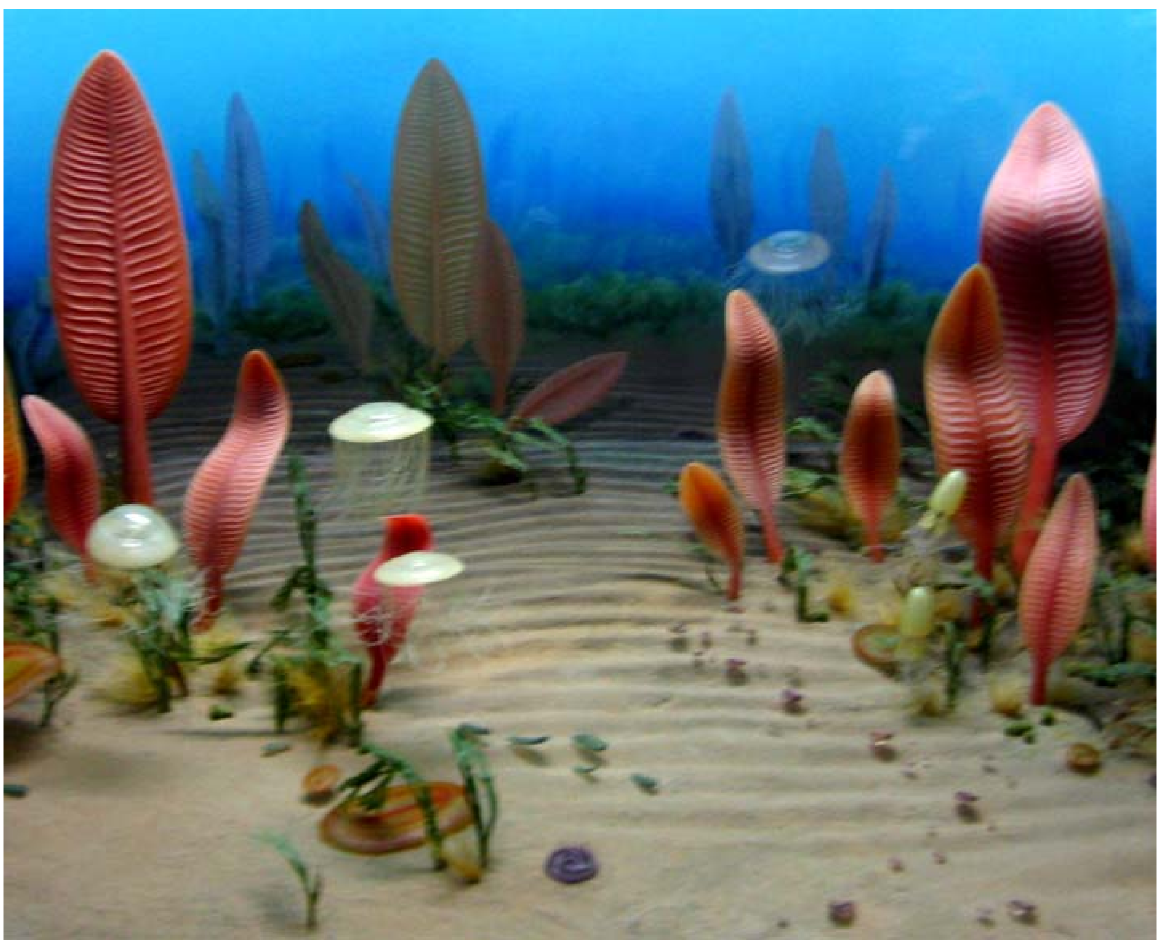
Ben: Ah yes, all those live oysters that businessmen love to let crawl down their throats. That's a big reason why I am not a business major.

Dr. Fondah: I know another reason.

Ben: What's that?

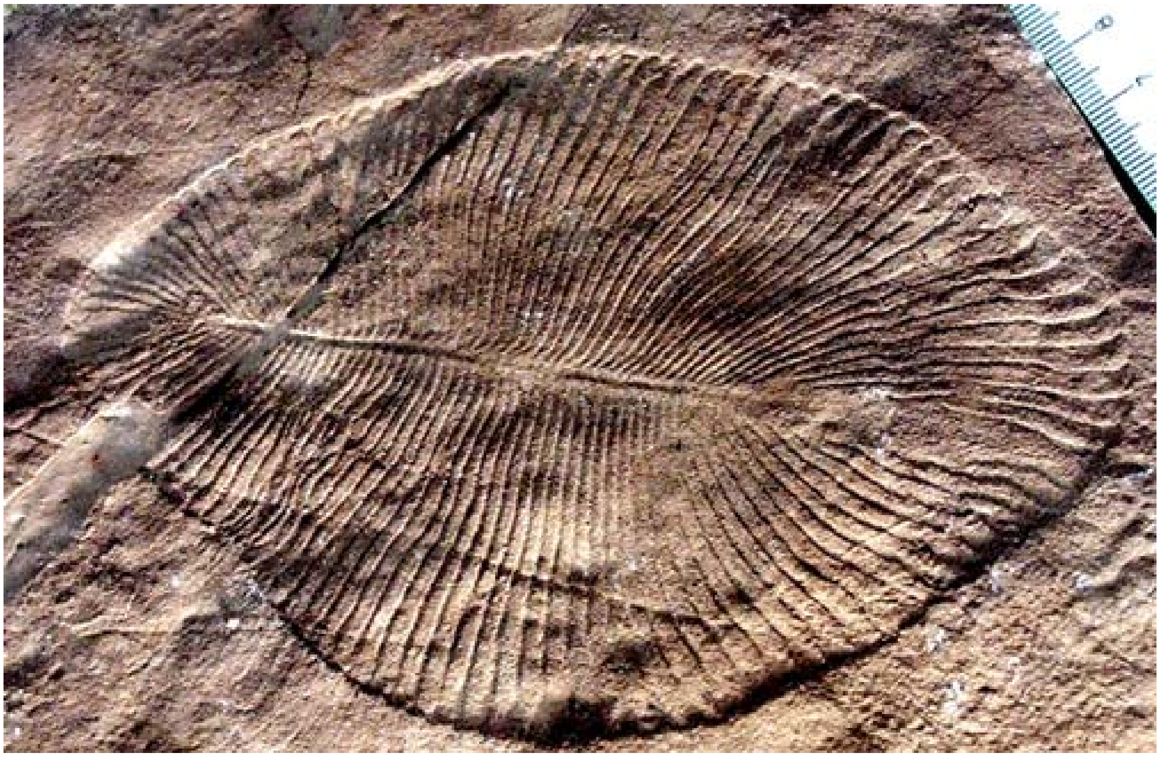
Dr. Fondah: I have watched you try to play golf.

Ben: I must admit that my golf game is primitive, but not as primitive as marine life 560 million years ago. Here is how the Smithsonian portrays life before there were any large swimming animals on Earth.



Dr. Fondah: Most of what we see here is animal life, even though the holdfasts make these animals look like rooted plants. I remember the first time that I swam on a coral reef and kept thinking that the corals were plants instead of animals because they were rooted in the seafloor. Then I saw where some coral had been broken during a storm and still thrived, even though it was now just sitting loosely in the sand.

Florence: The Smithsonian's diorama of ancient life illustrates the so-called Ediacaran assemblage. The Ediacaran assemblage does not survive anywhere in the modern world, so this diorama is based on fossils like the following one, measuring 18 centimeters (7 inches).

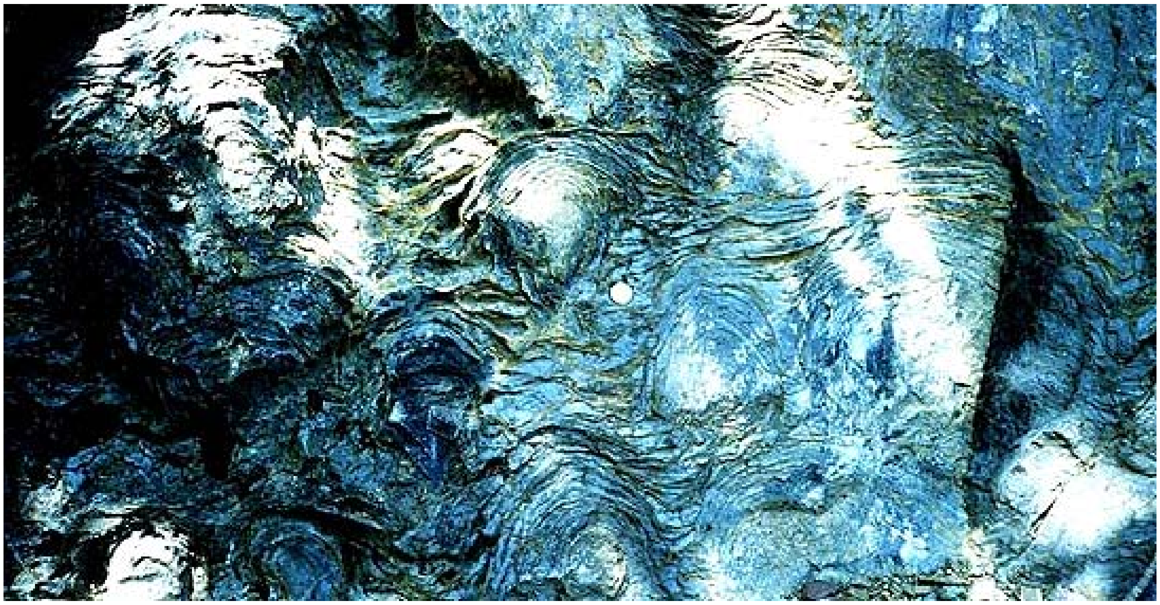


Ben: Although the assemblage is gone, we continue to search for similarities between individual fossils and living species. For example, the following Ediacaran fossil has been compared to a modern sea pen. The Smithsonian diorama makes these animals look similar.

Dr. Fondah: The Ediacaran was the first known time for marine animals of any kind, but there is plenty of evidence of marine plants as far back as we can see in the rock record.

Florence: Earth's oldest rocks are about four billion years old, and even these rocks contain indirect evidence of life. Strictly speaking, the very oldest rocks contain chemical evidence of life rather than fossil shapes. Life processes concentrate the lightest isotope of carbon, carbon-twelve, and we find these concentrations in black sedimentary remains of all ages.

Dr. Fondah: I was lucky enough to find the world's oldest morphological fossil, dating from 2.8 billion years, in the Canadian Arctic. To mark the location, I got the government to name an adjacent lake, Outerring Lake, in this uncharted territory. This fossil is nearly five times older than the Ediacaran assemblage. It occurs as mounds that resemble a stack of buttered slices of bread. In this case, the "butter" consists of microscopic organisms such as cyanobacteria and the "bread" is sediment trapped by the sticky organic matter. The stack is not flat like a loaf of sliced bread but highly contorted because the microscopic organisms were growing in all directions, competing with each other. The mounds are called stromatolites. Here is an example.



Florence: Although stromatolites are fairly common in ancient limestone, we did not know of any modern equivalents until they were discovered in Shark Bay, Western Australia in 1956.

Ben: Despite the name of Shark Bay, the stromatolites do not have to compete with much modern marine life because the local salinity is about twice that of the open ocean. Most marine animals cannot tolerate excessive salinity.

Florence: Before finding Shark Bay, we discounted the possibility of finding any modern stromatolites because we thought that any such growth would be quickly consumed by grazers. There is no fossil record of grazers during the portion of Earth history when stromatolites flourished.

Dr. Fondah: The Shark Bay stromatolites have taken 3000 years to reach their present size, so they do not grow fast enough to recover from any grazing. Nonetheless, marine biologists have counted three billion cyanobacterial cells per square meter (square yard). Those cyanobacteria must be very slow about trapping sediment.

Ben: Throughout most of Earth history, the only marine organisms that left any fossil record were the cyanobacteria, so we should study them more closely.

Florence: Despite being so primitive, cyanobacteria are rather diverse. Their single common feature is an ability to obtain energy through photosynthesis despite otherwise sharing the simplicity of bacteria.

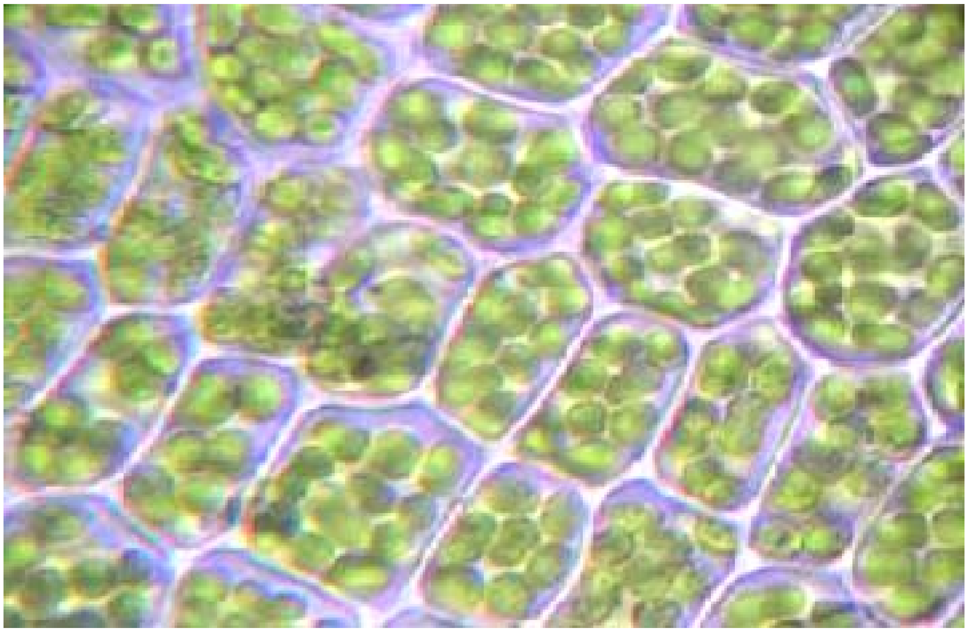
Dr. Fondah: The prefix, cyano, comes from the Greek word for azure blue, *κυανός* (pronounced kyanós).

Ben: Azure is a purplish blue and I must say that I have never seen any purplish-blue cyanobacteria. Perhaps this cyano prefix was applied because they were trying to make subtle distinctions among all the greens that characterize photosynthesizing organisms.

Florence: Here are a couple of cyanobacteria, the filamentous *Anabaena sphaerica* on the left and the spiraling *Anabaena spiroides* on the right. There are 45 other species of just this *Anabaena* genus. The scale in the lower right corner of the *Anabaena sphaerica* photo is just ten micrometers long. One would have to lay 100,000 of these filaments side-by-side to reach a width of a meter (yard).

Dr. Fondah: Of course, you would not really want to touch all those strands of *Anabaena sphaerica* because this is one of the few cyanobacteria that contain a neurotoxin.

Florence: The positive contributions of cyanobacteria as a phylum vastly outweigh the negative effects of this single species. Except for a few thermal vents on the deep seafloor, life on Earth depends upon photosynthesis. As far as we can tell, cyanobacteria invented photosynthesis, and the subsequent evolution of more advanced green plants involved the agglomeration of cyanobacterial cells. The cyanobacterial cells became the chloroplasts of green plants, like those illustrated here.



Florence: Life processes are much more efficient in the ocean than on land because the ocean provides a constant supply of life's most essential ingredient, water.

Dr. Fondah: Even terrestrial animals such as humans are mostly composed of water. A man who is in good physical shape is about 60% water, 17% protein, 17% fat, and 6% bone. Of the 17% that is classified as fat, one-fifth is water, so water is even more dominant than it seems from this list.

Florence: Terrestrial animals expend a lot of energy searching for and defending sources of water. Modern cities are primarily a product of municipal water supplies. Terrestrial plants have to conserve water between rainfall events whereas marine plants are constantly bathed in it.

Dr. Fondah: The largest cyanobacterial mat that I have found covers a spring of seawater that enters a hypersaline pool on Margarita Island, Venezuela. The kilometer-wide pool lies a few meters below sea-level and is separated from the Caribbean Sea by a couple hundred meters (yards) of permeable sand. Caribbean seawater continuously percolates through the narrow sand bar and bathes the cyanobacterial mat along the edge of the pool. Strong evaporation under intense tropical sunlight makes this environment too tough for any plant other than the hardy cyanobacteria.

Florence: Modern cyanobacteria generally occur in places where more advanced plants cannot survive. This is a general rule in evolution. If a new life form does not completely replace an old life form, then the remnants will be found in places where it is difficult to survive. The new life form tends to be more complicated and it is the simplicity of the old life form which allows it to survive better under harsh conditions.

Dr. Fondah: That sounds like the simplistic motto of my older brother. He keeps saying that when the going gets tough, the tough get going. As for me, I prefer to be pampered on a cruise ship.

Ben: Although we sometimes think of algae as being the simplest life in the sea, I gather that algae represent a big step upward in the evolutionary sequence from cyanobacteria, and that algae have appeared relatively recently.

Florence: Algae are more advanced than cyanobacteria in that their cells contain nuclei. Organisms with nucleated cells are called eukaryotes. In Greek, "eukaryote" means "true nut".

Dr. Fondah: I have met a few of those.

Florence: The cells of the primitive cyanobacteria lack nuclei, so they are classified as prokaryotes.

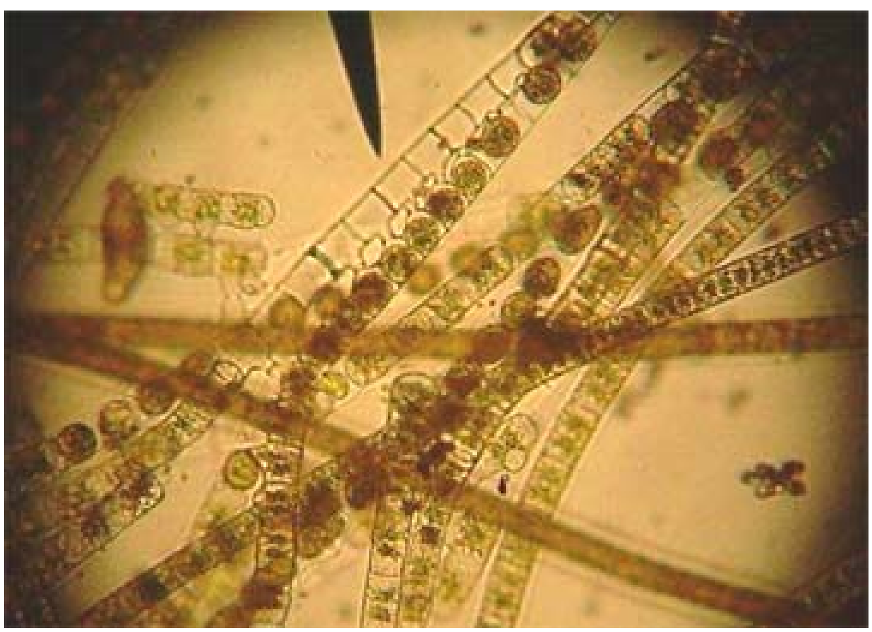
Dr. Fondah: The oldest known algal fossil is 1200 million years old. Like the 2800-million-year-old stromatolite that I found at the eastern end of Outerring Lake, this ancient red algal fossil occurs in arctic Canada. It looks just like a living red alga.

Ben: Here is a typical red alga from Hawaii. Like all other algae, it lacks leaves, roots, and specialized organs, but it is more sophisticated than are cyanobacteria.

Florence: There are four main groups of algae, classified by color. One group is the silica-precipitating diatoms. They are made of clear glass. The other four types are pigmented in green, brown, or red.

Dr. Fondah: There are roughly as many species of green algae as of red algae, about 6000. However, one group of green algae is better known than any type of red algae. That is seaweed. Green seaweed commonly becomes eroded offshore and deposited on the beach, as shown here.

Ben: Marriage vows may include the figurative phrase of two people becoming one, but some green algae take that vow literally. One alga invades the other, leaving its cell empty, as here.

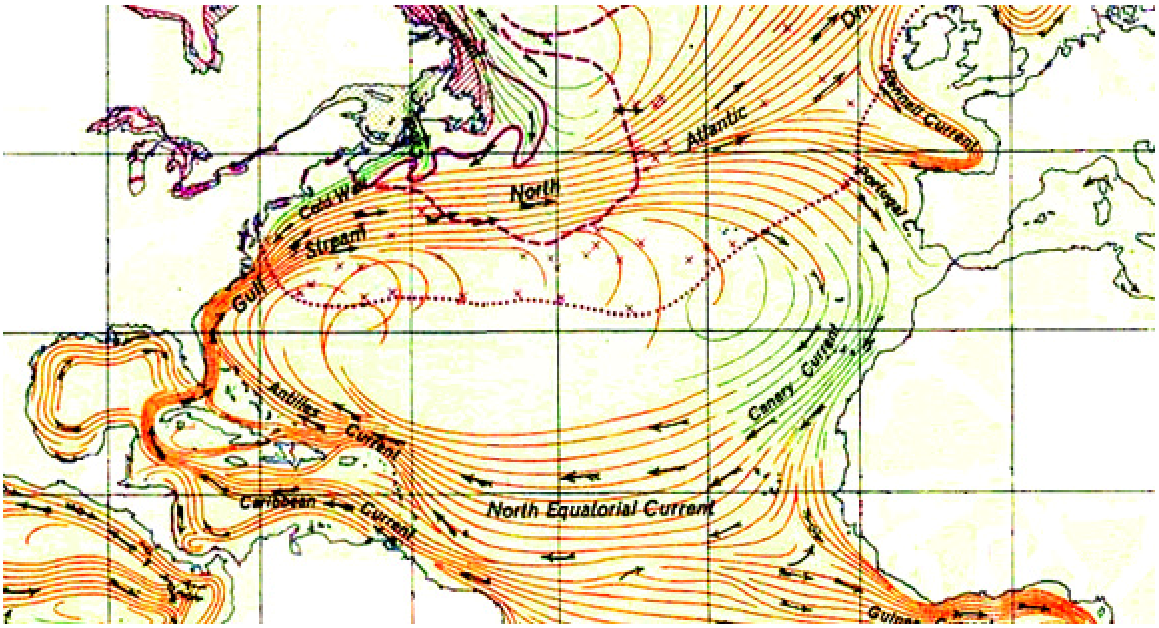


Florence: Seaweed on the beach is not always green. Brown algae have just one-third the number of species as either green or red algae, but the brown seaweeds are relatively abundant in northern waters.

Dr. Fondah: Brown algae may occur as kelp that form voluminous submarine forests in which individual strands extend up to 60 meters (yards). The first image is Pacific rockweed from Washington State and the second is Sargassum from the Sargasso Sea. Sargassum commonly floats to shore because its berry-like bladders are filled with gas.

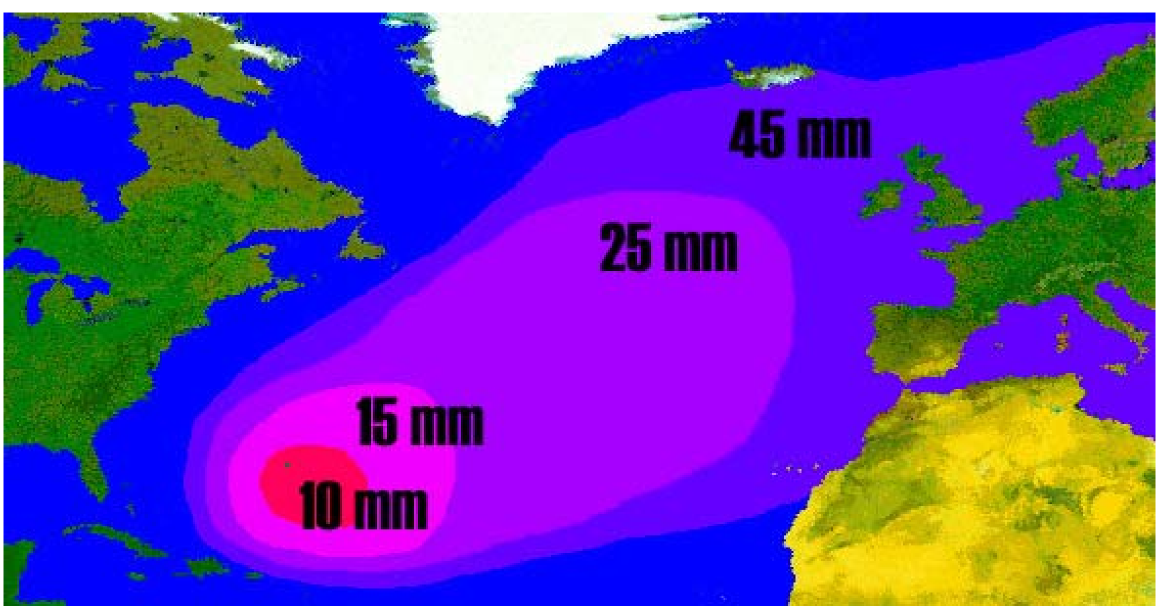
Ben: While sailing your yacht back to France, do you expect to go through the Sargasso Sea, named for its high concentration of floating Sargassum?

Florence: No. The Sargasso Sea lies south of our route to France. As you can see here, it lies at the center of the North Atlantic gyre. We have an auxiliary motor on our yacht but the old sailing ships had to rely upon wind and currents. They could get stuck in the Sargasso Sea.



Ben: Does anything get in and out of the Sargasso Sea, other than fish?

Dr. Fondah: Both American and European eels like to spawn there. As the resulting larvae mature, they get larger and larger the farther away that they migrate from the Sargasso Sea. Like the eel larvae, sea turtles seem to like the Sargasso Sea because the floating Sargassum camouflages them from potential predators. Here we see the increase in size of eel larvae.



Florence: Some restaurant menus include eel, especially Japanese restaurants, so the brown alga, Sargassum, indirectly contributes to providing food. A more direct contribution is made by the red alga, Dulse, which always has been a food source in Iceland and more recently has become popular in Atlantic Canada. Here is a plateful to tempt you.

Ben: Let's put it this way. If you are a great fan of spinach, then this is the meal for you.

Dr. Fondah: As world population increases, we seek more efficient ways to feed people. People live on land, so urban growth comes at the expense of farmland, leaving us less land to feed more people. The best hope for increasing food production comes from aquaculture, growing food in water-filled ponds or tanks. Aquaculture now accounts for one-third of the world's total aquatic production and that proportion is increasing rapidly.

Ben: That's great !! Maybe my buddies and I will eventually be able to go sport fishing without having to compete with all the professionals who sweep the sea of every living thing. Some of their nets would haul in the Statue of Liberty if it were sitting on the seafloor. They can clean their ponds while I clean what I catch in the open ocean.

Florence: So far, most aquaculture uses fresh water. Aquaculture that uses seawater is called mariculture. Although mariculture is normally associated with fish, it also works well for some types of algae. I must admit that there is a joke that all of France is a mariculture pond because the country produces so many cultured girls named Marie.

Ben: I don't care how cultured they are. I am sure that I could tempt them with ice cream. A key ingredient in ice cream comes from kelp, a seaweed that is a brown alga. This ingredient is alginate.

Dr. Fondah: Alginate is a viscous gum that occurs in the cell walls of brown algae. Its key characteristic is that it rapidly absorbs water. This makes it useful for waterproofing, in the manufacturing of both paper and textiles, and for stiffening cosmetics.

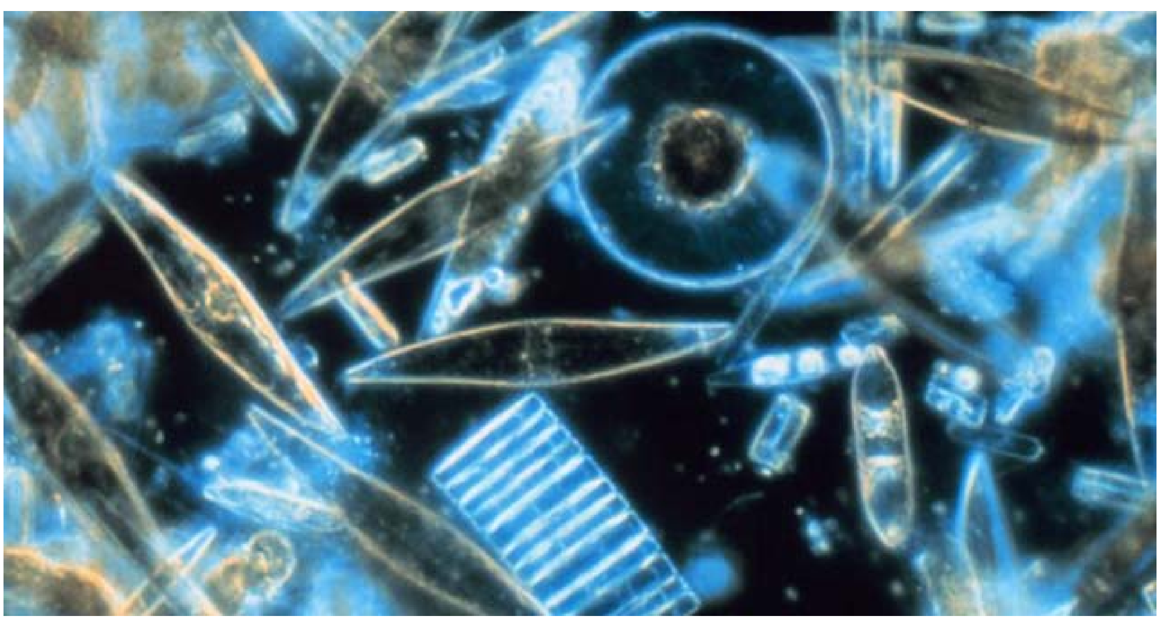
Ben: I am not brave enough to trying buying cosmetics for the young ladies in Paris but I have faith in the universal appeal of ice cream. Most people prefer stiff ice cream to runny ice cream but adding crushed ice can make it so hard that the slender French shopkeepers cannot scoop it. Alginate stiffens ice cream without making it too hard to scoop.

Dr. Fondah: If you continue on to Germany, you will not have to worry about finding ladies who cannot scoop hard ice cream.

Ben: I must confess that I have seen that first-hand. My uncle is stationed in southern Germany and my family visited him there last year. In Munich's Hofbräuhaus, I watched German Fräuleins heft twenty pounds of liter-sized beer mugs in each hand all night long. They let me try it and I could just barely hold those ten huge mugs for more than a minute. Of course, this whole scene got a little blurry after they visited our table several times.

Florence: Before you become too blurry today, I will show you some massive kelp like that which is harvested for alginate. In California, they have boats with blades like lawnmowers and they repeatedly harvest the uppermost kelp just as you cut your lawn. The kelp is kept from drifting away by attaching it to ropes. Here is some of that massive kelp.

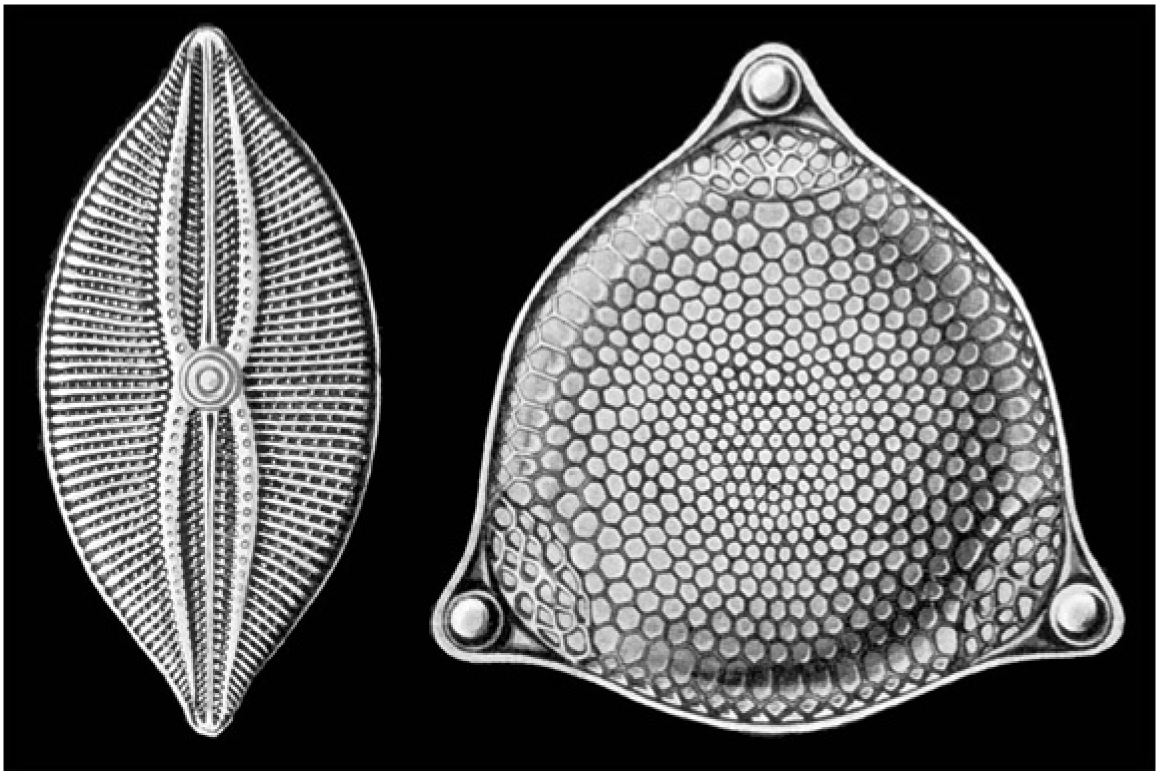
Dr. Fondah: Now that we have seen green, brown, and red algae, let's move on to the remaining type of alga, diatoms. Unlike the forest-sized kelp, diatoms are so small that we need a microscope to see these glass houses.



Florence: Diatoms are much more diverse than the other types of algae. There are twenty times more diatom species than either red or green algae.

Dr. Fondah: Among this myriad of shapes, the diatoms share one peculiarity. They have two halves that fit together like a gift box. In Greek, their name means "cut in half".

Ben: I love to look at diatoms with a microscope. The tops of the diatomaceous boxes are even more ornate than gift boxes from Cartier's jewelry store in Paris.



Florence: Even Cartier realizes the beauty of diatoms so they have asked me to design a new line of gift boxes based on diatom patterns.

Ben: I have learned enough about business law from my girlfriend to suggest an ulterior motive for your contract with Cartier. A diatom cannot sue them for copyright infringement but if they accidentally use the same box design that some other company has patented, they could get detrimental publicity, as well as a big fine. The jewelry business largely involves maintaining a spotless image since the cost of obtaining any jewel is less than 10% of the sale price.

Florence: Perhaps you and I should go into the jewelry business. I will design boxes based on diatom patterns and you find the jewels.

Ben: Why would one of the richest young ladies in France want to go into the jewelry business?

Florence: My father keeps telling me that I should make more commercial use of my diatom studies and build a plant that processes diatomaceous earth, soft sediment that is almost entirely composed of diatoms.

Ben: Process it into what?

Dr. Fondah: Have you ever heard of Nobel, the guy behind all the prizes? His fortune came from mixing one part of diatomaceous earth with three parts of nitroglycerin, producing dynamite. Without the diatomaceous earth, nitroglycerin is too dangerous to handle.

Florence: Nobel's patent in 1867 made him rich enough to become the world's most famous philanthropist. Even Jimmy Carter and Al Gore have benefitted from Nobel Peace Prizes.

Ben: Nobel's dynamite has killed more than a million people in subsequent wars, so I suppose that he was trying to become remembered for more than mass slaughter. Are there other uses of diatomaceous earth?

Florence: Plenty. The prime use is filtration, especially marine diatoms because they have tiny crystals of quartz that form a mesh which can trap bacteria. Marine diatomite is used to filter swimming pools, public water supplies, beer, and wine.

Dr. Fondah: Initially, diatomite was used as a mild abrasive and some types of toothpaste still use it for that purpose.

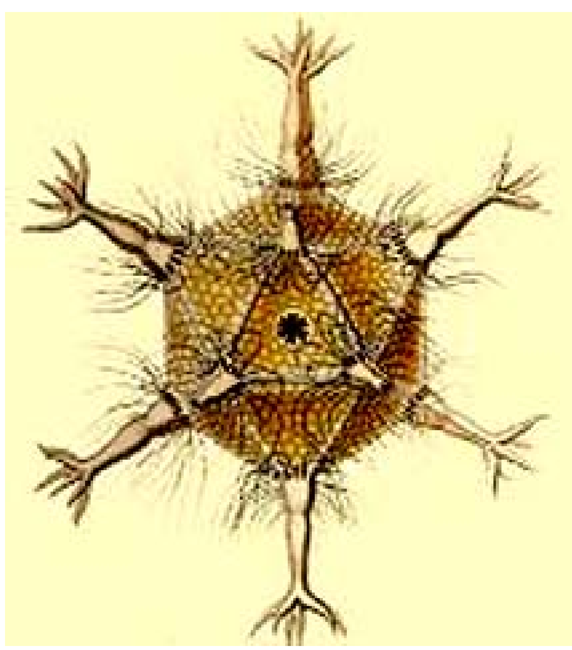
Florence: I like to use diatomite against the nasty slugs which try to eat my beautiful flower garden back in Paris. I know that here in America you put out a saucer of beer so that the slugs will happily drown, but we have better things to do with beer in France, so we prefer to use diatomite. Diatomite can absorb fluids out of their bodies until the slugs become fatally dehydrated.

Dr. Fondah: I do not have an extensive flower garden but I do have a couple of cute cats and they remain cute as long as they remember to use their kitty litter box. Diatomaceous earth is a prime component of kitty litter, given its high porosity and absorbancy.

Ben: Flower gardens and kitty cats !! Let's find a more manly topic. How about radiolaria?

Florence: Radiolaria are bigger than diatoms and they have been around three times longer, about 600 million years. They are manly in that they appear to have a thick covering of hair on their siliceous bodies.

Dr. Fondah: Here's a radiolarian that should impress any super-organized businessman. This is Circogoniaicosahedra. Hidden within that long name is the word, icosahedra, which refers to a symmetric object with 20 equal faces.



Ben: I had to study icosahedra in my geometry class. This is the most multifaceted member of the so-called Platonic solids.

Florence: Does that have anything to do with Platonic love?

Ben: Not really, but we can get into that later. A Platonic solid is a convex polygon in which the faces only meet along their edges. At each vortex, one finds the same number of faces meeting at that point. There are only five Platonic solids, the tetrahedron, cube, octahedron, deodecahedron, and icosahedron.

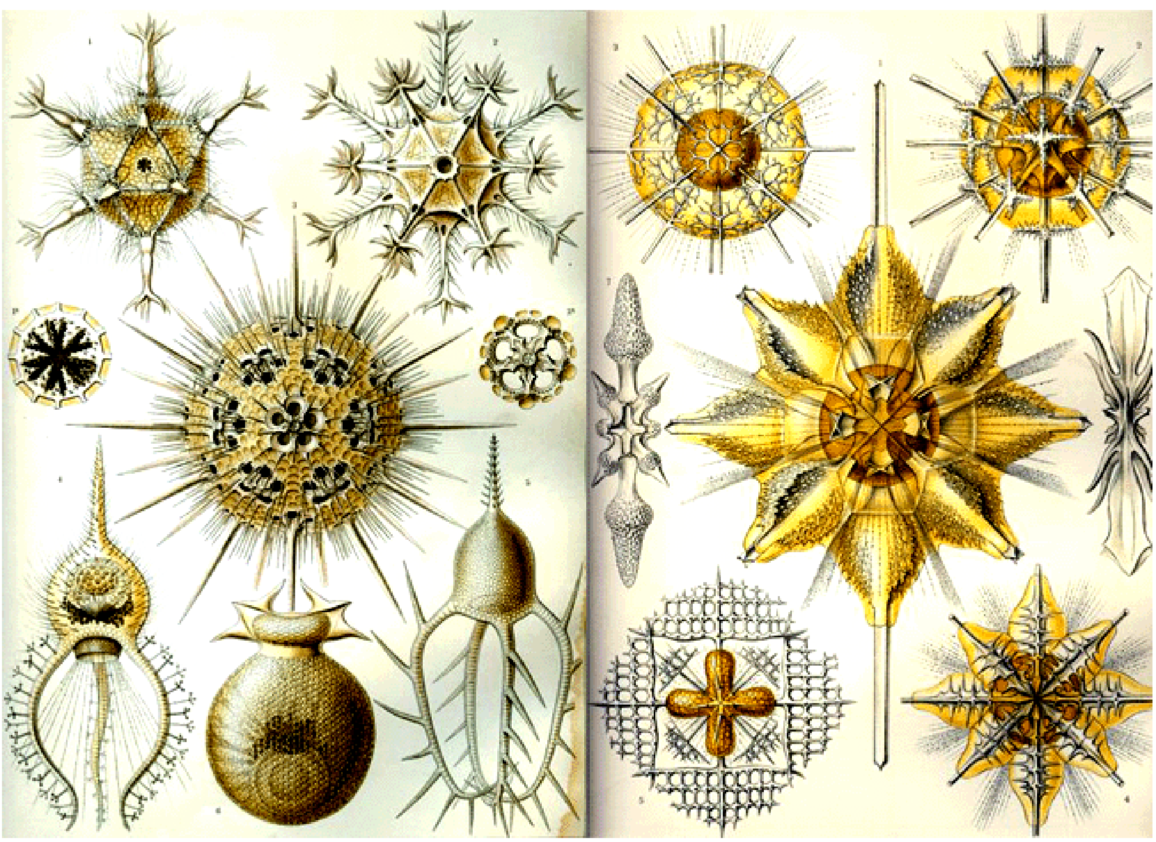
Dr. Fondah: Very good. All but the icosahedron are important in mineralogy. The tetrahedron is the pyramidal form that is the basic building block of all silicates. Cubic crystals include table salt and fool's gold, iron pyrite. Octahedral crystals of magnetite can be found in most beach sand by simply dragging a hand magnet through the sand. Dodecahedral crystals of red garnet occur in lots of metamorphic rocks and are used in some types of sandpaper.

Ben: Besides this icosahedral radiolarian, there also are octahedral and dodecahedral species.

Dr. Fondah: It is not just the radiolaria that like this icosahedral form. It is also popular among viruses, especially viruses of the type that make Platonic love a good idea.

Ben: I guess that you are referring to some twerp's herpes. Plato was the original advocate of curling up with a good book instead of someone named Brooke. Plato's prime passion was his Platonic solids and he tried to shoe-horn the world's complexities into these highly symmetrical forms. Twenty-five hundred years later, philosophers still praise Plato even though scientists consider him a failure.

Florence: We French have never wasted much time on Platonic love, so let's see some more radiolaria. Here is Plato's friend, along with other radiolaria that look more like mines.



Dr. Fondah: I am sure that Jordan and Janna do not want to hear about mines, after all the submarines that were sunk by mines in World War Two. Some areas around Indonesia have not yet been fully cleared of World War Two mines.

Ben: It must be scary, knowing that some of those mines are still out there, just waiting for somebody who is too “touchy feely” for their own good.

Florence: Of course, these radiolaria which resemble mines are actually very tiny. The biggest radiolarian reaches the thickness of a nickel (2 mm) and the smallest is seventy times smaller than that.

Dr. Fondah: Nonetheless, some of these animals are big enough to enclose a subservient green alga, zooxanthella, just as the corals do.

Ben: I wouldn’t mind finding a comfortable symbiotic relationship myself.

Dr. Fondah: If you do not graduate, you will have trouble maintaining a symbiotic relationship with an alga, or even with Helga, the world-famous drag queen.

Ben: Yuk !! OK. I’m back on task. Radiolaria are versatile in that they can be either filter feeders or predators. Moreover, they can reproduce either sexually or asexually.

Florence: Not only have they been on Earth for three times longer than the diatoms but they have experimented with a wide variety of shapes through the millennia, making it easy to determine the age of a given rock by the shape of the radiolaria within it.

Ben: This has been particularly important for petroleum exploration because just a small volume of rock is obtained by drilling, generally too small to contain an entire fossil clam, for example. Nonetheless, there could be hundreds of radiolaria with a small rock volume.

Florence: Petroleum geologists need to understand the age sequence of the sedimentary rocks that they are drilling. This study of rock-age sequence is called stratigraphy.

Dr. Fondah: Let’s move on to another group of tiny animals that are used by stratigraphers who work for petroleum companies. These are the foraminifera.

Florence: Foraminifera are the first cousins of radiolaria. Both are amoeboid protozoa that have existed about 600 million years. Whereas radiolaria are covered with permanent hair-like microtubules, the foraminifera extrude and retract strands of cytoplasm that combine to form a net. The net is used for anchoring, locomotion, or capturing food.

Ben: Obviously, the food must be small fry such as bacteria and diatoms, given that typical foraminifera only reach the thickness of a dime (1 mm).

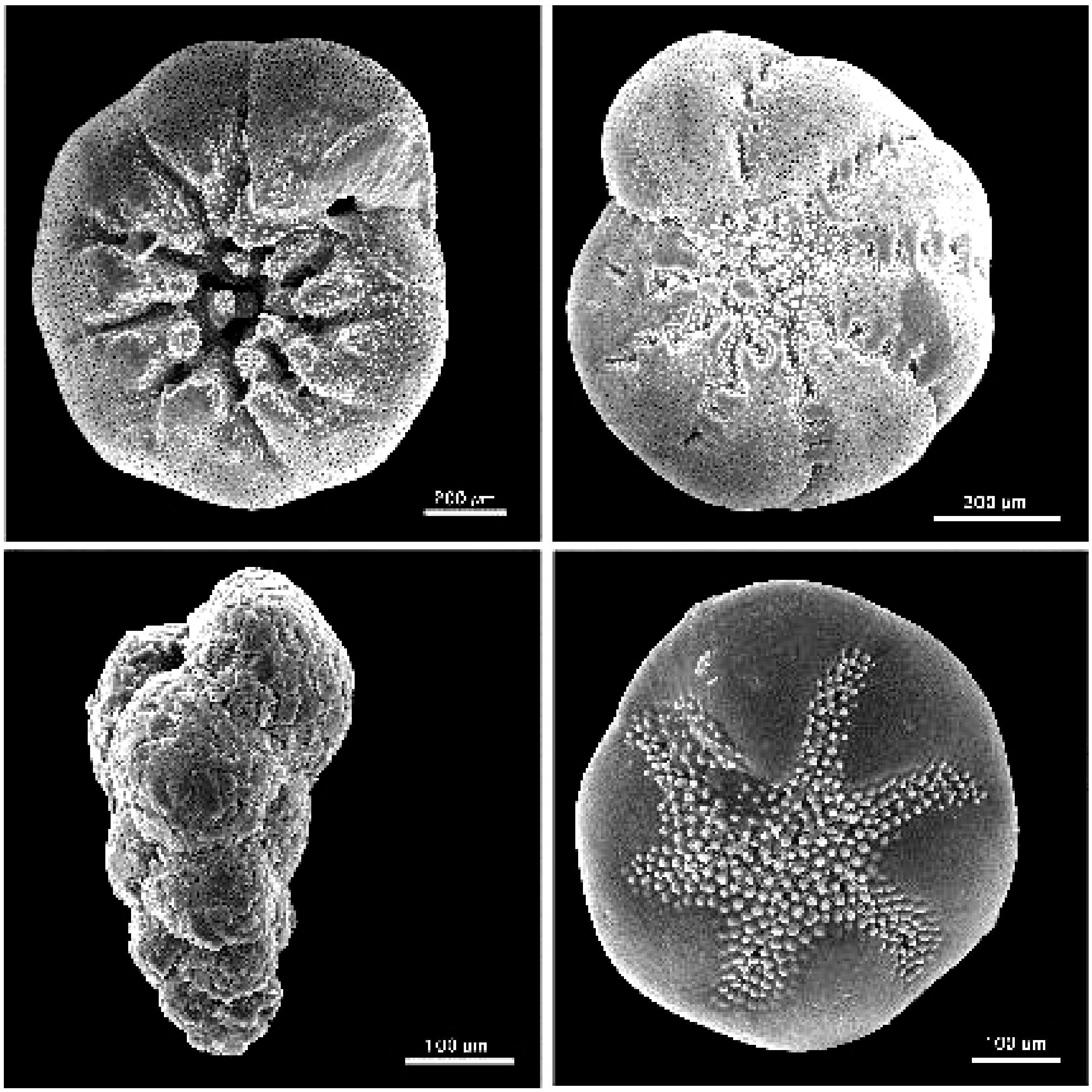
Dr. Fondah: The foraminifera are less choosey than radiolaria when it comes to holding slaves. Within their shells they may hold dinoflagellates, diatoms, and other types of algae, such as green, golden, or red algae. Foraminifera will even extract plant chloroplasts and keep them producing food outside their original host.

Florence: Foraminifera typically have shells composed of calcium carbonate, in contrast to the siliceous shells of radiolaria. However, the foraminifera are more variable. Some glue sediment grains together to form a shell. Some rely upon an organic coating and a single species even precipitates silica like the radiolaria.

Ben: Like Helga, there also is a weird radiolarian. It precipitates strontium sulfate instead of silica. If I could find a few million tons of that, I would get a lot of money for the strontium.

Dr. Fondah: Some foraminfera are like the radiolaria and “go with the flow”, wherever the prevailing current takes them. These are planktonic. Other foraminifera prefer to settle down onto the seafloor and live in their dream house, waiting for food to land on top of them. These are called benthic.

Florence: Like most terms in marine biology, "benthic" comes from the Greek. It means deep. Few marine animals burrow more than a meter beneath the seafloor, so the seafloor is about as deep as they get. Do you remember the Trieste bathyscape that reached the bottom of the Marianas Trench? The name, bathyscape, comes from the same Greek root. Here are some benthic foraminifera.



Dr. Fondah: Foraminifera are so prolific that they precipitate a large proportion of all the calcium carbonate that becomes limestone. Some limestone is almost entirely composed of tiny foraminiferal shells, called tests.

Ben: I don't particularly like tests of any kind, so I will call them shells.

Florence: I have seen the world's most-visited foraminiferal limestone. However, I doubt if even a handful of the millions of visitors to that desert site have known that they were looking at a pile of benthic foraminifera, specifically *Nummulites*. *Nummulites* is a large, cone-shaped foraminifera that has its chambers arranged in a spiral, rather like the Ekman spiral of wind-induced current directions.

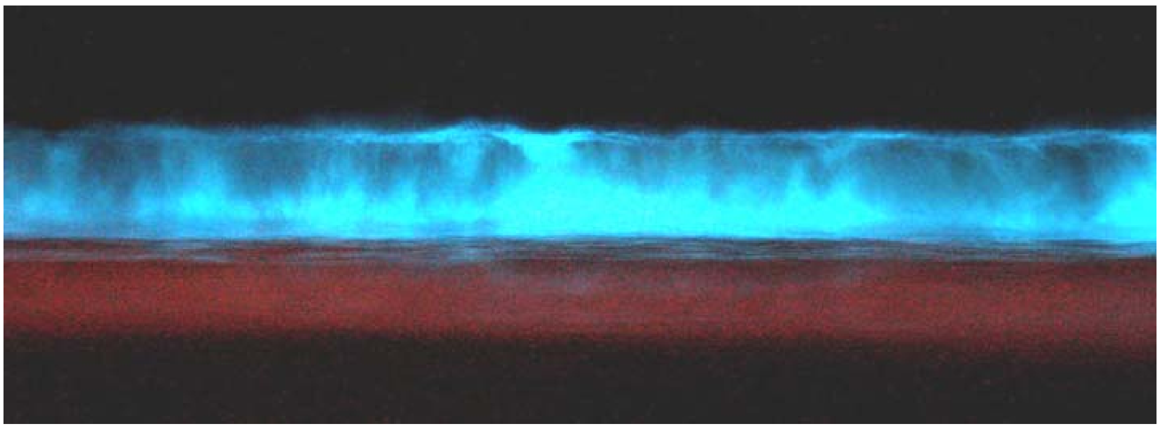
Ben: What have all those millions of visitors thought that they were seeing?

Florence: They were only interested in the "big picture", so they returned home to brag about having seen the Egyptian pyramids.

Dr. Fondah: Maybe I can get a grant to research *Nummulites* and choose the pyramids for my study area. I would love to study Egyptian history from a biological viewpoint. How did the Egyptians organize their society so that every member worked for a common cause? How did they manage to maintain the same icons for millennia? We have had Mickey Mouse for 80 years but the Egyptian cat icon has lasted for 4000 years.

Florence: The first rule of biology is that cats eat mice. We biologists claim that all domestic cats have descended from the Egyptian cats, but I suspect that my own cat is partly human. She pouts, whines, and threatens me unless I feed her by hand. She can be as dangerous as one of the tiny organisms that we mentioned within the foraminifera, the dinoflagellates.

Ben: Dinoflagellates !! Those are the critters that show up as red tides ! Here is a California beach at midnight while a red tide is rolling in. Of course, the bioluminescence of red tides is not always red. It can be yellow-green or even blue, as we see in this crashing wave.



Dr. Fondah: If I were to see that red tide while out for a midnight stroll on the beach, I would stick to eating hamburgers for the next week.

Florence: Some dinoflagellates carry a nasty neurotoxin which can accumulate in shellfish. That neurotoxin can be fatal to those who eat the shellfish, or at least make them very sick.

Dr. Fondah: Fish that eat dinoflagellates also acquire some of the neurotoxin but not at the high concentration that may occur in clams and other shellfish. Here is a truly red red tide.

Florence: That looks like La Jolla, California. Fortunately, there was no red tide when I was at La Jolla, visiting a friend at the University of California at San Diego. Let's look at an individual dinoflagellate. This one is just one-eighth of a millimeter long, about one-eighth of the thickness of a dime.

Dr. Fondah: Dinoflagellates and diatoms constitute the largest groups of algae that have nuclei within their cells, the so-called eukaryotic algae. Both groups exhibit boom-and-bust cycles in population dynamics. However, only the dinoflagellate blooms have a direct effect on us, in the form of red tides.

Florence: Diatoms are characteristically photosynthetic but only about half of the dinoflagellates can photosynthesize. We have already heard about the famous dinoflagellate, zooxanthella, and its symbiotic relationships.

Ben: Yes, and I am still looking for **my** symbiotic relationship.

Florence: Perhaps you will find it in France.

Dr. Fondah: I'm not sure about Ben's French connections. He needs to pass an exam on marine small fry before he starts cooking up something with French fry.

Ben: We might have to postpone my biology exam for a couple of weeks because Florence introduced me to her younger sister last night and she has invited me to go skiing for a couple of weeks at St. Moritz in Switzerland.

Dr. Fondah: You are no great shakes at golf but at least you have tried it. I doubt if you know anything about skiing.

Ben: Florence's sister has promised to teach me everything that I need to know.

Florence: And then some. It was probably a mistake to introduce Ben to my sister. She tends to swirl men around like a dinoflagellate. Too much exposure to Diane, the Roman goddess of the hunt, can have the effect of a red tide.

Dr. Fondah: I have never watched your sister whirl through a cocktail party but I **do** love to watch dinoflagellates swirl their propeller. Of course, it's not really a propeller but a finger-like protrusion, a flagellum, that extends out the side of the tiny alga and whirls like a propeller. Another flagellum extends out the back to steer the dinoflagellate.

Ben: Dinoflagellates are so tiny that we need a microscope to observe their whirling motion.

Florence: The whirling is so characteristic that the prefix, dino, is taken from the Greek word for whirling.

Ben: Does your sister's name, Diane, also come from "dino"?

Florence: Diane is actually named for Diane de France who was the love-child of King Henry the Second in the sixteenth century. Diane was widowed twice before she became a favorite of Henry the Third and then Henry the Fourth. She was famously adaptable.

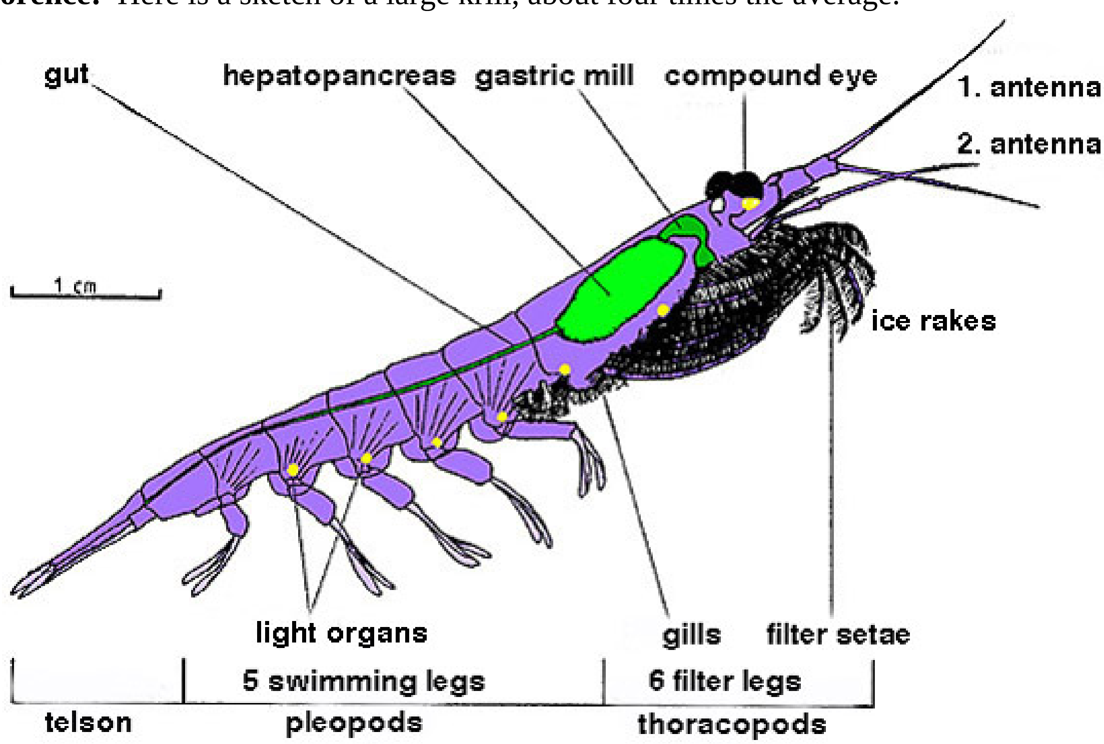
Dr. Fondah: Her life cycle sounds as complicated as that of a dinoflagellate. They too know how to survive changing times. Like the grizzly bears in winter, dinoflagellates can hibernate if resources become scarce. Just like the bears, they ingest excess fat and oil and then slow their metabolism. The bears grow extra fur for the winter whereas dinoflagellates cover themselves in a hardened case that may include spikes.

Ben: When conditions improve, the dinoflagellates break out of their shell and let the good times roll.

Dr. Fondah: They often roll straight into the mouth of a tiny animal whose very name, krill, means "small fry" in Norwegian.

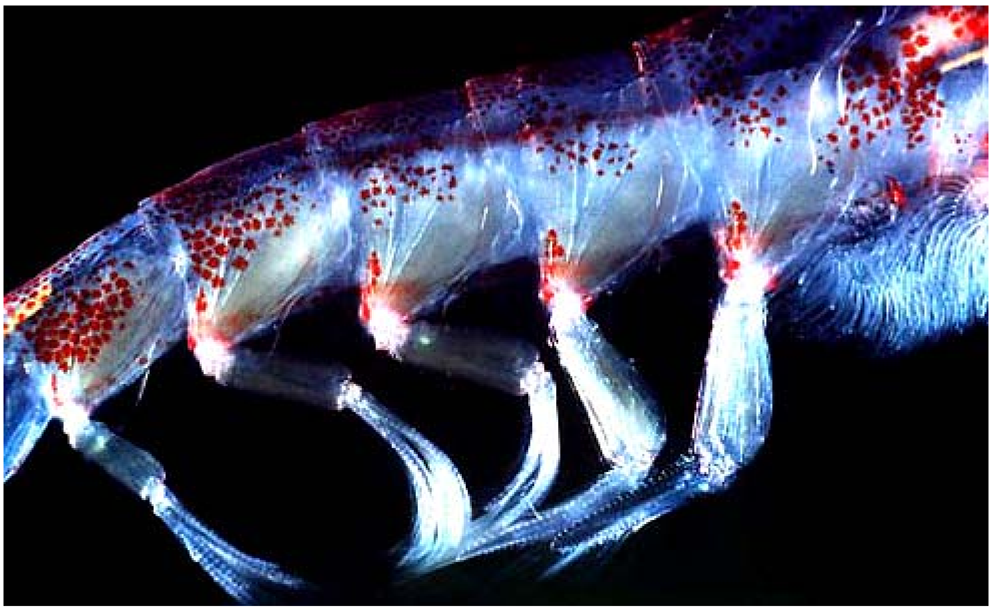
Ben: Krill average just half-an-inch long, about one-to-two centimeters, but they come with most of the body parts of a larger animal.

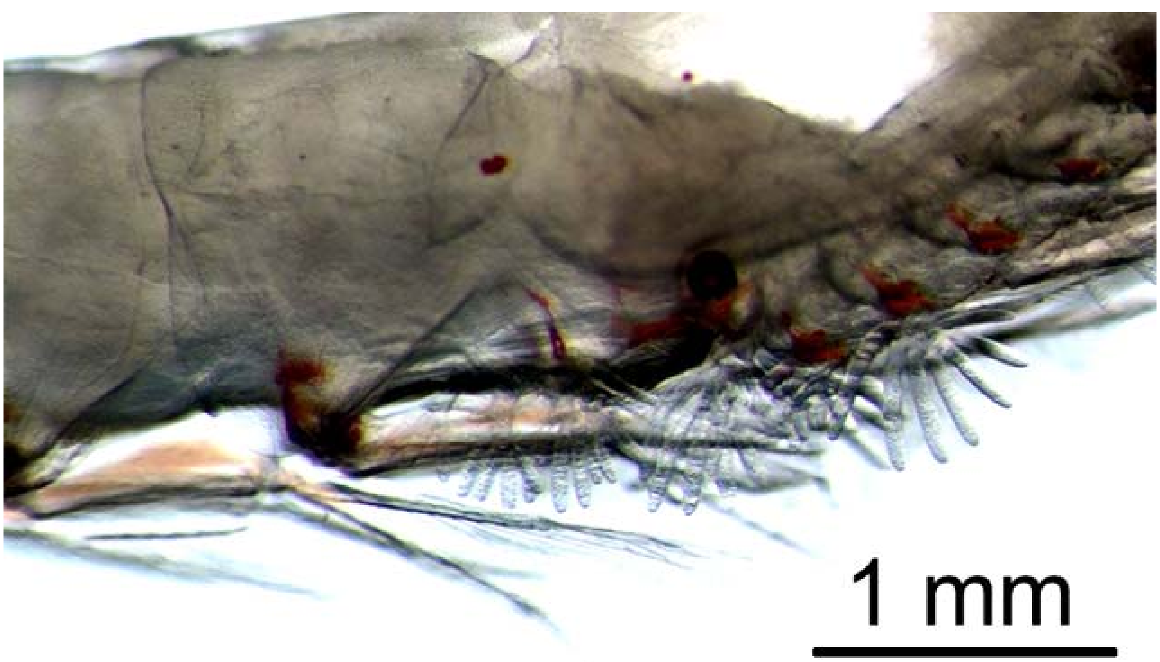
Florence: Here is a sketch of a large krill, about four times the average.



Florence: Like shrimp, krill have a shell, so they are crustaceans. The shells of krill and shrimp are made of chitin, a long-chain polymer that is derived from glucose sugar. Chitin is the most common substance in flexible animal shells, including the shells of insects, crabs, and lobsters. As with shrimp, we prefer to remove the chitin before using krill as food because the krill chitin concentrates fluorine. Although we add a little fluorine to some water supplies, too much can be harmful.

Dr. Fondah: The krill are omnivorous filter feeders, so the tiny ice rakes near the mouth are busy sorting food as the krill swim through the water. Krill are excellent swimmers. As shown here, each swimming leg moves in sequence, like a racing thoroughbred.



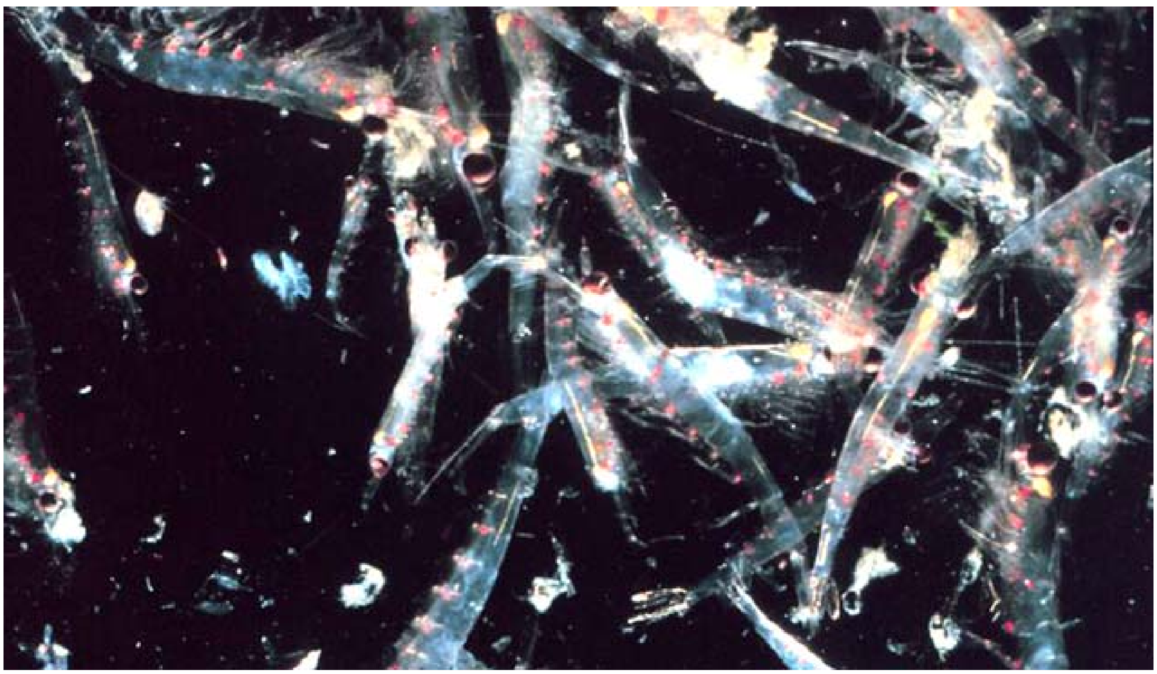


Ben: Krill can swim as fast as ten body lengths per second in the forward motion and can snap backward nearly thirty body lengths per second by flicking their tail (telson) if they sense danger. A lobster is an overgrown krill and has the same type of reflex, but with less effect.

Florence: Unlike shrimp, the gills of krill are exposed outside of the chitinous shell, as seen here. The one-millimeter scale bar in this photo is smaller than the thickness of a dime, so the hair-like gills are miniscule.

Dr. Fondah: Krill eat just about every tiny thing in their path. Ever since the days of the dinosaurs, diatoms have been the most abundant plankton, hence this green alga has been the most abundant food for krill. However, krill are just as happy eating animal larvae. After all, there are many mouths to feed.

Florence: Many mouths indeed !! Krill like to swarm together so that they look bigger than they really are, up to 30,000 of them within a cubic meter (yard). Here is a photo of a swarm.



Ben: Swarming backfires when a baleen whale appears. Baleen whales are not impressed by krill swarms, given that baleens include the Earth's largest animal, the Blue Whale. The Blue Whale reaches 33 meters in length. That is equivalent to a line of 2000 krill, head-to-foot. Swarming just makes it easier to satisfy a whale-sized hunger pang.

Dr. Fondah: If something smaller than a baleen appears, the krill may try to leave a decoy while they escape. The decoy is their chitinous shell. They may instantly molt and leave it behind.

Florence: Young krill are constantly molting as they outgrow their shell. It reminds me of all the money my parents had to pay for Diane's shoes when she went through a growth spurt.

Ben: Her feet feel fine now.

Florence: I need to warn you that Diane's equivalent of molting is jilting.

Dr. Fondah: If you get to St. Moritz with her, you might find all those jilted boyfriends sharing the same ski-lift with you.

Ben: Not to worry. All those high-class honkies will look like krill to a good ole boy.

Florence: In my experience, the reverse is true, but I will let you find out for yourself. Let's take one last look at a krill. They remind me of a transparent watch because I can see all the interior workings within their transparent shell.

Dr. Fondah: I doubt if any of us have snacked on a krill dip but we have all enjoyed a shrimp dip, so I am going to show you a "pretty in pink".

Ben: I can see that the shrimp do favor krill.
Florence: Just looking at shrimp makes me savor the classical French seafood soup, called bouillabaisse. Shrimp is the most essential ingredient.

Dr. Fondah: I enjoyed that soup at a convention in Montreal, but I had to point to it on the menu because my waiter could not understand my French. I must say that it was worth the embarrassment of pointing.

Ben: Here is the usual way that I see shrimp. I can go through steamed shrimp the way a Blue Whale goes through live krill.

Florence: Unfortunately, the world of small fry is not just bouillabaisse and shrimp rolls. It also includes nasty parasites. Many of these are nematodes, also known as roundworms.

Dr. Fondah: "Nematode" means thread-like in Greek and these simple animals do resemble round strands of thread. They lack both a circulatory and respiratory system, so they have to diffuse dissolved gases through their skin. Given no muscle within their body cavity, they rely upon external pressure to move food through their digestive system.

Ben: Nematodes are not only simple; they are simply everywhere. If there is life, there are nematodes, within both marine and nonmarine environments. Nematodes are estimated to represent about 90% of animal life on the seafloor. An acre of fertile topsoil may contain billions of nematodes.

Florence: Most nematodes are not parasites but the parasitic species can cause a lot of trouble. Although most nematodes approximate just a centimeter in length, they can grow much longer within longer animals. Not surprisingly, a huge sperm whale was found to have a record-length nematode, 8.5 meters long. The record within a human is about a meter.

Dr. Fondah: As much as I love sushi, I make sure that the fish has been frozen below -20^{o}C for at least a week, or else below -35^{o}C for at least 15 hours, because this kills the larvae of the common nematode in fish, *Anisakis simplex*.

Ben: I know that the Celsius and Fahrenheit temperature schemes coincide at -40^o, so -35^{o}C must be very close to the equivalent number in the Fahrenheit scheme.

Dr. Fondah: Why this sudden interest in cold Celsius temperatures, Ben?

Ben: Diane tells me that the texture of the snow at St. Moritz depends upon the overnight temperature and those temperatures are always listed in Celsius degrees.

Dr. Fondah: Does this mean that I will have to bring a different student to my next discussion with Florence, when we talk about large fry?

Ben: (*holding his hands like an old-fashioned weigh scale and slowly rocking sideways*) Let me see. I could either be talking about fish with you guys or skiing at St. Moritz with Diane?

Dr. Fondah: OK. Forget it. Just send us a postcard.

Florence: Bonne chance. With Diane, you will need it.

Chapter 8: Large Fry

Dr. Fondah: Ben has not yet sent us a postcard from St. Moritz. Is that a bad sign?
Florence: Mais oui. The life cycle of Diane's admirers starts with such an intense infatuation that they ignore all their friends and family.
Tim: And the next stage….
Florence: You might say that they molt.
Tim: Melt?
Dr. Fondah: Molt, melt, mangle, mingle. Anyway, Ben's a goner. In the case of pretty young women, the usual law of the sea is reversed and it's the small fish that eat the big fish.
Florence: Certainement. I have had to remove some rather large snoring carcasses from our various apartments and condos around the world. They had fallen asleep in one world but awoke in another, the street.
Tim: Please tell me that your sister, Juliette, is not like Diane. Juliette has invited me to go SCUBA-diving with her on your little island off the coast of Tahiti, and the shrimp that she served me last night were anything but shrimps.
Dr. Fondah: Another sister? I guess that your parents do not have to worry about saving up college tuition, no matter how many kids they have. Juliette must have been named for the Oscar-winning actress, Juliette Binoche. Binoche can make you believe that she is a teenager or a retiree, from one scene to the next. For many years, she kept saying, "French women bloom at 40. I can't wait!" Then when she turned 43, she posed for her first Playboy spread.
Tim: I can't wait for Tahiti, so let's devour these large fry and get on our way.
Florence: Sûrement. Although the krill that we discussed last time may be compared with tiny shrimp, jumbo shrimp are definitely large fry, and I do love eating them fried. Here's a couple of jumbo shrimp out for a Sunday stroll.

Florence: Did Juliette also eat jumbo shrimp? Even though jumbo shrimp tastes just like lobster to me, she usually prefers fresh lobster.

Dr. Fondah: I lived in coastal New England for a summer, doing research, and we had fresh lobster every other evening. I found that it was not like the usual restaurant lobster that has crawled around a tank for a couple of weeks, exchanging its body fluids with tank water.

Florence: Yes. Fresh lobster is so rich in active organic compounds that you dare not mix it with any milk or ice cream or else you will feel strange chemical reactions inside you.

Tim: I snapped a photo of the waitress bringing out Juliette's lobster for her inspection.

Dr. Fondah: Nice! I should dream up some more research in coastal New England.

Florence: Of course, you would not find a clawed lobster like that around Tahiti or any other warm-water place. You would find a spiny lobster like the one shown here. This is the most common type of spiny lobster caught around Florida or in the Caribbean.

Tim: Do they taste the same?

Dr. Fondah: Pretty much, so they all get called lobster even though they are biologically quite different organisms.

Florence: I prefer crab's legs. Crabs naturally come with the slender legs that actresses have to starve themselves to get.

Dr. Fondah: Crab legs are always slender compared to their body, but if you find a 4-meter-long (4-yard-long) Japanese spider crab, then those legs are going to look pretty big, even if they are proportionately small.

Florence: This is the largest living member of the largest group of animals, the arthropods. Arthropods are joint-footed animals with a flexible shell composed of chitin, a derivative of glucose sugar.

Dr. Fondah: Arthropods constitute 80% of all animals, with over a million species, including all insects, crustaceans, and spiders. Of course, the huge Japanese spider crab is a crustacean with no links to real spiders.

Tim: One of my buddies got a summer job at a Californian aquarium, tending to their spider crab. He claims that it can live for a full century. Their crab was eating shellfish in 300 meters of water depth off Japan when it was collected.

Florence: Although the spider crab is a delicacy in southern Japan, the vast majority of crabs have nothing to fear from a sushi chef because they are inedible.

Tim: Whenever I am "sitting on the dock of the bay" somewhere in the Caribbean, I watch the fiddler crabs scurry around their holes in the muddy tidal flat. Do they have fiddlers in Tahiti? I feel the urge to do some dockside research.

Dr. Fondah: There are nearly a hundred species of crabs within the Uca genus, the genus of fiddler crabs, and these fiddlers live on warm tidal flats all over the world. Do you know why they are called fiddlers?

Tim: I remember you pointing to one while it was eating. Its small claw was lifting algae-laden sediment up to the large claw as if it were lifting a violin bow up to a violin.

Florence: Very good. What else have you learned while sitting on the dock of the bay?

Tim: Besides developing an appreciation for Margaritas, I have spotted that only the fiddler males carry a violin claw and that they will occasionally do battle, presumably battling over some fair maiden.

Florence: In France, we think that the "fair maiden" image is just Austro-Hungarian goulash. My dark-haired sisters and I have never lacked for admirers ready to do battle for us. Juliette Binoche has played every part imaginable, except that of a blonde.

Dr. Fondah: If any of your battle-ready admirers lose some body parts in the fray, they will wish that they were fiddlers because fiddlers can regenerate body parts.

Tim: It's no wonder that the world's tidal flats are literally crawling with fiddlers. They must be virtually indestructible.

Dr. Fondah: Well, they only live for a couple of years. However, their gestation period is just two weeks and then the eggs are released into a receding tide so that they can become planktonic larvae for a couple of weeks before coming back to the tidal flat.

Florence: I love the neat piles of sediment balls around their holes on the tidal flats. They look like stacks of cannon balls from the era of Trafalgar.

Dr. Fondah: The balls are composed of sediment that has already been sifted for edible matter. By leaving those remains as balls, the fiddlers will not mistake it for fresh sediment that may contain something to eat.

Tim: In class, you keep talking about the exotic fauna that you saw while visiting the Galápagos Islands. Did you find any weird crabs there?

Dr. Fondah: Galápagos crabs are not particularly strange, but they certainly are photogenic. Here is a Sally Lightfoot sitting on vesicular basalt. All those holes in the basalt were once filled with gas bubbles as the lava poured over the Galápagos Islands. The main body of the crab, the carapace, is 8 centimeters (3 inches) across.

Florence: I have seen Sally Lightfoots all along the western coast of South and Central America. Like everyone else, I chase them just for fun, knowing that I have no chance of ever catching one.

Tim: I guess that that is how they got their lightfoot name. I wish that our running backs could be as evasive as those guys. Maybe our team could then get to play in something other than the Toilet Bowl.

Dr. Fondah: You are becoming too crabby, Tim. I think that you should "cool your jets" with the penguins of Antarctica. Although you keep seeing photos and even movies about penguins on land, there is nothing for them to eat on snow-covered land so they prefer to be in the water.

Tim: Cool !! Penguins are just about the only large fry without any fear of humans. There are no lions, or tigers, or bears in Antarctica, so penguins are not accustomed to anything chasing them on land. That is very different from the Arctic where polar bears will stalk and kill anything, including people.

Florence: In the water, penguins are eaten by the leopard seal, a mammal that stretches to 3 meters long whereas the tallest penguin, the Emperor penguin, is only about 1.1 meters tall. Nonetheless, most photos and movies make penguins seem to be taller than a yard.

Dr. Fondah: Penguins are flightless birds that first appeared on Earth about 62 million years ago, just after the extinction of big dinosaurs. Given the recent discoveries of feathered dinosaurs in China, penguins may well be a remnant of the dinosaurs.

Tim: Penguins are generally associated with Antarctica but I thought that you showed our class a photo of a Galápagos penguin.

Dr. Fondah: Yes. Mother Nature tricks the movie-makers once again. The equator runs through the Galápagos Islands and yet one still finds a penguin there, albeit well camouflaged.

Tim: I remember that the cold Humboldt Current sweeps up the Chilean coast from Antarctica but the water temperature still must be pretty warm by the time that current reaches the equator. I wonder how Galápagos penguins radiate body heat.

Florence: They stay near the water and pant like a dog if it gets too hot. They are only half-a-meter tall, so no part of their body is far from their heat-radiating surface.

Dr. Fondah: Although their small size helps them radiate heat, it makes them more vulnerable to predators such as sharks, fur seals, and sea lions in the water, and snakes, hawks, and owls on land. The penguins, in turn, mostly consume small schooling fish that follow the Humboldt Current, such as sardines.

Tim: I shudder to suggest that we return to Antarctica and check on the granddaddy of all penguins, the Emperor.

Florence: You would probably not be impressed if you approached an Emperor penguin and found that he barely reached your belly button.

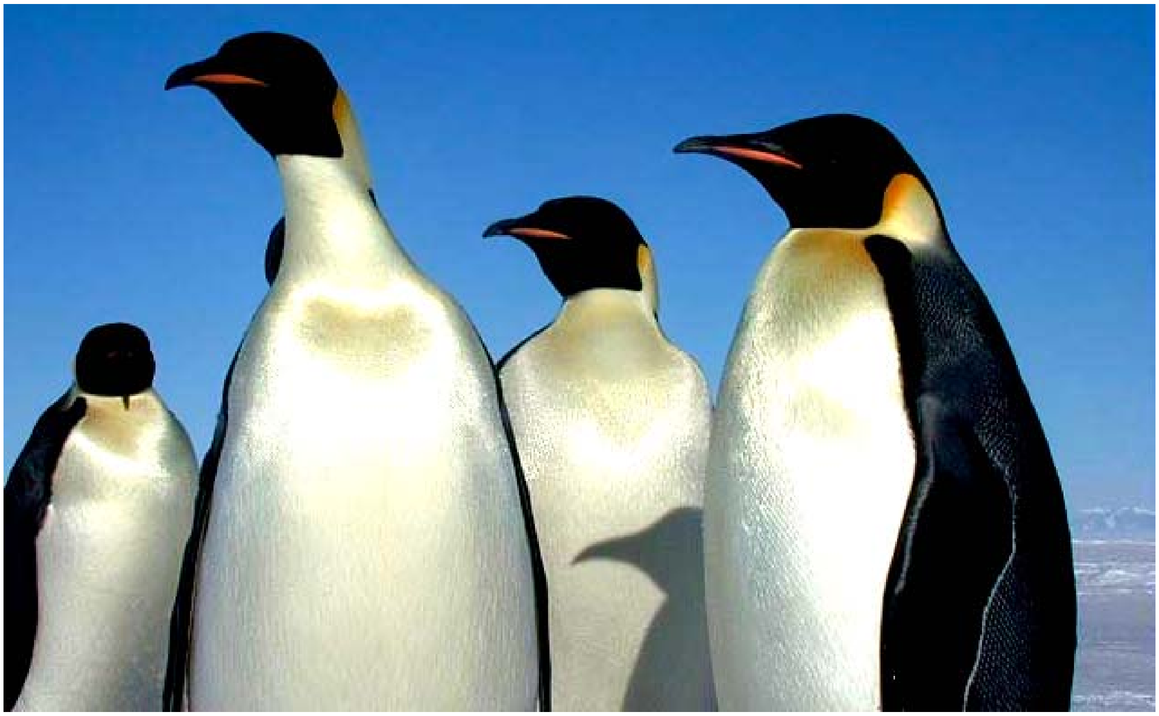
Dr. Fondah: Penguin documentaries normally emphasize the Emperor's patient endurance of the cold to keep their offspring safe from coastal marauders, and their selfless sharing of domestic duties.

Tim: There are so many movies and documentaries about Emperor penguins !! My theory is that girls love to make their boyfriends sit through those in the hope that something will rub off. Actually, I am more impressed at the penguins' ability to dive half-a-kilometer and stay submerged for nearly twenty minutes if chased down by a sea lion.

Florence: Penguins are well-adapted for deep diving, given strong bones that can support the pressure of overlying water, special hemoglobin that works well at low levels of oxygen, and an ability to shut down non-essential body functions.

Tim: Living in a place without unfrozen fresh water, they have adapted to drink seawater. They have a gland that filters excess solutes from their blood and they excrete that salt through their noses.

Dr. Fondah: Here are some of the famous Emperors. Fortunately, they did not have any runny noses when this photo was taken.



Florence: In coastal Antarctica, their food source is mostly crustaceans such as krill. They raise a single egg per year and typically live about 20 years if they make it past the first few months of life.

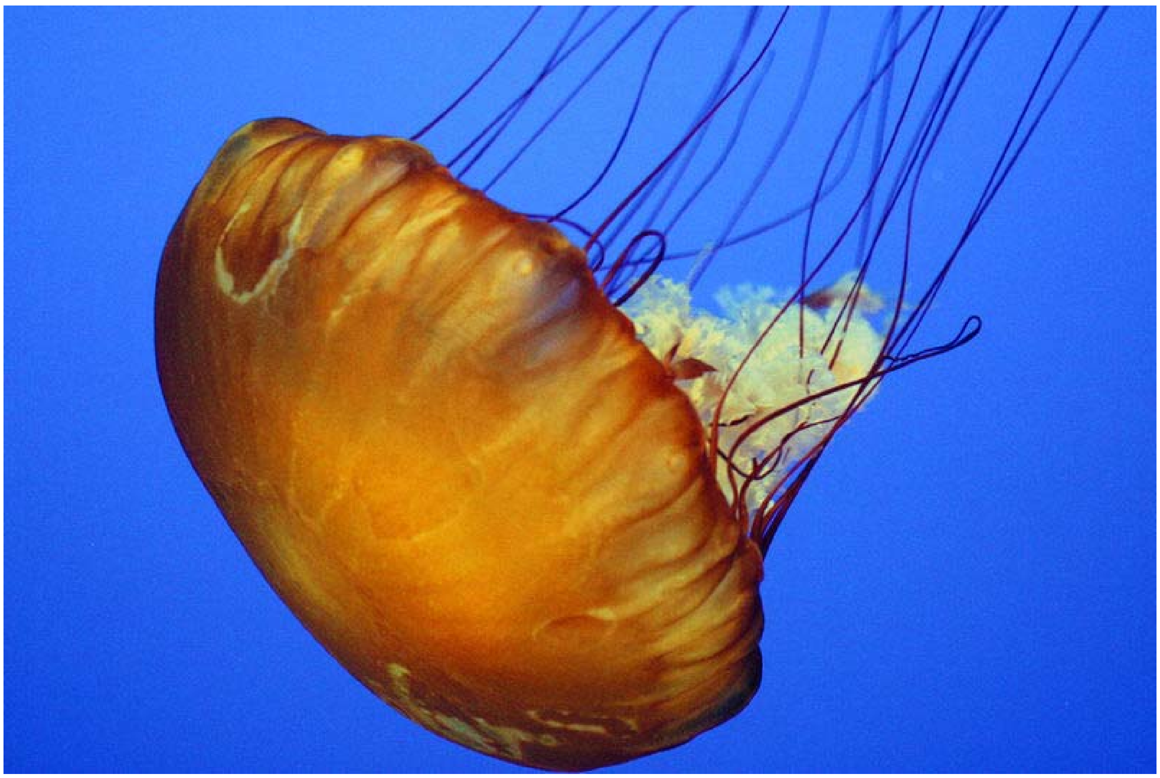
Dr. Fondah: Penguins were among the first flightless birds to become well-adapted to diving and swimming, given a streamlined body and wings that have become powerful flippers. Their feathers trap a layer of air that provides insulation against both the cold air and cold water.

Tim: The sharp color contrast between the black top and white bottom must be camouflage. An upward-looking predator would have trouble telling a penguin from the bright sea-surface whereas the black top would resemble the dark depths of the ocean to a downward-looking predator.

Dr. Fondah: Penguins, crabs, lobsters, and jumbo shrimp are all rather substantial animals. Let's consider something more slimy, a jellyfish.

Florence: As you know, the term "jellyfish" is a misnomer because these animals have nothing to do with fish. If anything, their name should be "jelly-anti-fish" because their numbers increase wherever overfishing opens environmental niches to these slimy creatures. I am going to call them what virtually every other Western language calls them, "medusa". If the English can abandon "tidal wave" for "tsunami", then perhaps they will abandon "jellyfish" for "medusa" some day. In the meantime, I will say "medusa".

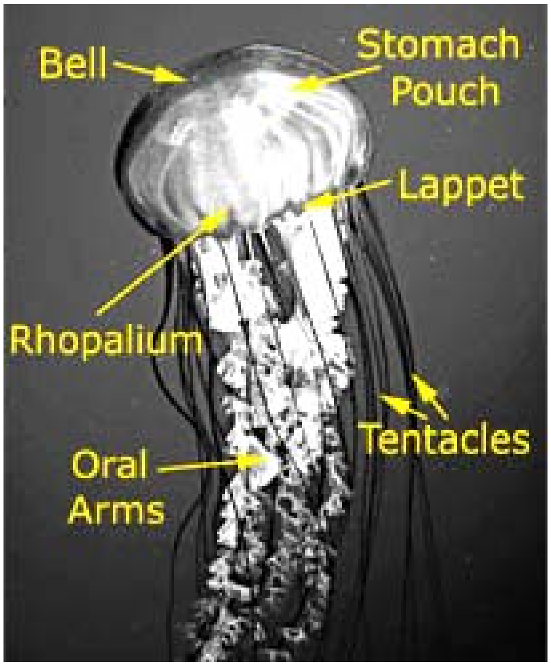
Tim: I doubt if logic will prevail with the English language. My high-school teachers told me not to bother trying to learn English grammar because it is so inconsistent. You would have to learn more exceptions than rules. Calling something a fish when it is not a fish seems pretty trivial compared to that.
Florence: Yes, but French does have grammar and logic, so I will say "medusa". Juliette also says "medusa".
Tim: Well, that settles it.
Dr. Fondah: I can't fight both of you, so I will join your Club Med. Here is a typical medusa, a sea nettle. This is a brain-less bag that moves where the currents take it.



Tim: Having been stung, I do have respect for the long tentacles of some medusae. Although rarely directly fatal, a medusa sting may cause a swimmer to panic and indirectly kill him.
Dr. Fondah: The vast majority survive with some tentacle fragments and their nematocysts still attached to the swimmer. These need to be removed with something like a credit card. Like treating a wasp sting, the best home remedy then involves a paste made from baking soda and ingestion of an antihistamine.
Florence: A medusa is an efficient predator despite lacking a central nervous system, a circulatory system, a respiratory system, a digestive system, or even a system to control the salinity of its body fluids.
Tim: The mouth also serves as its anus. How gross is that !!
Dr. Fondah: Oxygen has to diffuse through the skin to compensate for the lack of a respiratory system.
Florence: Although some medusae look fairly substantial, water typically constitutes more than 95% of their body mass. There is not much food value for us in medusae but we do

consume so-called cabbage heads here in the Southeastern USA. These are called cannonball jellyfish on the Pacific coast because they look like white cannonballs.

Dr. Fondah: When they are catching food rather than being food, medusae slowly open and close their bells to push themselves toward zooplankton and tiny fish that become entrapped in their stinging tentacles.



Florence: The ring around the base of the bell is called a lappet and it contains sensory nerves called rhopalia. If something touches a rhopalium, the tentacles get the message. Crude light sensors indicate the up-down direction. The oral arms have inspired famous paintings.

Dr. Fondah: This is Caravaggio's "Medusa". Snakes portray the oral arms in most paintings.

Tim: Medusa was a beautiful sea nymph in Greek mythology. After messing around with the god of the sea, Poseidon, she acquired the job of scaring away evil spirits, like the gargoyles on the corners of old buildings. I too would try to evade those oral arms.

Florence: Although the medusae of paintings are always female, there is an equal number of males in nature. Sperm are broadcast into the water and it is up to the sperm to swim into a female's mouth and fertilize an ovum. As we noted at the very beginning of our discussion of marine biology, this common practice of discharging sperm into the ocean does not favor the social dynamics that we mammals enjoy.

Dr. Fondah: Besides the familiar floating form of medusae, there usually is a juvenile sessile phase in their life cycle. Attached to the bottom, the juvenile's tentacles face upward to catch passers-by. The complete life cycle typically lasts just a couple of months.

Tim: What about my nemesis, the Portuguese Man O' War?

Dr. Fondah: I presume that you mean the colorful animal rather than the colorful ship from the fifteenth century. Most folks think that the Portuguese Man 'o War is some type of large medusa because it stings like one but it really is an even more primitive colony of tiny medusae and polyps.

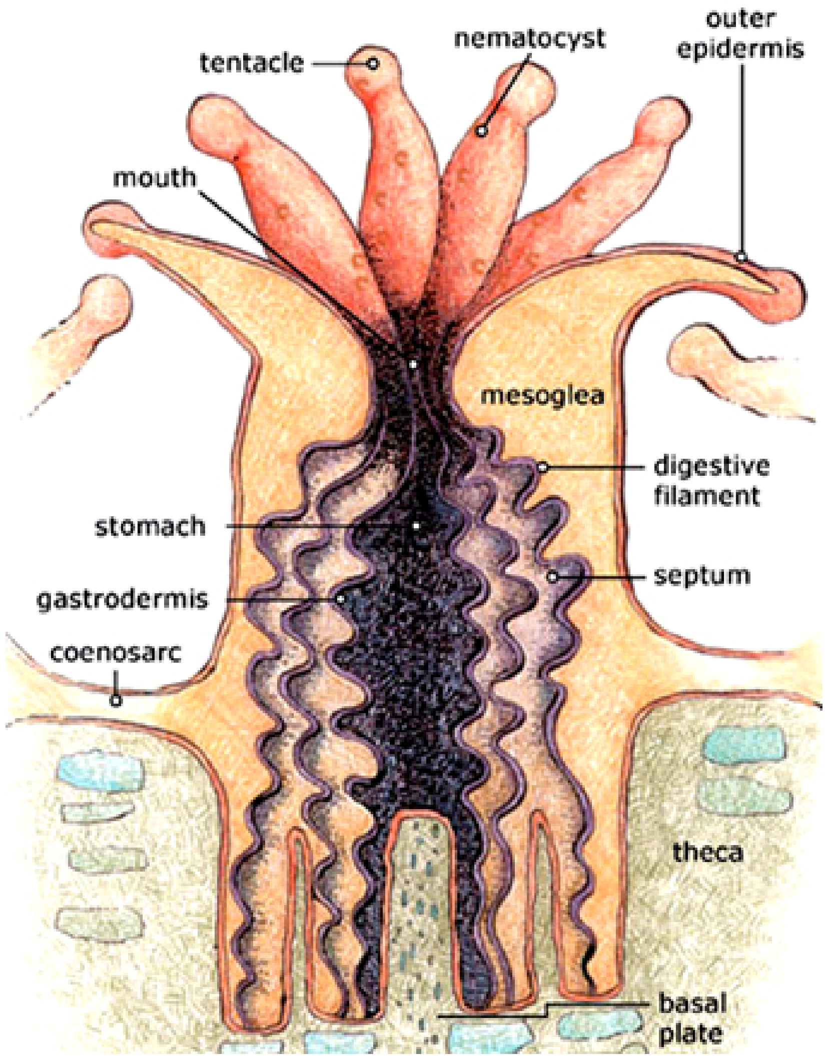
Tim: Unlike large medusae, the Portuguese Man 'o War has no means of locomotion. Its air bladder keeps it at the surface where the wind carries it. In my case, the wind carried it onto my back and the pain was excruciating. My friends applied hot compresses until they could get me to a hospital.

Florence: That was smart. Water around 45°C (113°F) can chemically alter the venom and make it less potent. If hot water is not available, one may apply ice to keep the venom from spreading. If the venom ever reaches a lymph node, the pain gets even more intense.

Dr. Fondah: Now that you have had a bad sting, even a minor encounter with a Portuguese Man 'o War could prove troublesome because you may have acquired an allergic reaction.

Tim: At least they are so brightly colored that I should be able to see them coming.

Florence: The most famous colony of polyps is, of course, coral. Divers and snorkelers sometimes discover too late that these beautiful structures also have stinging cells, nematocysts.



Dr. Fondah: Some of these labels seem intimidating but they are actually simple. The epidermis means “outer skin” in Greek whereas the gastrodermis refers to the stomach lining. Coenosarc is pronounced “see-nuh-sarc” and means “common tissue” because it is the tissue which adjacent polyps share.

Florence: In Europe, we used to consider colonial animals like coral and the Portuguese Man ‘o War to be fascists. They have strength through numbers. Fascism is a concept that dates from the Roman Empire. The symbol of authority for a Roman magistrate was a bundle of sticks wrapped around an axe. When Mussolini published his fascist manifesto in 1919, he called for an end to discrimination based on social class. If everyone worked for the common good, everyone would be fed and protected. He demonstrated this to the crowd by picking up a stick and breaking it. He could also break two or three sticks, with increasing effort, but he could not break four sticks tied together.

Tim: The original Roman concept was even popular in America through the 1930’s. Here is a dime that carried the fasces symbol.

Dr. Fondah: Here we see polyps working together in a staghorn coral.

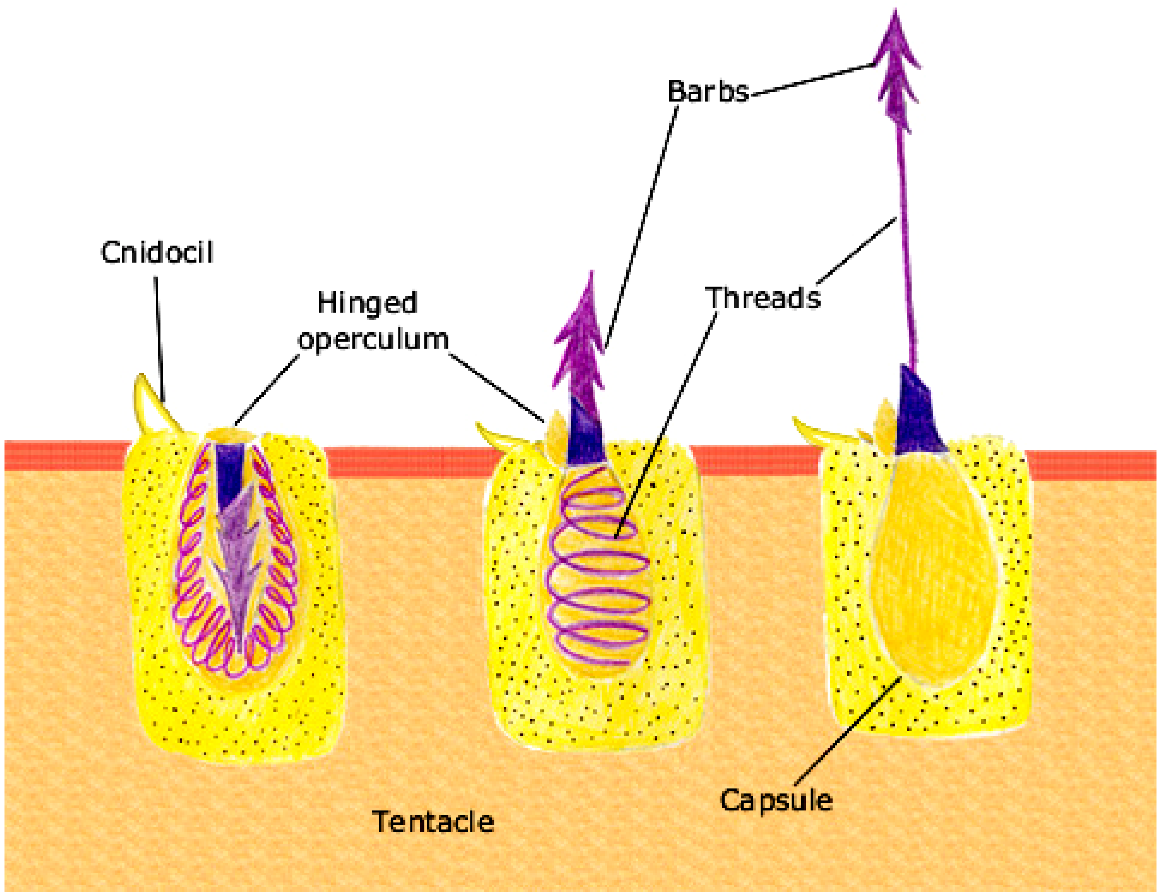
Florence: Here is a closeup of a cavernous star coral in the Florida Keys. The polyps shown here are just a couple of millimeters wide, about the thickness of a nickel, so these tentacles would be difficult to see with the naked eye.

Tim: When I get to Tahiti, I want to see a myriad of intergrown corals like these beauties.

Florence: When you get there, be sure to keep more clothes on than you see in television documentaries about exploring reefs.

Tim: Is this "clothes-on song" another cautionary jingle about Juliette?

Florence: No. This is a reminder that Cupid is not the only one that hunts with barbed arrows. Here is a sketch of what awaits you if you touch fire coral with your bare skin. Despite swimming in warm water, I would recommend a full-length, three-millimeter-thick wetsuit and a pair of tight-fitting but flexible gloves. Admittedly, only the fire corals will make you feel like you are on fire but you do not want to waste your time trying to spot them.



Dr. Fondah: The coral's illustrated ejection of a venomous barb is one of the fastest responses among all living organisms, estimated to take less than a microsecond.

Tim: Less than one-millionth of second? That beats the best electronic responses. I suppose that tiny prey are passing so fast that you either have to be quick or die of hunger. Like a gunfighter, you either are the quick or the dead.

Florence: I fear that the famous gunfighter phrase misinterprets Saint Peter who wrote of "…him that is ready to judge the quick and the dead." (1 Peter 4:5). By "quick", Saint Peter simply meant "alive", not necessarily the fastest draw in the West.

Tim: OK, but these corals have always had the fastest draw. How has one of the world's oldest and most primitive animals managed that?

Dr. Fondah: Besides being quick on the draw, corals are one of the fastest precipitators of calcium carbonate in the ocean. They combine these two abilities when they sequester a high concentration of calcium ions in their nematocysts and then pass those ions into the barb-holding cnidocyte when something presses the nematocyst's trigger. The high concentration of calcium ions invites dilution from ordinary seawater through a process called osmosis. As seawater rushes inward, the volume expands, blows the lid off the missile tube, and fires the barbed harpoon.

Tim: Gotcha!! I can't wait to put on my wetsuit and gloves to play with that type of Barbie.

Florence: The stunned prey becomes reeled in by the tentacles and swallowed.

Dr. Fondah: Despite development of this sophisticated predation, corals meet most of their energy requirements without lifting a finger, or should I say "tentacle". They largely rely upon a class of symbiotic algae living within them, the *zooxanthallae.*

Florence: The algae are safe within the calcareous structure and happily use both the carbon dioxide and nitrogenous waste from the coral's kills. However, the coral may become tired of the symbiont and evict it.

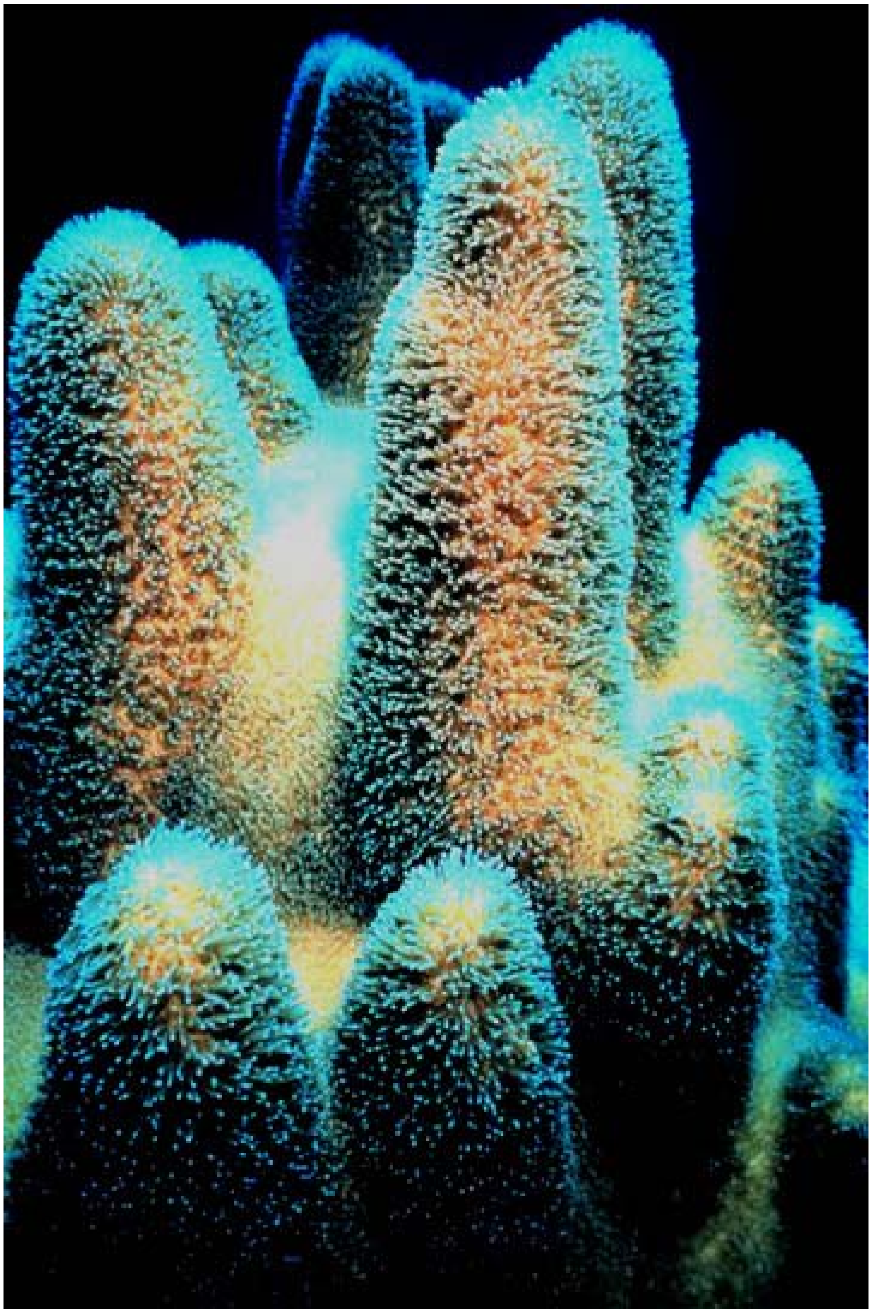
Dr. Fondah: It is obvious if this happens because the coral loses the brown pigmentation that comes from the algae. The coral appears to be bleached.

Florence: Although obviously suffering from stress, a bleached coral is not dead and may regain some symbiotic algae. Nonetheless, environmentalists may point to bleached coral as a potential indicator of marine contamination.

Tim: The bleached coral shown here seems to have responded to the stress of being eaten. Spiny sea urchins erode the calcium carbonate to create a nesting place.

Dr. Fondah: There are two types of calcium carbonate minerals, calcite and aragonite. They differ in the bond angles and distances among the calcium, carbon, and oxygen atoms. Some genera of corals precipitate calcite whereas other genera prefer to make aragonite.

Tim: I don't care what minerals are in corals. I just want to get lost among their gorgeous pillars as I swim around Tahiti. I could glide for hours, watching this vibrant interplay of tiny fish darting among waving tentacles.

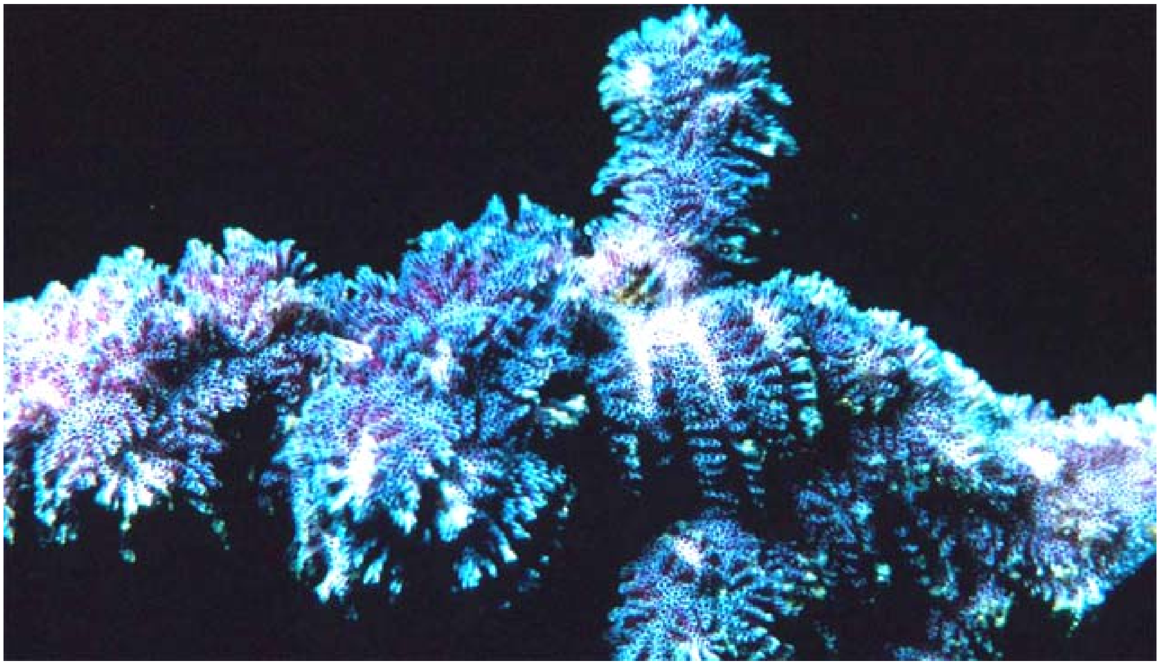


Florence: If you spend day-after-day swimming among the corals with Juliette, you might become just another of the simple life forms that populate reefs. Corals are among the earliest and most primitive animals, having been around for the past 542 million years.
Dr. Fondah: Given enough tropical sun and sangria, you could become a mellow mushroom coral, like this one.

Tim: Are you implying that my head will shrink smaller than this brain coral?

Dr. Fondah: To inspire you to contemplate something other than Florence's sister, let's get you to think about the sister organism for coral, the bryozoa. Bryozoan colonies are easily confused with coralline colonies but the individual bryozoans are much more sophisticated anatomically. Like us, they have organs within a fluid-filled body cavity, making us both coelomates (*pronounced "see-luh-mates"*).

Florence: Although more sophisticated than coral polyps, bryozoan zooids are no bigger and there may be more than a million within a colony, as shown here.



Tim: Zooid? I wonder if that is the source of my cousin's name, Zoey, spelled with a "y".
Dr. Fondah: Your cousin must not be in high-school yet.
Tim: How do you know that?
Dr. Fondah: Zoey with a "y" is a new species on this planet, having evolved from the "y-less" Zoe about a dozen years ago.
Florence: The bryozoan zooids evolved at least 480 million years ago. They may have evolved even earlier than that and lived without calcite-aragonite houses. Of course, only the houses become preserved as fossils. Here are some of those early fossils.

Tim: Every time I see a fossiliferous outcrop like that, I close my eyes and imagine myself swimming in that ancient ocean.

Dr. Fondah: You might have been safer in that ancient ocean than in the modern one because sharks had not yet evolved when these bryozoa were catching their daily ration of plankton.

Florence: Bryozoa and corals get eaten by something less massive but more prickly than a shark. They face the spiny sea urchin.

Tim: My diving buddies have had more trouble with sea urchins than with sharks, even though the spines are not venomous. Stepping on spiny urchins has proven to be painful and occasionally requires minor surgery to remove the spine, given that it will not dissolve like a sliver of wood. Here is one of those rascals, just waiting for a false step.

Florence: The name, urchin, comes from a nickname for the hedgehog, a European mammal that curls into a similar-looking spiny ball if scared.

Dr. Fondah: Although the sea urchin looks perfectly spherical, it is not. It belongs to a five-sided phylum called the Echinodermata, along with more-obviously five-sided animals such as starfish.

Florence: The spineless remains of sea urchins commonly wash up on shore and these tests display the five-fold symmetry clearly.

Tim: I got lucky and found a couple of fossil specimens while on a field trip. These guys come from the 45-million-year-old Castle Hayne Formation. Castle Hayne is near Wilmington, North Carolina. My instructor told me that urchins are among the most ancient animals, first appearing in the Late Precambrian. That was more than 600 million years ago.

Dr. Fondah: To live long and prosper, an animal must be good at catching food. If anything touches a sea urchin's spine, the other spines converge and help to hold it. Tube feet allow the sea urchin to roam and find new food.

Florence: If sea urchins migrate over an area, they can eat all the kelp, clams, sponges, and other types of echinoderms, leaving a desert in their wake. However, sea otters and wolf eels prey on them, helping to maintain an ecological balance.

Tim: I want to look at another echinoderm, the common starfish that is found in the northern Atlantic seaboard.

Dr. Fondah: These guys have two stomachs, one of which they can eject and wrap around prey that is too big to pass through their mouth, including clams and small fish.

Florence: Starfish can live for several weeks without feeding, apparently because they are able to absorb dissolved organic matter from seawater.

Tim: I am more impressed by their ability to regenerate legs. They can lose four of their five legs in battle and regenerate the missing four. This reminds me of all the movies about bionic people, people that have been regenerated after losing major body parts in accidents or warfare.

Dr. Fondah: My top students in marine biology go on to become medical researchers, so we keep getting closer to having life imitate art.

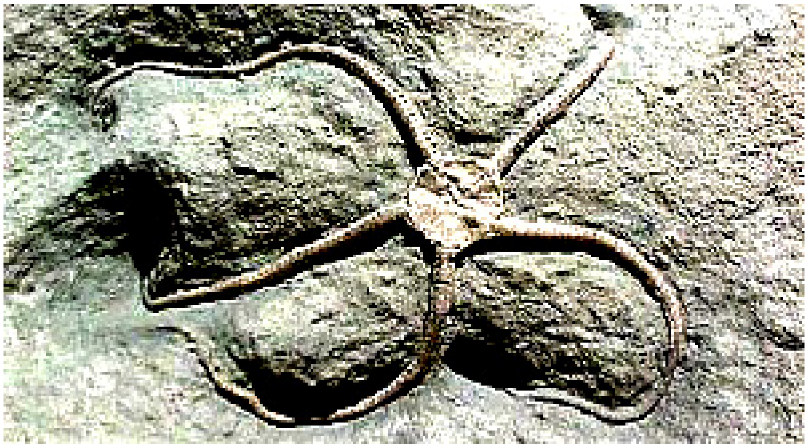
Florence: Like us, starfish have an internal skeleton, an endoskeleton. This allows both of us to preserve our shape while moving.

Dr. Fondah: Although they lack a brain, starfish have a complex nervous system that lies both within and beneath their skin. Besides responding to touch and the presence of water, starfish are sensitive to temperature, light, and their orientation.

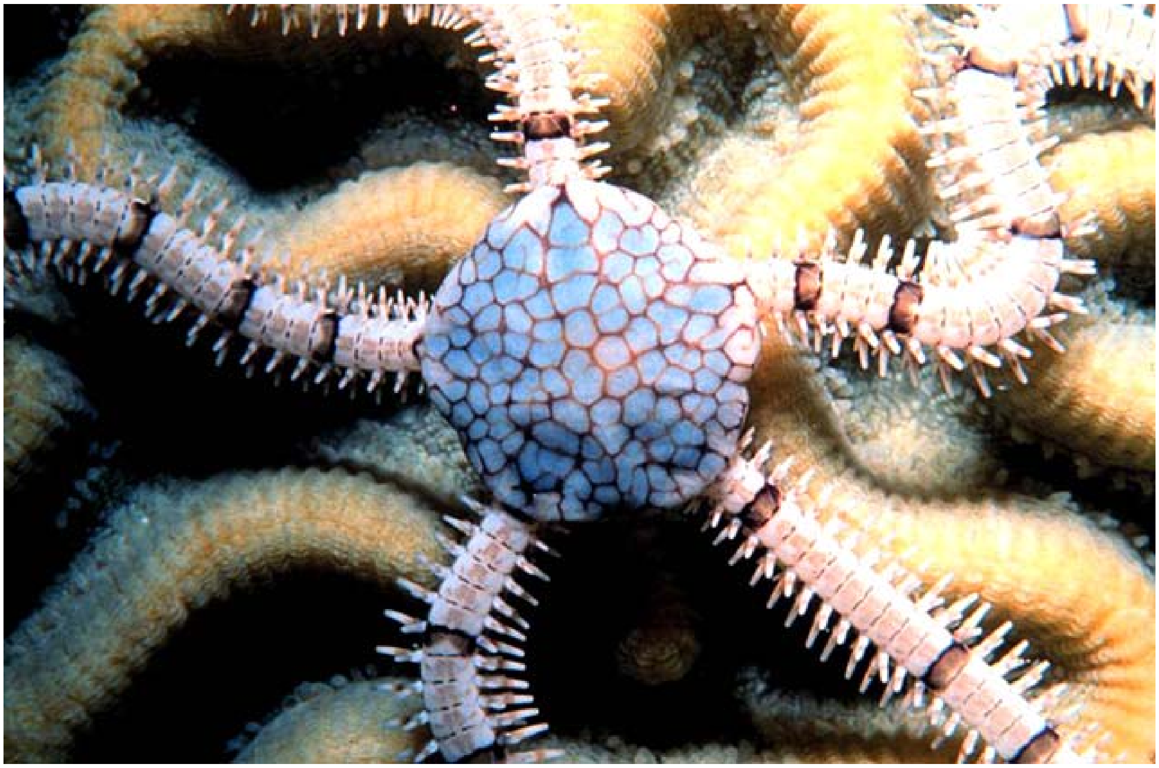
Tim: Starfish remind me of a hovercraft because they move by shooting water out tubes on their underside, much as a hovercraft shoots jets of air. The intake valve is on the top, a little off-center, as seen here.

Florence: Tube feet are not used for locomotion by a closely-related echinoderm, the brittle star, as seen here. Brittle stars bend their slender arms to slither around like snakes.

Dr. Fondah: These beauties were around with the dinosaurs in the Jurassic Period, as proven by this fossil.



Florence: Here is a brittle star that rivals the best turquoise brooch sold by Cartier. This brittle star is resting on a brain coral.

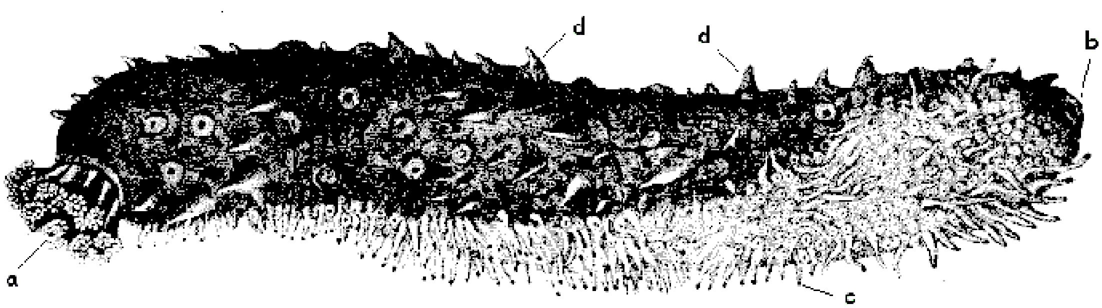


Tim: I am not impressed with jewelry but I enjoy playing with another echinoderm, the sea cucumber. As implied by its name, it looks and feels like a cucumber so it cannot readily defend itself. When stroked, it reacts by puffing itself up and shooting water out one end. The Chinese have been so excited by this reaction that they have been importing sea cucumbers for centuries and selling them as an aphrodisiac.

Dr. Fondah: There is no biological reason for sea cucumbers to be an aphrodisiac but there is increasing evidence that they help in the healing of human tissue. Like all echinoderms, sea cucumbers are masters at self-healing and they are rich in fatty acids that help in the repair of human tissue.

Florence: I love to approach these harmless sea cucumbers when diving. I have had so many cucumber slices placed on my eyes by makeup artists that I feel a close association with these guys.

Dr. Fondah: Given that they are harmless, let's dissect one of these creatures. The mouth and its tentacles are on the left (labeled **a**) whereas **b** labels the anus. The Spanish word for sewer, cloaca, is normally applied to the sea cucumber's anal area. One of the myriad of feet is labeled **c**. In keeping with the Spanish-Latin nomenclature, these are called ambulacral feet, literally "walking feet".



Florence: Yes; "ambulare" is the Latin verb, "to walk". Napoleon invented the walking hospital, l'hôpital ambulant, to care for his wounded troops. That gave rise to the modern ambulance.

Tim: These cucumber feet look more like crawling feet to me.

Dr. Fondah: The feet are on the ventral side whereas label **d** is on the dorsal side. Virtually all large fry are described with this same ventral-dorsal nomenclature because a horizontal extension is the marine standard. In contrast, more of us land-lubbers extend vertically so that we can see over the next guy.

Tim: … and dunk over him.

Dr. Fondah: Label **d** refers to small protuberances called papillae. These contain sensors.

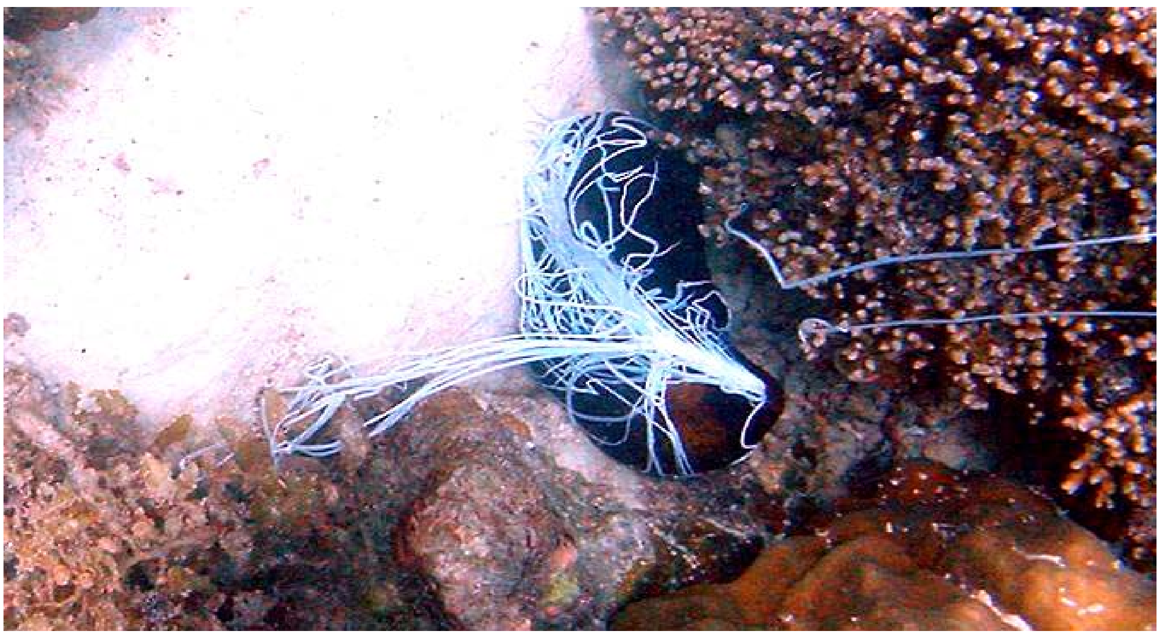
Florence: The human tongue also has papillae to help us taste our food. Of course, French people have far more papillae on their tongues than any other ethnic group.

Dr. Fondah: … or at least you guys make better use of the ones you have. Was it you that convinced Tim that sea cucumbers are Chinese aphrodisiacs?

Florence: Of course. How else could the Chinese have become the world's most populous ethnic group?

Tim: Now I'm confused, so I am going to take a closer look at the squirty end of a sea cucumber. I am not alone here because there is a wide range of animals that swallow their pride and live within the sea-cucumber's anus for protection. These pay-nothing boarders also get first dibs on leftovers from the sea-cucumber's digestive tract. The free-loaders include tiny fish, crabs, and worms.

Florence: Once I startled a sea cucumber and he slimed me, to borrow a phrase from the Ghostbuster movie. The effect was pretty much like the movie. I spent so much time trying to get the sticky goo off of me that I lost all interest in catching him. It did not make it any better to know that the slime came out of his anus. Here is a sliming sea cucumber.



Tim: Hey. That does look like the movie.

Dr. Fondah: The original Ghostbuster movie was released a quarter-century ago. Somehow, I doubt if our own little production will be remembered that long.

Tim: What if they discount our DVD after a while, the way they discount Ghostbuster DVDs?

Dr. Fondah: Let's face it. After a couple of years, they won't be able to give them away.

Florence: Oh no. I think that I have been slimed again, and by a professor this time.

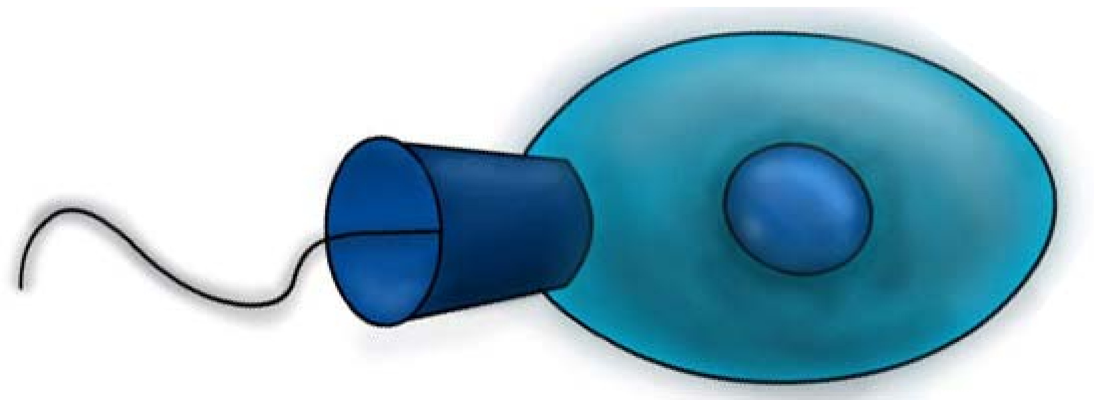
Dr. Fondah: Undaunted, we move on to sponges, an even more harmless animal. There was a time when all domestic sponges were natural sponges, harvested for that purpose. One may still buy a natural sponge but the petroleum industry has effectively taken over that business, along with its takeover of the rubber, clothing, carpet, and candle businesses.

Florence: The sponge is one of the most ancient animals on Earth, dating from nearly a billion years ago. They are sessile water pumps that lack muscle, nerves, or any internal organs.

However, they have adapted to every water depth from the intertidal zone to nearly the deepest depths of the ocean.

Dr. Fondah: We know of 5000 sponge species and keep finding more, as we explore the lower ocean with our deep-diving submersibles.

Florence: The pores of sponges are rimmed with cells that are very similar to an independent organism called a choanoflegellate, shown here. It is these flagellae that keep water moving through the porous sponge structure.



Tim: On my last Spring Break, my buddies and I bought all the sponges shown here and we had "sponge wars". We would saturate them and heave them off our balcony at passing beauties. Of course, the girls collected the sponges and retaliated whenever we left the hotel. They won that war because they had higher balconies and lower concerns about actually hitting someone on the head.

Dr. Fondah: You're lucky that nobody ended up with a broken neck. Natural sponges contain hard spicules made of either silica or calcium carbonate.

Florence: We French ladies do not have to resort to caveman tactics of hitting someone over the head.

Tim: I'm not sure about that. Juliette has landed on me like a penthouse sponge bomb.

Florence: Well, I did warn you to duck. You never should have taken that midnight stroll with her onto the tidal pool.

Tim: She gave me a couple of strawberry daiquiris and then took me out to see these beautiful pink sponges.

Florence: If you are not careful, you will end up like this shell from a North Carolina beach, perforated by boring sponges. Even Al Capone did not drill his enemies that many times.

Dr. Fondah: Despite being animals, sponges seem more like plants because of their sedentary life-style. Another sessile animal is the tunicate, shown here.

Florence: Although stationary as an adult, tunicates are more similar to the mobile sea cucumbers than to sedentary sponges. Like sea cucumbers, tunicates have yellow, vanadium-enriched blood rather than the iron-enriched blood of mammals. Like sponges, they ingest plankton and have a fossil record back into the Precambrian Era, more than 600 million years ago.

Dr. Fondah: Tunicates get their name from a thick coating, a tunic that they develop once they achieve the sessile stage.

Tim: Tunicates would not last long in my hillbilly hometown. They are AC/DC.

Dr. Fondah: AC/DC? I presume that you refer to them being hermaphrodites, having both male and female genitalia.

Tim: I have known some girls who were in love with themselves but being a hermaphrodite takes this notion too far.

Dr. Fondah: Another strange tunicate characteristic involves eating its own brains. Once a mobile larva cements itself to a rock and begins its sessile stage, it "burns its bridges" by eating the portion of its brain that it previously used for navigation.

Tim: When they get locked up, the key is thrown away.

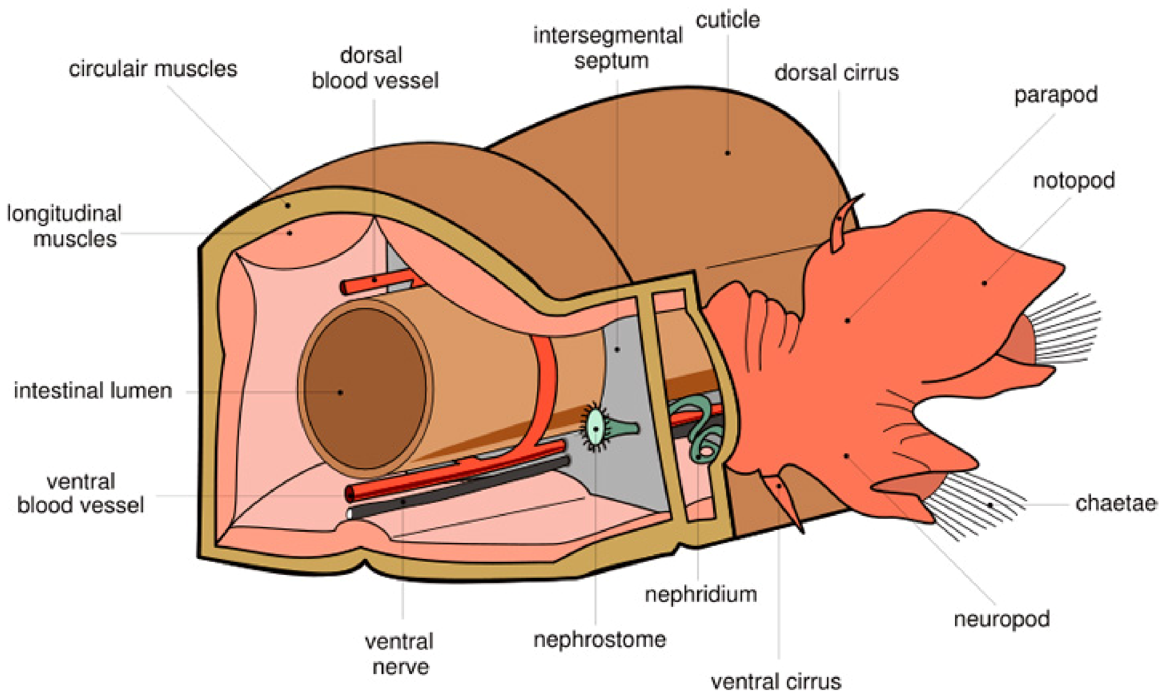
Florence: Aquaculture managers would like to find that key because tunicates are one of the worst scourges in their huge tanks, adversely affecting the cultivation of useful seafood.

Dr. Fondah: Like tunicates, bristle worms are more complicated than they seem at first glance. Also known as polychaetes, bristle worms get their name from bristle-looking chitinous protrusions that extend from each segment of their body.

Tim: Typically, they burrow into the seafloor and construct mounds around their excavations with the burrowed sediment. One of my buddies in grad school got an extension hose for his shop vacuum cleaner and sucked up one of these polychaete mounds, worm and all.

Dr. Fondah: Yes, and his advisor got a widely-cited publication out of it. That gave him one more publication than me for the year, and a much bigger raise.

Tim: I guess that proves that the best faculty members are those with suckers for grad students. Here is what they published when they sucked up that polycheate and dissected it.



Florence: Even these polycheates have a dorsal top and ventral bottom. The wing-looking parapod is the chitinous protrusion between each segment. It helps with locomotion but also serves as a gill, acquiring dissolved oxygen.

Dr. Fondah: The nephrostome collects body waste and passes it outside through the nephridium. In anatomy, a lumen is a cavity through a tubular animal.

Florence: That's a rare usage of the term, lumen. A lumen is the metric unit for the flux of light, and that is what lumen almost always means.

Tim: The most remarkable feature of polycheates is their ability to withstand extremely high temperatures, higher than those tolerated by any other complex animal. That tolerance allows them to inhabit hydrothermal vents on the deep seafloor.

Dr. Fondah: Despite near-boiling temperatures, the hydrothermal environment offers the advantage of providing lots of bacterial food. The bacteria obtain their energy by catalyzing the precipitation of solutes carried by the hydrothermal effluent.

Florence: The deep-sea environment is the best-protected environment for any of Earth's animals. The deep sea is little affected by climatic change, volcanic eruptions, or tsunamis.

Dr. Fondah: Even the asteroid-impact disaster that knocked off the big dinosaurs would not have affected these deep-sea polycheates because their food source is independent of photosynthesis. The global demise of big dinosaurs has been attributed to occlusion of sunlight for a couple of years due to atmospheric dust from an asteroid impact.

Tim: I have never liked that dinosaur theory because the dust from massive volcanic eruptions comes down within a couple of months rather than a couple of years. Moreover, the demise of the big dinosaurs was not as instantaneous as implied by the asteroid theory.

Dr. Fondah: I must admit that only about half of the dinosaur experts support the asteroid-impact theory even though virtually all of the scientific journalists and introductory instructors support it.

Florence: Whenever one doubts a theory that is championed by all the textbooks, it is best not to vocalize that doubt but remain "as silent as a clam".

Dr. Fondah: Clams !! Allow me to vocalize about clams and other mollusks. You may recall that my other student, Ben, did not like oysters slithering down his vocal chords. I wonder what crawling he is doing now for Diane.

Florence: You can be sure that Diane has him crawling like a doomed oyster.

Dr. Fondah: Within tropical lagoons, oysters are most commonly found on the roots of the red mangroves that rim the lagoons. The vertical range of live oysters conveniently records the tidal range in the lagoon.

Tim: Oysters must have been a readily available food source for ancient peoples because my archeology instructor showed us lots of photos of oyster dumps left by those ancient civilizations. One site in Maine accumulated oyster shells from 200 B.C. until 1000 A.D., reaching a thickness of 10 meters over an area of 500 meters by 500 meters. One can only imagine the number of Native Americans who ate all those oysters.

Dr. Fondah: You are not supposed to rely upon your imagination in science. You are supposed to estimate quantitatively.

Tim: OK. The volume of that oyster dump is 2.5 million cubic meters. The space occupied by each oyster shell is about 250 cubic centimeters, making a total of 500 cubic centimeters for each bivalve animal. That amounts to five billion oysters. The 1200-year time span of oyster dumping totals about 440,000 days, so the consumption rate approximated 10,000 oysters per day. If everyone who used the dump ate five oysters per day, then the local population of consumers would have approximated 2000 people, on average, throughout the 1200 years.

Florence: Are all Americans born to calculate like businessmen? I know that some American entrepreneur ignored this priceless native heritage a century ago and ground up most the oyster shells for use as chicken feed.

Tim: Unlike Ben, I **love** to eat raw oysters. This is what I like to see on my plate.

Dr. Fondah: Although movies commonly show somebody finding a pearl within an edible oyster, pearls actually occur within inedible species.

Florence: The most famous pearl collector in all of history was a guy who did not set out to find pearls. He was not exactly on a humanitarian mission either. It was Columbus.

Tim: So this Columbus dude ran into the richest real estate on Earth and all he managed to bring back to Spain was pearls?

Florence: Well, they were some of the biggest pearls that anyone has found anywhere. Columbus discovered them just south of Dr. Bowles' island, Margarita. In fact, Columbus chose the name, Margarita, because it means "Cry of the Sea", a nickname for pearls.

Tim: Finding a Margarita-sized pearl would certainly make **me** cry for joy. Here is somebody digging out one of those sweethearts.

Florence: Queen Isabella of Spain did not use Columbus' pearls very wisely. She distributed them as gifts to the other European royalty and that started the equivalent of a gold rush as several other countries sent ships to Margarita to find additional pearls. The Spanish countered by producing false maps which were designed to mislead those sailors. Here comes Christopher to visit Isabella, hat in hand.

Dr. Fondah: Dr. Bowles tells me that there are so many clams around Margarita Island that nobody goes hungry. However, oysters are not the most-commonly-eaten variety. Much more abundant is a small clam that thrives in the surf zone, a variety that is called chipi chipi in the Caribbean. In America, it's called a bean clam. The shell is about an inch wide (2.5 cm).

Florence: On some Caribbean beaches, I have found that if you wade out until your legs are covered with water and then bend over to scoop up the sand with both hands, you will almost always find one of those clams in that sand. I used to collect them to garnish my spaghetti. They are very tasty, and the price is right.

Tim: Juliette gave me a necklace made of those shells. Every shell in the necklace had slightly different color markings. Here is just a small sampling of the variety.

Dr. Fondah: Clams are a peculiar combination of haves and have-nots. They generally have a mouth, heart, kidney, and anus, but no eyes. In fact, they have no head, except in the case of scallops. Here is a scallop, one of my favorite types of seafood. Scallops are relatively large and long-living, surviving up to 18 years. Like the tunicates, they are hermaphrodites because they can change their sex.

Tim: I somehow doubt if Juliette could do that.

Florence: It might be a cure for your sad case of infatuation.
Dr. Fondah: Scallops belong to the Pectinidae family. The pecten shape has become internationally famous as the logo for Shell Oil Company. Here is a fossil pecten that lived about 350 million years ago within a shallow sea that covered Ohio.

Tim: I have had my fill of shellfish. How about some real fish?
Florence: Fish on a plate may taste good, but they are not very interesting. If you want to find interesting fish, you need to swim in the natural equivalent of an aquarium.
Tim: You mean that I can swim among the same tropical fish that I see in an aquarium? You may sign me up for that tour of duty.
Florence: No problem. You just need to get Juliette to take you to Boca Chica in the Dominican Republic. She knows it well. It's just fifteen minutes from the main airport. Of course, that makes it just thirty minutes from the three million people living in the capital, so Boca Chica gets crowded on the weekends. Through the week, however, it's just you and the tropical aquarium.
Tim: Why are all the colorful fish there?
Florence: The Boca Chica lagoon is protected by a drowned reef that serves as a breeding ground for lots of life forms. You will have to swim out about four hundred meters to the mangrove islands along the former reef to see the fish. However, once you approach those

islands and become surrounded by gorgeous tropical fish, you might even forget about Juliette for a while.

Dr. Fondah: I have not swum in the placid waters of the DR's Boca Chica but I have seen a similar display of tropical fish in the rough surf of Playa Hobos, at the northwestern corner of Puerto Rico. The Playa Hobos surf is so dangerous that the Puerto Rican government has posted a "No Swimming" sign there, but your personal safety on land is so much greater in Puerto Rico than in the Dominican Republic that it all balances out.

Florence: I have swum among the surfers at Playa Hobos and I admit that the total variety of sea life there probably exceeds that at Boca Chica, but if you are just interested in colorful fish, you cannot beat Boca Chica. Here is a sampling. Let's start with a yellowish angelfish.

Dr. Fondah: I prefer a deep-blue-and-red angelfish, like this one.

Tim: My folks have lots of royal gramma in their aquarium, just like this purple beauty.

Florence: A common sight at both Boca Chica and Playa Hobos is the yellow butterfly fish.

Tim: If I were being stalked by a shark, I would want to be like the butterfly fish and appear to be heading in the opposite direction from which I would actually go to escape. Of course, it would be even better to fade into the background like the clownfish.

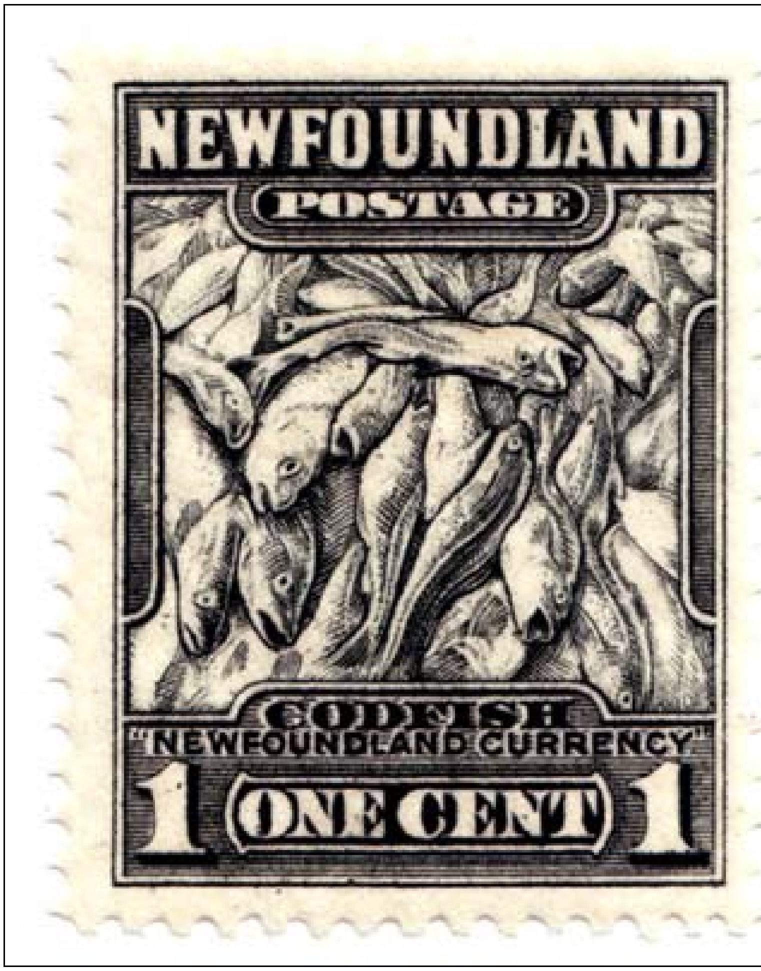
Dr. Fondah: Before you try stalking these little beauties, you should learn to stay away from the venomous lion fish that often accompanies them, as shown here.

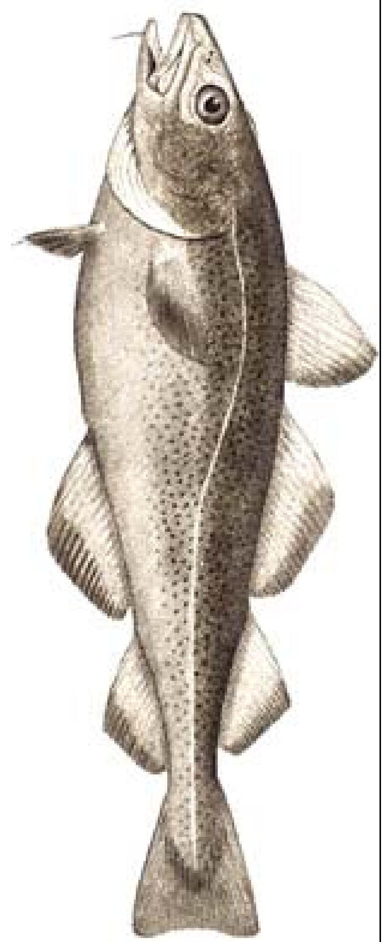
Florence: The venom in the spines of the Caribbean variety of the lionfish has an effect like that of a wasp bite whereas the venom in the spines of the similar-looking Pacific variety could kill you. That difference follows the general rule that Pacific cousins of all venomous Atlantic species tend to be deadlier.

Dr. Fondah: We have presented just a few of the tiny tropical fish that delight our visual senses. Rather than examine dozens more, let's move on to some larger fish that delight our sense of taste.

Florence: Unfortunately, too many people like the taste of cod, tuna, grouper, swordfish, and sea bass, so these fish have all become overfished, at least locally. If you take Juliette to a seafood restaurant, you will see her pull out a chart of endangered species before she places her order.

Tim: I would borrow her chart for the opposite reason, to make sure that I get to taste one of these delicious fish before they disappear. I cannot believe that cod is on that list. The Grand Banks of Newfoundland used to be swarming with cod, right where the nutrient-rich Arctic current meets the warm current from the south. I even have an old stamp which claims that cod is the currency of Newfoundland.





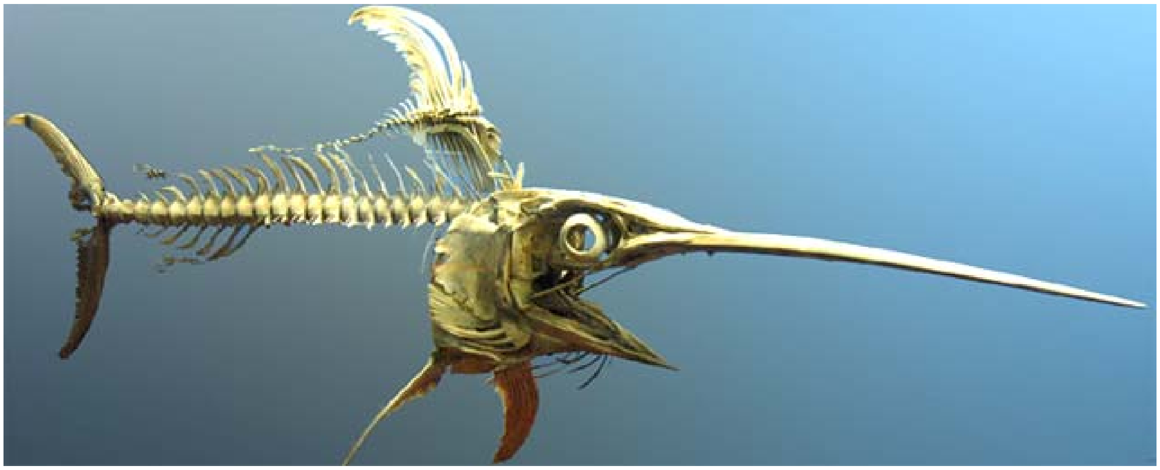
Florence: Perhaps the greatest fishing story of all time has come from John Cabot who discovered Newfoundland for the English in 1497. He claimed that the cod were so plentiful that they slowed his ship.

Tim: Tins of tuna keep getting added to the grocery shelves even though tuna has been added to some lists of endangered fish.

Dr. Fondah: I hear that a whole tuna at the Tokyo fish market may sell for thousands of dollars, and that a sushi-grade tuna may sell for tens of thousands of dollars.

Florence: The Tokyo fish market is the biggest in the world, and a favorite destination for tourists like me. Each tuna is auctioned after it has been sampled for its sushi potential.

Tim: Another big fish that I enjoy is the swordfish. My favorite exhibit at the National Museum of Natural History is a swordfish skeleton that I have nicknamed "Don Quijote".



Florence: I did not know that you were so literate. Maybe there is hope for you and Juliette after all.

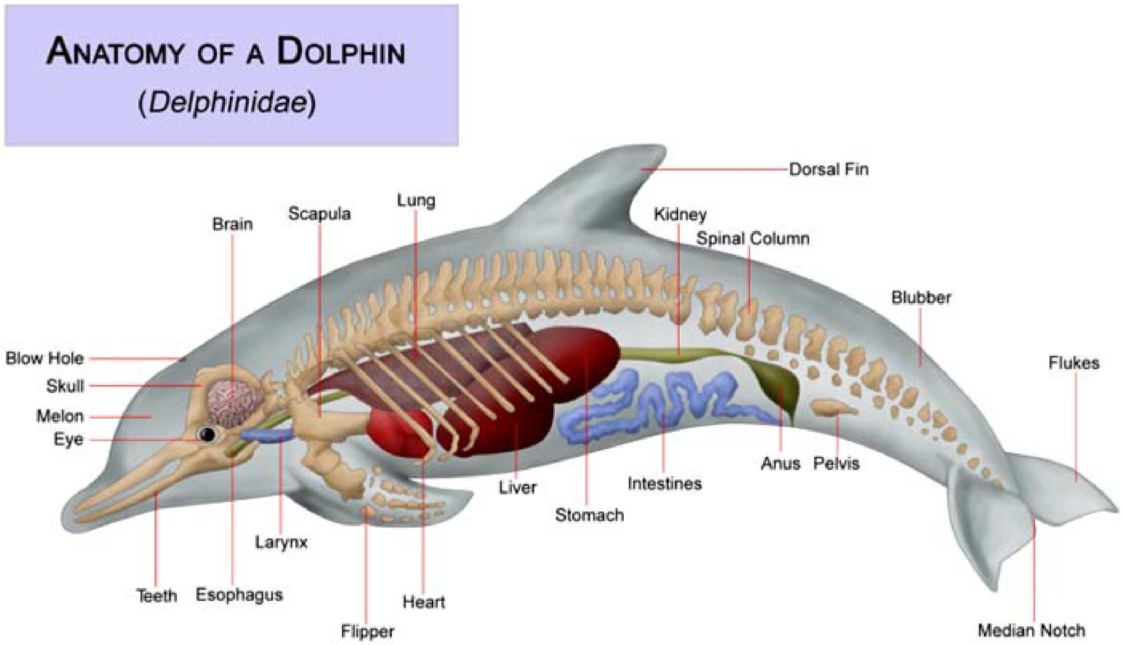
Tim: Only if I can get her interested in deep-sea fishing. Of the roughly 22,000 types of cold-blooded bony fish, the swordfish is one of just a handful that provides tiny heaters for its brain and eyes. This is no glassy-eyed moron but a great competitor for sport fishermen.

Florence: My favorite creature in the sea is the dolphin. While lounging on the bow of our yacht, I love to watch the dolphins race along beside us, occasionally diving under the yacht to reappear on the other side. They must know that we are both mammals. Here is a human-like dophin fetus that is just one inch (2.5 cm) long. The scale is a hairpin.

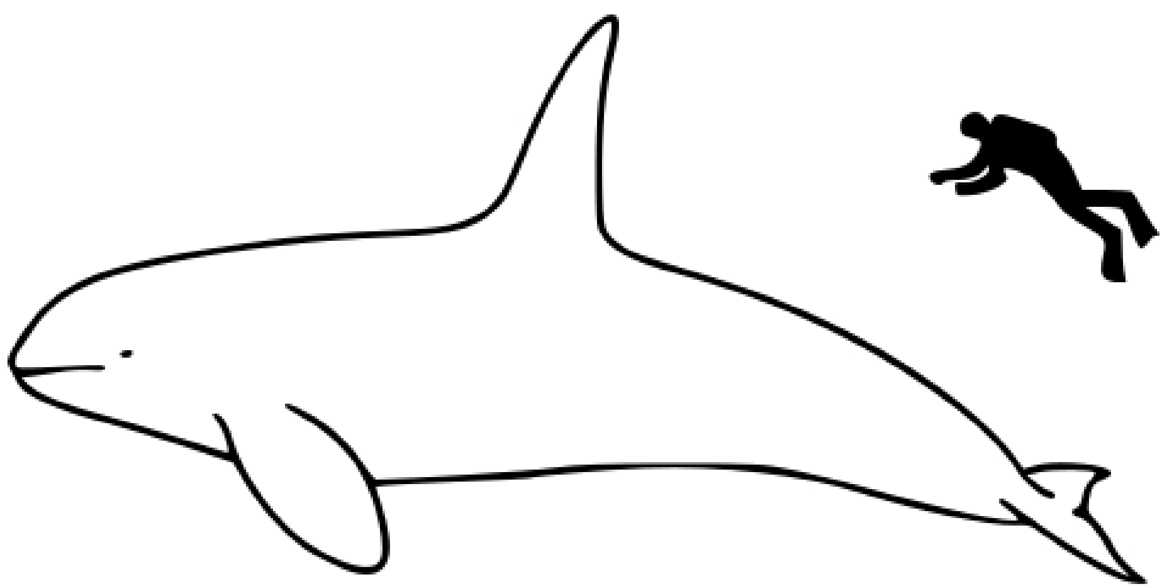
Tim: I don't get to see dolphins alongside a yacht but I love watching their acrobatics at an aquarium.

Dr. Fondah: Although the dolphin starts out as a humanoid fetus, it develops into a mammal that is wonderfully adapted to the ocean. Whereas our pelvis is the biggest bone in our body, it is reduced to a trivial size in the dolphin. Although we blow air out of our mouth, the dolphin blows it out of the top of its head. Whereas our fingers are all separate to grasp objects, finger bones in the dolphin are all enclosed within its flippers. The dolphin's teeth extend farther back into its head, allowing it to hold prey that we would hold with our hands.

Florence: Here is a sketch of dolphin anatomy. My favorite part is the flukes which have inspired countless "tails" of mermaids.



Dr. Fondah: Dolphins have also inspired the French monarchy since the thirteen hundreds when they started calling the heir apparent the "dolphin". Calling the equivalent English heir the "Prince of Wales" sounds more respectable to me.
Florence: Le dauphin, s'il vous plaît, mais jamais le "dolphin". Quelle honte !!
Tim: Before you guys restart the Hundred Years War, let's consider the greatest animal on Earth, the whale.
Florence: ….et n'oubliez pas que le plus grand guerrier dans la Guerre de Cent Ans était Joan d'Arc.
Tim: Hey, truce !! I'm bringing in a killer whale to restore order here.



Florence: Wrong again !! The so-called killer whale is not a whale at all, but a type of dolphin which is better named an orca.
Dr. Fondah: Alright, but they do deserve the name, killer, because they prey on sea lions, seals, fish, and even whales that are considerably bigger than they are.
Tim: The Romans named the orcas after Orcus, god of the Underworld. I think that I would rather take on the Underworld than an orca.
Dr. Fondah: The orca world is well-organized socially, with a tendency for matrilineal associations. In other words, all members relate back to a great-grandmother through their mothers. Orcas live about as long as do humans and come to sexual maturity at a similar age.
Florence: Orcas cooperate closely while hunting and they sing to each other. As with humans, different groups have distinct dialects. Here they are breaching near the Aleutians.

Tim: Although orcas rarely attack people, those rare attacks are often fatal. It is more common for people to be attacked by sharks but those attacks are less frequently fatal.
Florence: If the dolphins are not around my yacht, I may see a shark cruising by. Contrary to popular belief, they do not consistently display their dorsal fin as they swim.
Dr. Fondah: The shark is designed to take chunks out of its prey rather than swallow it whole. That allows it to take on large prey like people. The shark may lose so-called teeth in the process, but that does not bother the shark since they are not really teeth. They are just overgrown scales that can readily be regenerated. Here comes one of those killing machines.

Florence: I was chased by a blue shark once, off the northwestern coast of Andros Island in the Bahamas. I only had ten meters to go to reach a rock ledge whereas the shark had to swim 150 meters to reach me. The shark won that race, but it decided to rub against me first and spin around while determining if I were some type of bait. By the time it turned back to bite me, I had climbed up the ledge. It filled all the meter-deep water under the ledge for a couple minutes, trying to figure out where I had gone. I nearly fainted and fell on him.

Dr. Fondah: That must have been scary. The closest that I came to shark trouble in the Bahamas was the day that I was sitting on the edge of a research raft with one of my flippers dangling in the water, getting ready for a dive. A shark bit off the end of that flipper, just missing my toes. My research crew then decided that it was a good day to work on their tans.

Tim: It's strange, but I never see those stories in the travel brochures. I guess that they do not want to scare away the tourists.

Florence: When I told my shark story to the Bahamians, they assured me that only the tourists are dumb enough to go in the water. They also noted that an orca will occasionally show up in one of their bays and become the resident consumer for a few weeks.

Dr. Fondah: Before marine biology becomes marine necrology, let's try to find a real whale. Given their enormous size, it should not be difficult.

Florence: Whales are closely related to the hippopotamus, so they should be as easy to spot. As you can see here, the hippopotamus also loves water.

Tim: If tuna is the chicken of the sea, does that make whales the hippos of the sea?

Florence: I'm not sure. Why don’t you ask one?

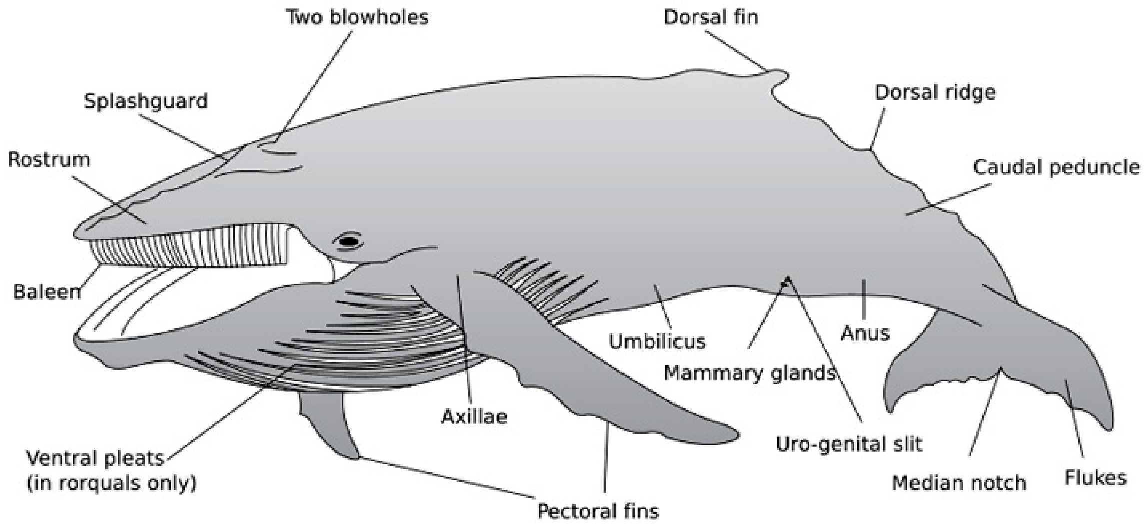
Dr. Fondah: Hippo grunts are not very pleasant, compared to the beautiful songs that whales sing to each other. Some enterprising musicians have made a lot of money recording those songs.

Florence: Like us, whales are warm-blooded and feed their young with milk from mammary glands, hence the mammalian classification. They use lungs for breathing and even have a little hair.

Tim: They have a remnant pelvis which is useless since they do not stand around all day lecturing like Dr. Fondah.

Dr. Fondah: Nobody lectures like Dr. Fondah. Here is a schematic for the largest type of whale, the baleen.

Tim: He must be a "real blowhard" because he merits two blowholes and a mustache that he stole from Adolf Hitler.



Florence: If we are digressing into hippos and Hitler, than I think that we should wrap up this discussion of marine biology.

Tim: I suppose that we should. Long John Silver is calling me. However, I still cannot get over the size of a baleen, the ocean's giant vacuum cleaner. He's the guy that we calculated to be 2000 krill long.

Florence: Juliette has the standard T-shirt that proclaims, "Save the Whales" but I must confess that I ate some whale in Japan and it was so delicious that I could never wear such a T-shirt. I will encourage her to save some whales for my soirées.

Dr. Fondah: If Jordan hears that you have been feasting on whale, she will not pay for this video, so I had better edit out that confession. I will just close with an innocent smiley face. How's this?

Epilogue: Bells, Belles, Beaus, and Bye

Jordan: (*loosely holding a cell phone and a DVD*) Bells? Why have the Swiss installed hand-bells on my state-of-the-art sub? Every month, they send me a high-definition DVD showing their construction progress and they usually emphasize the latest high-tech gadgets but this DVD shows that they have installed hand-bells. Hand-bells !!?? The cave men probably had hand-bells on the dug-out trees they floated across glacial lakes.

Janna: The Swiss must be practicing some of the philosophy that has kept them afloat for thousands of years while all the countries around them have repeatedly sunk into the quagmire of war-after-war. The hand-bells will surely be our most reliable instrument, or do you really want to try shouting every time you try to find me? You could just ring the closest bell and you will soon be able to tell from the sound of my bell where I am. When I was picking cherries for my grandmother on her 15-acre farm, I could hear her dinner bell anywhere on that farm. It was the best sound I would hear all day.

Jordan: OK. At least the Swiss engineers have included mufflers for the bell clappers to keep them from ringing every time the sub rolls a little. I see that they also have a wired intercom system in case we have to communicate at a distance. Hey, look !! What is up with this raised-relief Swiss flag they have inserted into every room, a white plus sign on a red background?

Janna: If this is a state-of-the-art DVD as you claim, you should be able to click on any of those Swiss flags and the DVD will tell you what it is.

Jordan: Great !! You are right. The DVD pops up a text message saying that this is a remote control for steering the sub rather than just a decoration. A remote control !! This means that we will be able to steer the sub from any part of it. We will not have to take turns in the central control area. I will even be able to control the sub while sitting in the washroom.

Janna: Yes, but that would be a really gritty idea. Having watched you swerve your car while talking on your cell phone, I had better ask if you have had any experience with remote-control steering. Did you ever play with a remote-control toy?

Jordan: No, but my mom claims that I can make dishes fall by just looking at them.

Janna: No wonder you got the nickname, Klutz. I have a nephew with lots of remote-control toys. I can get him to make a training video to show you how to steer remotely.

Jordan: OK. I was flipping through the Target® flyer today and saw a couple of neat toys that I could buy him for his video, Roboraptor® and DragonFly®. I cannot wait to try those toys myself. You know why I missed all that robotic fun? I was living with my family in Paris while all my friends back home were going through the Middle School robo-craze. While they were flipping tanks for kicks, I was flipping francs for tips. When they were crashing remote-controlled cars, I was nibbling on caviar. As I was sipping my first champagne, they were painting their hot-rods with flames. While I was gazing from le Tour Eiffel, they were making those hot-rods smell. I missed all that odor and pyrotechnics. By the time I returned State-side, my group's robotic craze had crashed and burned. They had moved on to dresses and perms.

Janna: I am sure that my nephew can help you make up for lost time. Just like us, his name starts with a "J". He's James. You should let me call him on your cell phone.

James: (*voice only*) Hi Auntie Janna. Yes; I know all about Roboraptor® and DragonFly®. DragonFly® is like a submarine because you can travel in any direction. I love my DragonFly® but I am pretty sure that my mom is going to banish it to the outdoors. My grandmother has given us so many fancy china figurines that I have created a bit of a mess flying inside. Besides, my mom dislikes being around any kind of insect, even a plastic one.

Janna: Thanks, James. We will have to cut this short because I am using Jordan's cell phone and I hear that she has an incoming call.

Jordan: *(taking the phone from Janna)* Hello Grayson. Yes; Janna and I are still planning to launch our submarine next month and spend a year circumnavigating the world. You and Brent can visit us in a couple of ports along the way. What? You have a better idea than circumnavigating the world in a sub? Marriage? You want me to marry you? Just a minute. Let me talk to Janna. *(covering the receiver with her hand)* Well, Grayson has finally proposed --- over the telephone !! I knew that he would never be brave enough to do it in person.

Janna: You're happy about that? I thought that the submarine trip was to get away from Grayson and his conceited frat friends.

Jordan: You know that I live to impress my dad and the submarine trip would do that, but marrying into a family as rich as ours would probably impress him even more.

Janna: Does that mean that you are going to marry him and ditch both me and the sub?

Jordan: Not exactly. I guessed that this might happen, so I have made arrangements that include us sailing the sub to Haiti. We'll marry our boozing beaus there and then sell the sub, once it is fitted with the nuclear reactor that I have already purchased from the French Canadians.

Janna: A wedding in Haiti? Are you kidding me? Performed by a voodoo priest?

Jordan: When will you learn that the super-rich have super secrets? One of the most expensive and exclusive resorts in the world is in Haiti. The super-rich work hard to avoid the middle class. The only way to get into the middle class in Haiti is to sit in the middle of the classroom.

Janna: You mean that this multi-million-dollar submarine project was only intended to get Grayson to propose?

Jordan: A girl does what she has to do. Cheer up. Grayson also told me that Brent is going to propose to you later today and that he too wants to get married in Haiti. There is a legal advantage to Haiti, you know.

Janna: What's that?

Jordan: Having been founded by the Roman Catholic French, Haiti marries you for life, not until your next soap-opera episode. These guys will find it difficult to run off with their cute young secretaries ten years from now.

Janna: And what about the submarine? How is Bates going to recoup his investment if he does not have us doing a year's worth of reality TV for him?

{ *Switch to scene of Dr. Fondah, Florence, and Tim in Florence's NY apartment. Florence's cell phone is ringing. A small handbag is on the table. Dr. Fondah also has a cell phone on the table*.}

Florence (*to cell phone*)**:** Bonjour. Est-ce que je peux vous aider ? Oh, hello Jordan, how are you? (*pause*) Do I want to buy a nuclear submarine? I must admit that the thought had not crossed my mind lately. I presume that this is one of your telephone games where everyone at the party bets on what the response will be. Who guessed my response?

Tim: I've played that game, but my friends use better questions.

Florence: Vous êtes sérieuse !? The sub is coming to Haiti? (*pause*) Wow, you want a lot of money. I only have one friend who might be interested. I will call him. (.. *pulls phone away from ear* ..) Dr. Fondah, would you please look for a sheet of paper in my handbag and enter its French telephone number into your cell phone for me?

Tim: { *Dr. Fondah hands the sheet of paper to Tim who proceeds to read the number as Dr. Fondah picks up her cell phone.* } OK. It's 1-011-58295-96861.

Florence: { *.. while still holding her own phone well away from her face, Florence takes Dr. Fondah's cell phone and places it next to her other ear…* } Bonjour Hugo, c'est Florence. J'ai une amie qui veut vous vendre un petit sousmarin nucléaire qui sera amarré au Haïti. Enverrez-vous quelqu'un pour jeter un coup d'oeil à lui ? Bon, et n'oubliez pas une petite commission dans l'intéret du vieux temps. Vous parlez meilleur français maintenant. Avez-vous une nouvelle petite amie ? Au revoir, cherie.

{ … *after pulling Dr. Fondah's phone away from her ear and bringing her own phone back to the other ear* …} I think that you have a deal. I will handle the money for you just to be sure that you do not lose anything to a commission. (*pause*) Bon. Au revoir, cherie.

Dr. Fondah: Your telephone call was not directed to France.

Florence: How do you know?

Dr. Fondah: The country and city codes are built into each international telephone number. The 58 refers to Venezuela and 295 is Margarita Island. I know that code because Professor Bowles gets me to call and check on his Margarita properties whenever he is on an extended research cruise.

Tim: There can't be anybody living on Margarita Island with enough money to buy Jordan's submarine.

Dr. Fondah: I agree. There can't be any permanent resident who is that rich, but Margarita has lots of weekenders from Caracas, Venezuela's capital, and some of those guys have enough oil to float their own oil tankers.

Tim: Come to think of it, I have seen a Venezuelan named Hugo on the evening news. He looks pudgy enough to be mistaken for an oil tanker. You know, I think that I will pass on this whole sleazy affair and let you super-rich types go live your crazy lives without me. I will be looking for Jordan and Hugo shackled together at the Court of International Justice in The Hague, Netherlands.

End of "Discussing Oceans"