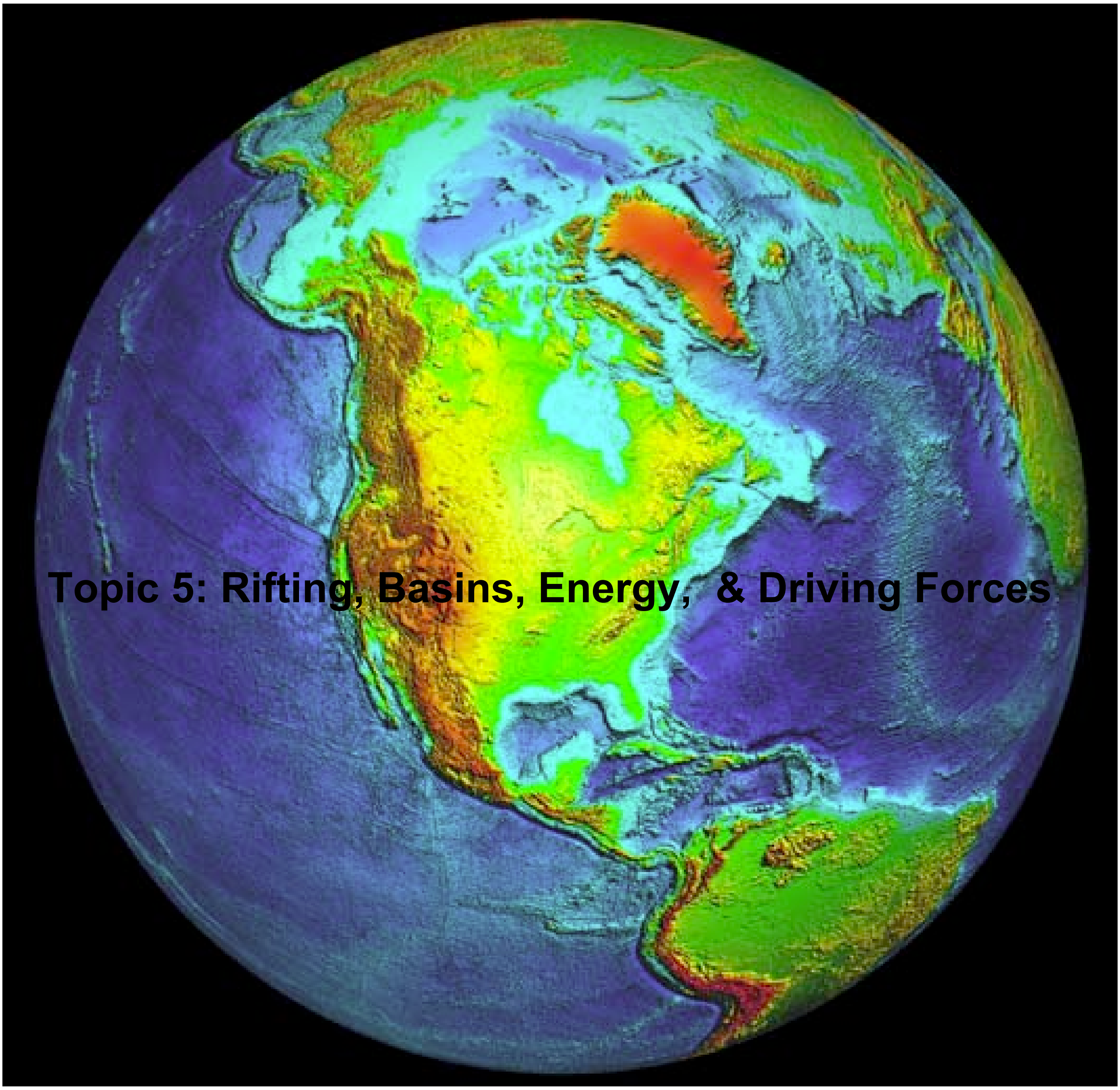
Planet Earth: An Introduction to Earth Sciences



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Planet Earth Topic 5: Rifting, Basins, Energy, & Driving Forces

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We have seen how continents form and deform, but not yet why they fit back together like a jigsaw puzzle. The process that caused the rifting apart of those great continents produced a legacy that affects our daily lives more than any other natural phenomenon. More than earthquakes shake and destroy, more than volcanoes billow and burn, more than hurricanes and tornadoes kill and terrify, hydrocarbons (oil, gas, and coal) and the electricity generated by that energy govern our modern existence. Fertilizers feed our masses, gasoline powers our engines of war and peace, plastics form our consumer products, gas heats our homes, and coal makes our electricity. Believe it or not, all these things come from the past rifting and colliding of the continents.

Did you ever wonder where oil and gas come from? Or why they are often found just offshore on the continental margins? To begin to understand the process of rifting, consider the fit of the East coast of North America and the Northwest coast of Africa and Europe. First of all, do they really fit back together all that well? Not if you cut along the present coastline. But if you cut at the edge of the continental shelf instead, an excellent fit occurs, as can be seen in Figure 5-1 between Eastern Canada and Greenland. The shallow water of the continental shelf often extends for a hundred miles or more away from the coast.

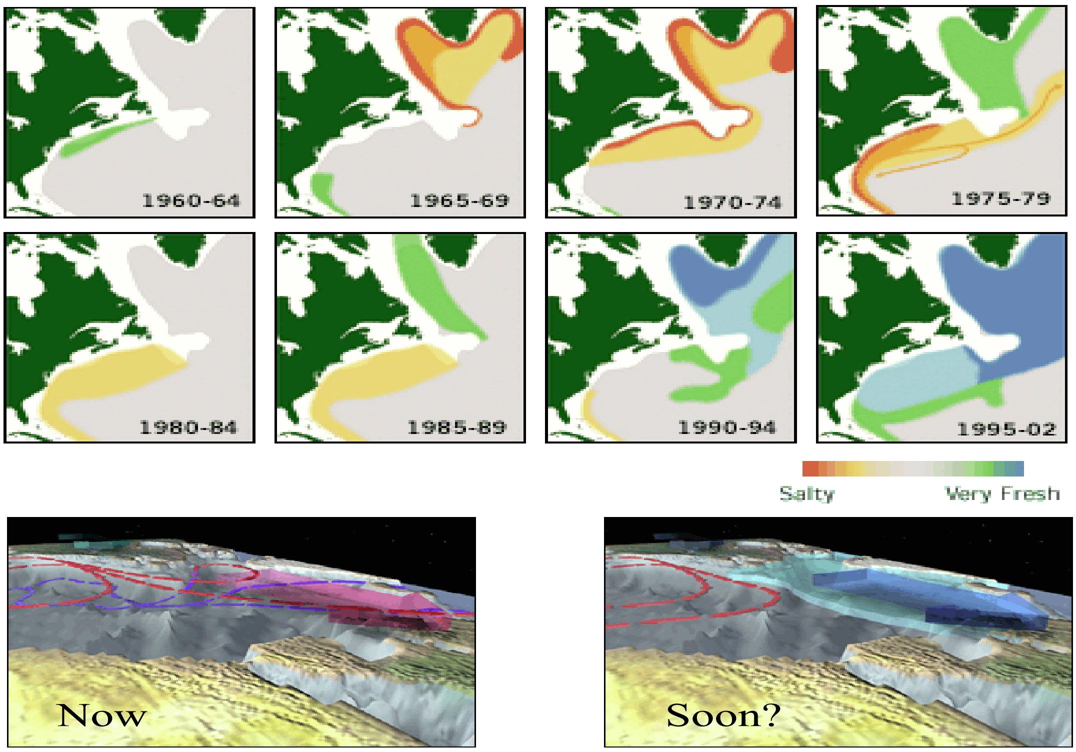

Figure 5-1. (Top) North Atlantic waters at depths between 1,000 and 4,000 meters are becoming dramatically less salty, especially in the last decade of the 20th century. Red indicates saltier-than-normal waters. Blue indicates fresher waters. Oceanographers say we may be approaching a threshold that would shut down the Great Ocean Conveyor Belt of deepwater circulation that keeps the Ice Ages at bay. and cause abrupt climate changes. (Bottom) Then the warm atmospheric circulation (red arrow at left) that keeps Europe warm would be replaced by cold, frigid air (Blue arrow at right) and another Ice Age would be set off. Water to supply the glaciers would lower sea level by 100 meters and expose all the continental shelves of Planet Earth, yet again. (From Wood Hole Oceanographic Institution).

The reason the continental shelf must be included in the continental fit is that the present-day sea level is really quite a tenuous place upon which to stake a claim. Sea level has varied by up to 300 m in the last 100 million years. Sea level is partially controlled by how much water is in the oceans versus in the glaciers of the ice caps (Figure 5-1). It is easy to see that if global warming should ironically set off another ice age, as it was only a 20,000 years ago, the oceans would be at a low point. Just that long ago, the New York and New Jersey coast extended 150 miles out to sea. Manhattan was merely a hill among many on the edge of the Hudson River. The Texas and Louisiana coast was 100 miles to the southeast of its present coast. Why? Because the shelves of the continents are very shallow, and they extend for long distances offshore. The Falkland Islands are 500 miles offshore Argentina, for example, but the water is never deeper than a few hundred meters between the two. If the climate chills just a little bit, then the polar ice sheets expand at the expense of water in the oceans, and the sea level recedes.

Consider now the carbon dioxide problem: The burning of so much fossil fuel will fill our atmosphere with carbon dioxide and the greenhouse effect will increase the temperature of the surface by a couple of degrees. A greenhouse is transparent to light entering, even in the winter. But the light hits the floor and splits into all the wavelengths of the spectrum. The infrared portion of the spectrum tries to bounce back out the greenhouse walls, but the humid atmosphere trapped within the greenhouse is opaque to infrared light, and those wavelengths are trapped inside. This energy is retained as heat because the infrared energy bounces around the room ricocheting off the countless water and carbon dioxide molecules in the attempt to escape.

If we continue to pump more and more carbon dioxide into the atmosphere, thus increasing its opaqueness, the result will be an increase in the planet's average temperature. An increase of just a couple of degrees will cause enough ice to melt to flood all of the great port cities of the world. Texas, for instance, would have new port cities of Austin, San Antonio, and Dallas. Florida would have no cities above water. Such a result might be temporary though, because the heating also occurs in the oceans as well. There, a great ocean "conveyor belt" of water circulation keeps the climate of the earth stable (Figure 5-2). Cold water fro the Arctic sinks into the North Atlantic Ocean. It then travels all the way to the South of Africa and into the Indian Ocean, then all the way into the Pacific Ocean, where it surfaces as a hot current that then loops back across the Indian Ocean and into the North Atlantic, Ocean. This conveyor belt is stable for long periods of time, but when climate change perturbs it, drastic climatic changes can be set off with rearrangement in the conveyor belt's pattern. Just such changes in the entry point of Arctic cold waters is beginning south of Greenland. Fresh water, which is more buoyant than salty water is piling up there because of the increases in surface temperature over the last one hundred years from Global warming. If this build up continues, it could interrupt the Artctic cold water current and set off a new ice age.

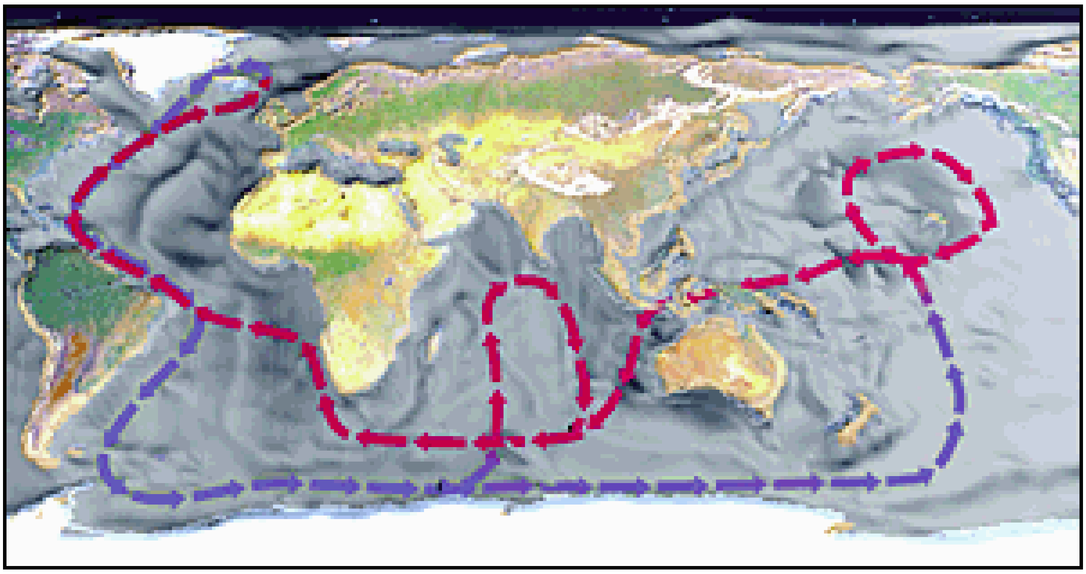

Figure 5-2. The ocean circulation system, often called the Great Ocean Conveyor, Belt, transports heat throughout the world oceans. Red arrows indicate warm surface currents. Blue arrows indicate deep cold currents. (WHOI).

Sea level is also controlled by an equally powerful force, a rather subtle change that can occur in the elevation of the bottom of the sea. The volume of ocean water is fixed at anyone time depending upon how much ice is in glaciers. If the spreading rate of mid-ocean ridges suddenly increases (e.g., from 1 to 10 cm/yr), then the slope of the sea floor away from the ridge crest and toward the deep ocean basins will become more gentle (less steep). The slope changes because the elevation of the oceanic lithosphere is not controlled by the distance of any given piece of rock from the ridge crest but by its age, since it has been cooling at a uniform rate ever since it was extruded volcanically onto the plate. The cooling of the plate is age-dependent. If the spreading rate is 10 times as fast, then there is 10 times more young rock on the newly accreting edge of the oceanic lithosphere. Then the elevation of the sea floor is higher than at the slower spreading rate because the hot rock stands higher. The ocean is a fixed volume, so the water level is forced upward and must go somewhere. The lithosphere literally pushes the sea level higher, flooding the edges of the continents.

This phenomenon is analogous to the rise in water level in a bathtub when you submerge all of your body versus half of it. The constant volume of water must go somewhere, and you have occupied more of the bottom space in the tub. Obviously, the spreading rate could just as easily slow down, forcing the sea level down and exposing most of the present continental margin to the forces of erosion. Then the port cities of Texas would be 100 miles seaward of Galveston or Corpus Christi.

Continental Rifting

How is it that the continental shelves were rifted apart in the first place? Plate Tectonics explains haw extension occurs to move them apart and create an ocean inbetween, but that is after the initial rift happened. By examining the geological evidence for how rifting occurs, we will learn not only how continents came to separate, but also why countries that were once together along the coasts, such as Angola and Brazil, are blessed with some of the world's largest hydrocarbon reserves.

The Amazon, Congo and other great rivers do not flow where they do randomly. They choose the easiest path from the Mountains down to the ocean. That easiest of paths is often a large, gently sloping valley that is the remnant of the rifting of South America fromAfrica.

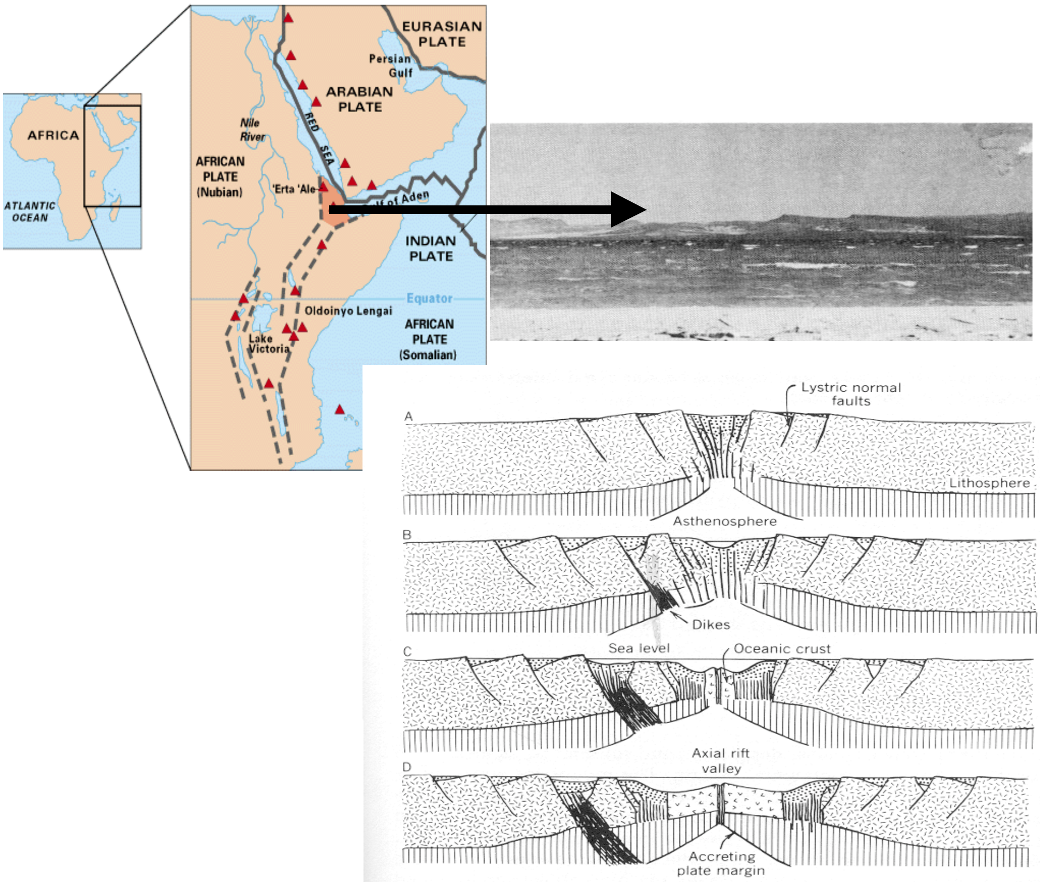

Figure 5-3. East and west Africa are being rifted apart at this very instant. The East African Rift Valley that extends south from the Red Sea is currently breaking apart the continent. Spreading centers are actually visible about ground in the north. Millions of years from now, East Africa will be in the middle of the Indian Ocean with a thousand miles of ocean separating it from western Africa.

We know how these great “Rift Valleys” work their magic, by extension identical to that at sea floor spreading centers (Figure 5-3). From among the forces driving the plates, a “pulling-apart” within a continent originates. The pulling apart "stretches" the continent. Since the surface rocks are too brittle to stretch, faulting occurs, and Rift Valleys are formed. A Rift is a faulted valley where both sides are normal faults sloping away from the center. As stretching occurs, faults break and the center block of rock falls down into the space left from the stretching-apart (Figure 5-3).

An analogous condition can be formed by pulling apart a Milky Way candy bar (not a Snickers Bar because the peanuts interfere with the stretching properties. The center is soft and stretches, but the brittle chocolate outer coating breaks apart and forms many “Rift Valleys”. If you continue to pull, two smaller chocolate bars result.

The form of the East African Rift (Figure 5-3) hints at the process that is actively rifting the continent apart. To get to either valley, you must negotiate mountains that flank both rift valleys. The extensional mechanism must produce uplifting of the rift edges as well as stretching within the valley, since mountains invariably surround such rift valleys. We have seen many times already on the planet that uplift often means that excess heat is present, and this example is no exception. The stretching produces faulting in the brittle continental crust, but the more ductile mantle below the Moho can thin like taffy that has been stretched. This thinning results in the upwelling of hot asthenosphere to fill the new gap. This hot material produces uplift on the valley walls by thermal expansion just as the mid-ocean ridges are elevated above the ocean basins by the same process.

As stretching continues, a crack is gradually made in the continental crust within the rift valley, and asthenosphere wells up to form volcanoes at the surface. As the stretching continues, volcanoes soon become continuous along the valley floor and ocean floor is made. It is ocean floor not because it is under water, necessarily, but because the rock is black, heavy basalt, which has only enough hydraulic head to rise to a mile or so below sea level. Remember that the surrounding continental mountains are composed of lightweight granites, which are much more buoyant than basalt filling what will soon be new ocean floor.

A long, linear valley full of erupting volcanoes a mile below sea level cannot help but eventually be flooded by the ocean. If we again look at the East African Rift and the Red Sea, we see that the former is not ocean, but the latter is. The Red Sea is a little wider and farther along toward the later stages of stretching than are the rifts. Yet even there, the ocean is beginning to infringe. In Ethiopia, the Afar Desert is basaltic "sea floor" resting below sea level, with the ocean held back by only one remaining natural dike. Soon this last dike will be broken and ocean will flood all of the Afar (Figure 5-3).

The Formation of Sedimentary Basins

As rifting continues beyond this volcanic stage, normal sea-floor spreading takes over and the new lithosphere added to the two sides of the original valley is indistinguishable from other ocean lithosphere. The present center of spreading between Africa and South America, the mid-Atlantic ridge, was once at the center of a sea as small as the Red Sea. “Blow torches” called Hot Spots are required to sever the continents (Figure 5-4). The great rivers find pathways to the sea opened by the expansion and “ torching” of the continental crust cut by the hot spots.

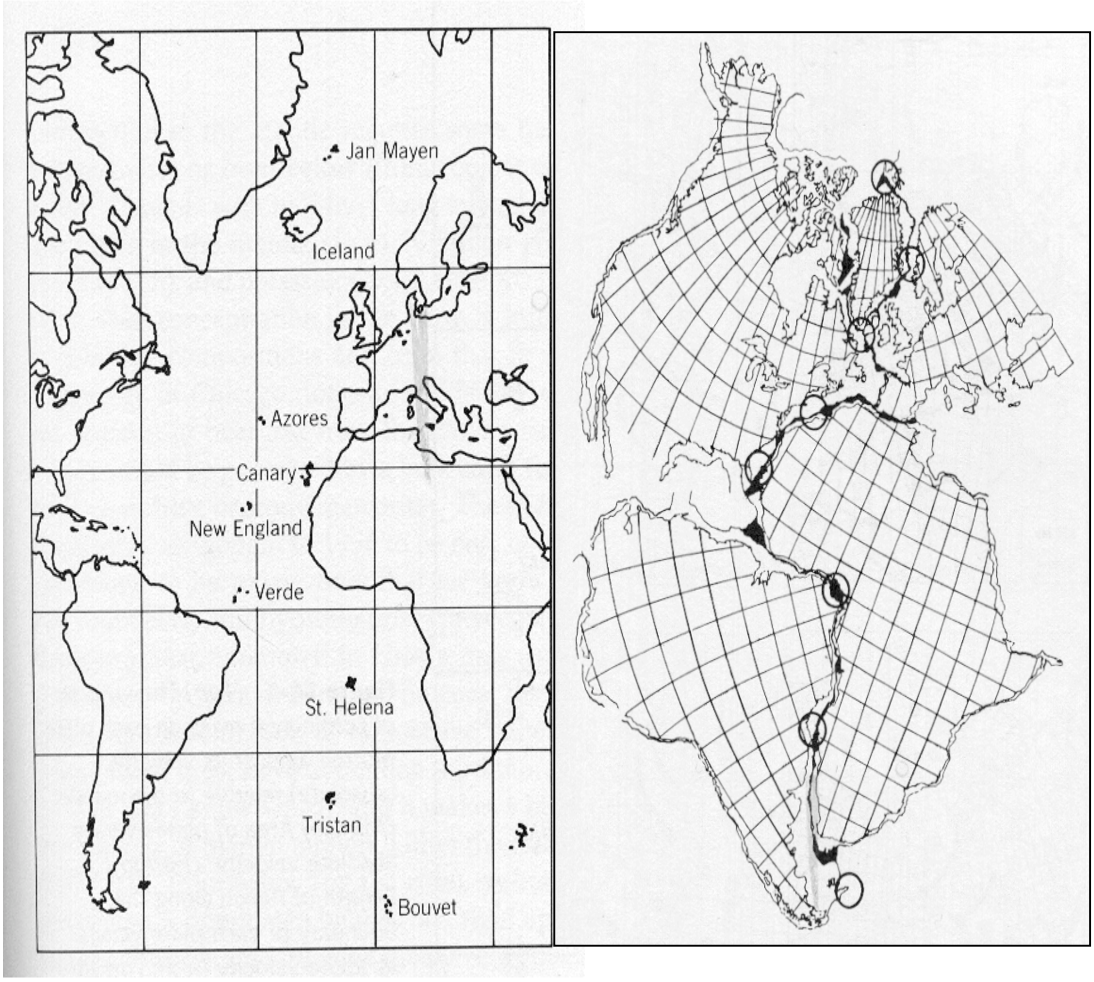

Figure 5-4. The opening of the Atlantic can be traced to the blowtorch effect of a few hot spots. Here the motion of the continents away from each other can be mapped by backtracking along hot-spot trails of islands and seamounts.

Repeated flooding events then occur because these Rift Valley walls are periodically build up in height only to be later broken back down by erosion. These flooding events result in evaporation if not connected to open ocean, and since the water is salty ocean water, great salt flats develop. For example, volcanic ridges across the southern, central, and northern proto-south Atlantic Ocean at the Rio Grande-Walvis ridges in the south, the Cabo ridge in the center, and the Bahamas-Canary ridge in the north isolated the Brazilian and Angola margins, the Nigerian margin, and the Gulf of Mexico to form the mother salt layer that today traps oil in each of these basins.

After initial rifting comes erosion, deposition, and subsidence, as these three processes then repeatedly shape the continental margin. The mountains surrounding the rift valley are slowly but inexorably eroded back toward sea level by the forces of ice, wind, and rain. The sediments from this erosion are deposited in the newly formed valleys, now called a sedimentary basins, by the great rivers. Erosion and deposition act in opposite directions to attempt to produce the same effect -- returning the surface to sea level. Erosion tears down anything above sea level and deposition fills up any depressions below sea level.

The continental margins become sedimentary basins because the subsidence of the rift valley floor continues long after the continents have drifted away from the spreading center. Just as with normal ocean lithosphere, the continent that has been stretched has had heat added to it. The rock subsides slowly with time as it conductively cools and contracts. However, the crust contracts to a deeper level than before rifting because it has been stretched and thinned so that it is not as thick as it used to be. It is below sea level even at its most heated stage because uplift from thermal expansion is offset by stretching. Cooling then results in even deeper subsidence. Rivers deliver sediments from erosion to fill the subsiding continental margin and force it even deeper with the added weight they bring (Figure 5-5).

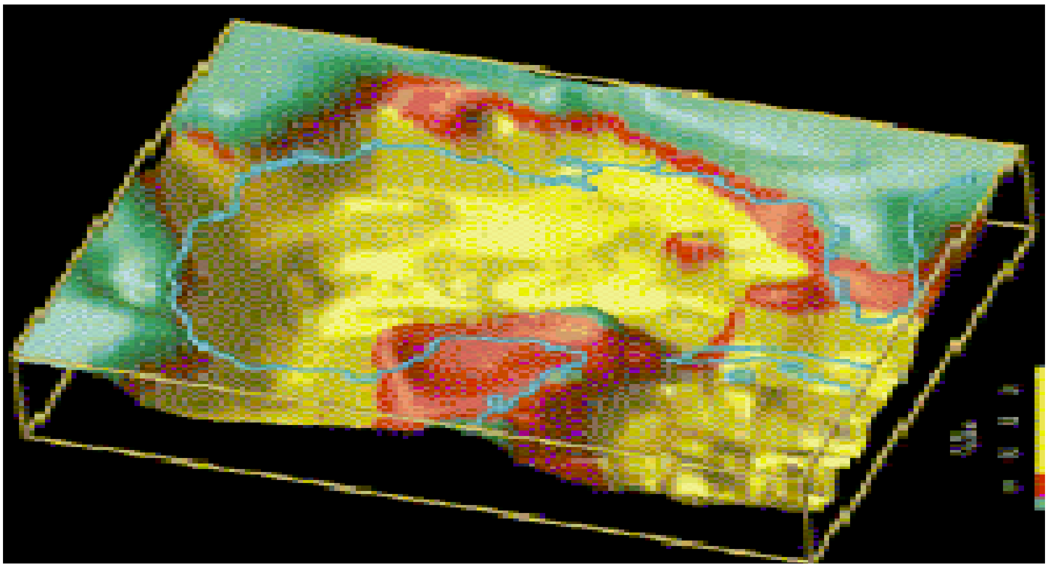

Figure 5-5. All post-rift forces act to deepen the pile of sediments accumulating along the continental margins as rivers deliver sediments from erosion to create deep, sedimentary basins, like here in the Gulf of Mexico.

Have you ever wondered why oil and gas are often associated with salt domes and sheets? Our concerns are (1) where the salt comes from and (2) why oil is found near the salt. In the early days of formation of the new ocean, the rift valley is repeatedly flooded with seawater. Episodes of flooding begin at intervals spaced far enough apart for the new ocean to dry up between floods, with all the water evaporating to leave only its salt behind. Flooding events gradually increase in regularity until an ocean finally appears permanently. The Red Sea is now at that stage. But left behind at the very bottom of the valley are thick layers of salt. The Red Sea has almost 1 km of salt at its bottom. Other major oil-producing basins such as the North Sea, the Persian Gulf, and the Gulf of Mexico all have salt at the bottom of their considerable piles of sediment. Whether a basin has salt at its base is simply a matter of circumstance. If a newly forming proto-ocean is sealed off by dikes, then evaporation can occur. If it is open at one or both ends, no salt will form because the seawater will be well flushed.

This poor circulation of flood waters also cuts off the oxygen supply, and organic plants and animals (mostly microscopic) die and fall to the bottom with the salt and early sediments. These become source beds for hydrocarbon formation because they have not been oxidized. Hydrocarbons that decay are oxidized. Un-decayed oil and gas are oxygenated, or burned, in car engines – that's what produces the power. But organics can only be burned once, so if the ocean is too free to circulate, there are no floods, there is no salt, and there is too much oxygen around in the water to produce good source beds for oil and gas.

However, neither he salt nor the hydrocarbons are stable at the bottom of the sedimentary basins because they are both much lighter than sediments, especially as basins become very deep. Some are 10 km or more thick. With time, both the salt and the newly formed oil and gas squeeze their way toward the surface as diapirs to form salt domes. When they reach the sea floor, they spread horizontally as sheets, or nappes, like that in the Northern Gulf of Mexico shown in Figure 5-6. Holes to form in the salt as it then slides downhill toward the center of the basin. The salt stretches as if it were taffy, making the “lunar crater” like appearance of the salt sheets.

Oil and gas that have formed above, around, or near the salt then flows, or migrates, upward with the salt because it provides a pathway for the equally buoyant oil and gas to rise. The salt sheets at the surface blocks its further progress, and traps of oil and/or gas form. Sometimes, the oil and gas seeps through the salt and sediment barrier and is expelled directly into the ocean. Natural seeps then form at the surface of the ocean that can be seen with satellite imagery (Figure 5-7). Since the earliest times, hydrocarbons have been found in the subsurface from natural seeps. Most of the tar on beaches comes from these natural seeps, as well.

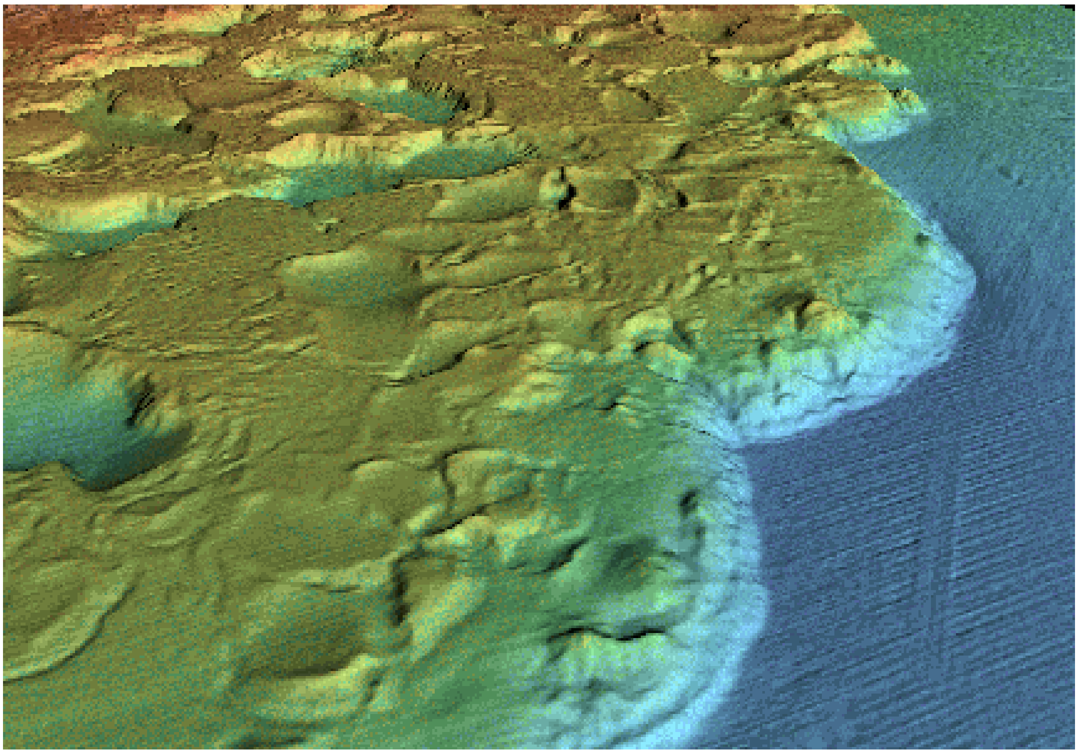

Figure 5-6. Salt near the surface produces the moon-like cratered appearance of the seafloor on the Southern continental margin of the United States in the Gulf of Mexico off Louisiana in this NOAA image. The “Cliffs” at the right are the 800 m high Sigsbee Escarpment, a shear wall of salt that would be every bit as impressive as the white cliffs of Dover if on land.

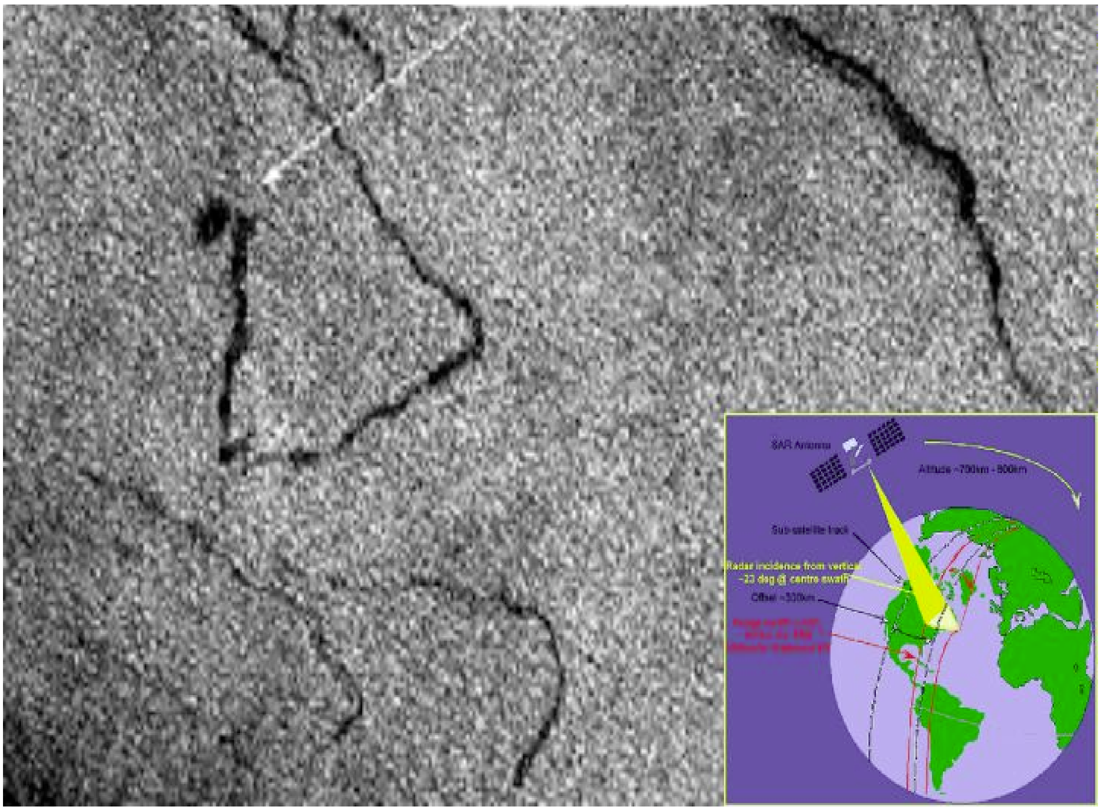

Figure 5-7. Blow-up of Satellite reflectivity image of the ocean surface showing oil seeps (black, snakelike trails) from Ultra-Deepwater Gulf of Mexico. The satellite uses radar to image the "smoothness" of the water caused by the emulsifying characteristics of oil – it smooths out the waves.

The secret to salt and hydrocarbon source bed deposition formation is the existence of rock barriers to the intruding ocean. Repeated flooding requires that these barriers periodically build up in height only to be later broken back down. Erosion alone is not enough because no mechanism for build-up exists. Volcanic activity appears necessary. For example, volcanic ridges across the southern, central, and northern proto-south Atlantic Ocean at the Rio Grande-Walvis ridges in the south, the Cabo ridge in the center, and the Bahamas-Canary ridge in the north isolated the Brazilian and Angolan margins, the Nigerian margin, and the Gulf of Mexico to form the mother salt that today traps oil and gas in gigantic quantities each of these basins (Figure 5-8).

Most of what we know about sedimentary basins comes from the drill bit. When an oil well penetrates into the depths of a basin, we benefit from the knowledge returned to the surface by cuttings of rock, fluids produced, or detected in situ by a widely used technique called wireline logging. In logging, a nuclear, sonic, or electrical source is lowered into the well, and a geiger counter, transducer, or electrode records the response of the rock to nuclear particle bombardment, sound energy, or electric current. The type of rock, its porosity, and whether oil, gas, or water fill the pore spaces can be determined from these records, called logs. Hundreds of thousands of oil wells have been drilled in sedimentary basins by now, and although only one in five finds commercial quantities of oil or gas, all yield valuable geological information.

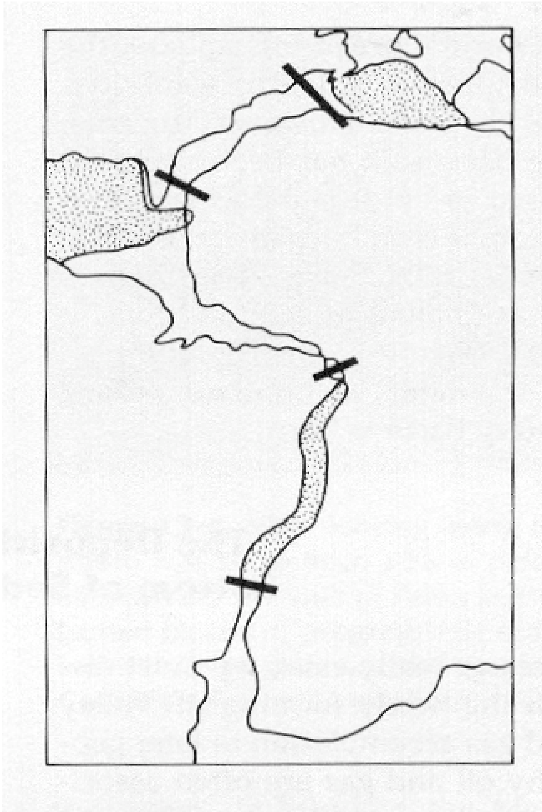

Figure 5-8. The land barriers that repeatedly produced flooding and desiccation as the Atlantic Ocean was growing in its earliest stages deposited the salt and hydrocarbons that are now produced from offshore Brazil, Angola, the North Sea, and the Gulf of Mexico.

The Formation of Oil and Natural Gas

Did you ever wonder how old the gasoline is that you now have in your car's fuel tank? Different brands of gasoline are likely to be of significantly different ages. ChevronTexaco gasoline, for example, will be about 10 million years old if it came from California. BP gas will be perhaps 50 million years old if it is from the North Slope of Alaska. ExxonMobil gasoline will likely come from the Middle East and will be 150 million years old. Shell gasoline from the Gulf of Mexico will be about the same age, but it did not move near to the surface until the last million years or so. CalTex gasoline from Indonesia will be about 60 million years old, and BP gas will be perhaps 200 million years old if it is from the North Sea.

But do not change from your favorite brand because of its age; new oil burns just as well as old. The ages are of the organic material that, after burial, became hydrocarbons. The carburator or fuel injection system of a car mixes gasoline and oxygen together so that a spark from the spark plug can ignite the mixture. The fire causes the expansion of gases and the release of heat and power, which are converted into push on the wheels of the vehicle.

Geological environments that promote rapid burial and heating under pressure in oxygen-free conditions make oil and gas (Figure 5-9). If the organic material is plants and cellulose instead of micro-organisms, then coal is formed instead of oil or gas. River deltas, continental margins, flood plains, and swamps come to mind (the latter because there is little oxygen in the stagnant waters of swamps).

Plate tectonics can help us find many terrains where these conditions were met in the past. Thus, we begin to see the preponderance of geologists working for oil companies. But burial before oxidation is not enough by itself to make oil. It must be cooked, but not too much, or all that pent-up energy will be lost. We call this process maturation of hydrocarbons. Oil and gas must be matured in a pressure cooker. Pressure, and more importantly, temperature, must chemically alter the organic hydrocarbons. Just as with a kitchen pressure cooker, you can cook either fast or slow with essentially the same result. If fast, then the stove must be on high heat; if slow, then on low heat (Figure 5-9).

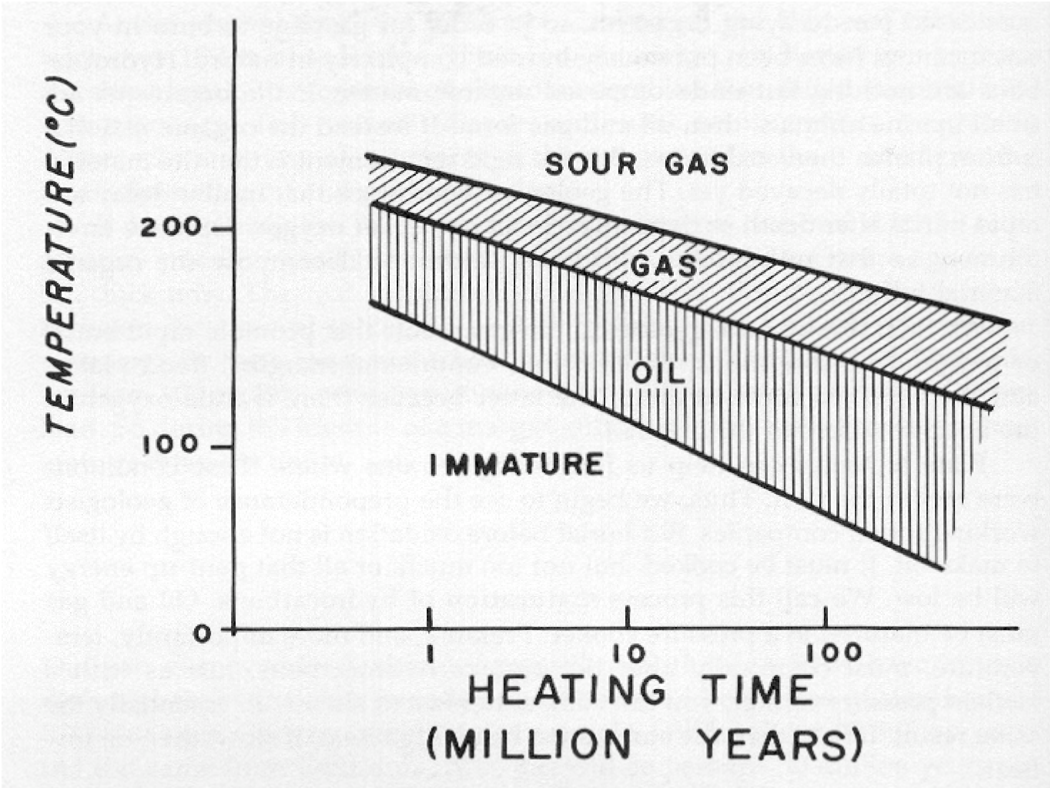

Figure 5-9. The generation of hydrocarbons in sedimentary basins is purely a matter of thermodynamics. The organic matter cannot have been heated too much for too long a time or first natural gas then sour gas would have been formed. Correspondingly, it could not have remained too cold either. Oil and gas do not form by luck; therefore we must look for sedimentary piles which were sufficiently heated in the past. Vertical hatching is oil-formation window; diagonal is for gas.

The way in which hydrocarbons are cooked depends on the depositional environment in which they happen to have come to rest. As with food, hydrocarbons can be overcooked; and gas is the result. Then even gas can be over cooked, and sour gas, heavy in sulfur and other undesirable chemicals, results. If, on the other hand, the hydrocarbons are not heated enough, the organic material remains immature and difficult to burn. Peat is immature coal.

When and where within a basin oil or gas is found depends upon when the organic-rich source material was deposited into the basin. If it was early in the stretching stages of rift-valley formation, then the environment is hot and the hydrocarbons mature very quickly. This is why ChevronTexaco found 10 million-year-old oil in the Santa Barbara rift basin off the coast of California.

If instead the organic-rich material is not buried until long after the hot stage of rifting, then it will take millions and millions of years to mature into hydrocarbons. Once an oil company has determined that a particular basin is likely to contain mature hydrocarbon source beds, the problem shifts to the determination of likely structures for capture of the migrating hydrocarbons. The driving force for this migration is buoyancy. Oil, being lighter than water, tries to force its way to the surface.

The need for a lid to keep hydrocarbons trapped was painfully revealed to the oil companies recently when the massive structure that was to have succeeded the North Slope as Alaska's next great oil discovery was drilled. Mukluk, as it is called, is in the Beaufort Sea off the northern coast of Alaska. The oil company had to build an entire island to drill the first well into Mukluk. The island and well cost over $2 billion. More than 5000 feet of producing sandstones were drilled through, but no oil was found. Instead, abundant evidence was found that oil once resided in the sandstones, but it is now all gone. It was not trapped successfully, and all escaped to the surface long ago.

Permeability is the key to the migration of oil and gas into traps. The more permeable a rock is, the easier it is for fluids to move through it. Unfortunately, there is no technique that detects permeability deep in a basin from the surface. Permeability depends not only on the porosity of the rock (which is easy to determine), but also on the pathway between pore spaces that the fluid must travel through. How tortuous the path determines how easy it is for hydrocarbons to migrate through any rock. The permeability pathway is thus called its "tortuosity".

A trap forms when gravitational buoyancy forces oil or gas upward into a dead-end permeability alley. A cap of impermeable rock must sit on top of a highly permeable structure. The oil then migrates through the permeable pore spaces until it is trapped by the impermeable cap rock. It will then remain there until some industrious drilling crew stumbles upon it by penetrating the cap with the drill bit. The gushers of olden days would then result from the overpressures of the trapped oil and gas. Now, we cannot waste the overpressures that blew out the early wells. Instead, we capture these excess pressures and use them to force the oil and gas from the ground naturally.

Any study of the geology of oil and gas must end with an inquiry into when we will run out of the commodity that seems so essential to our daily living. Here is a little-known energy fact from the past: Europe ran out of wood in the 1600's. It was only then that coal began to be used extensively. The result of burning so much wood throughout Europe was to strip away all the forests. From coal usage came the famous pea-soup fogs of London. There are no longer such fogs in England because the pollution level has dropped since oil and gas replaced coal as the energy source for the Industrial Revolution.

We would certainly miss hydrocarbons if we ran out of them, but the loss of gasoline and plastics would be felt less acutely than the loss of fertilizers. The "Green Revolution"" of the last 50 years has allowed us to gain in the battle of food production versus the consumption requirements of the global population. This revolution in agriculture has largely succeeded because of ammonium nitrate and other fertilizers made exclusively from hydrocarbons. Long after we are no longer allowed to fill our cars with gasoline, fertilizers will still be made from oil, and hydrogen to power fuel cells from natural gas.

Once a large oi or gas field is discovered, the hydrocarbons must be pumped to the surface. The very act of removing fluid from the pore spaces between rock causes the rock to collapse, destroying the high permeability vital to the recovery of oil. So we can only get about half of the oil out of any given field. Fifty percent of all the oil ever found is still in these old fields! As the commodity becomes more and more expensive, the technology for extracting this leftover oil will steadily improve.

We are already doing some extraordinary things underground. A fire has been burning for five years inside the earth in Bulgaria to force oil out of the ground. Oxygen is pumped down to burn the deepest oil right in the formation 2 km below the surface, producing heat to force heavy, syrupy oil to flow from the shallower levels of the field. Otherwise, earthquakes are artificially caused in oil fields to pro- vide new pathways of permeability along faults for oil to get to the well (hydraulic fracturing). Steam, acid, carbon dioxide, water, and nitrogen are pumped down old wells to improve their permeability and increase production.

In addition, several large geographical frontiers remain unexplored. The Arctic and Antarctica, China, the Falklands, and the coasts of Africa are all hot prospects at the moment. But don't sell your internal combustion car for fuel cells just yet. There is still plenty of oil still inside sedimentary basins. Our main problem now is how to find it and get it out of the ground at affordable costs. If it were not for the continual invention of new technologies, we would not be able to keep up with demand.

We will probably make it through the twenty-first century before oil and gas are replaced as our primary energy source on Planet Earth. Some forecasts push that date forward by as much as 50 years, but the truth is that there are enormous quantities of oil and gas still underground. As the price soars, the uses of the commodity will become more and more efficient, and the incentive to find even more will increase.

Then there is all that coal. Coal does not burn as efficiently as oil, but at the present time there is roughly 100 times more of it. As liquefaction and gasification technologies improve, pipelines will begin to transport coal to electricity plants with regularity by the end of this century.

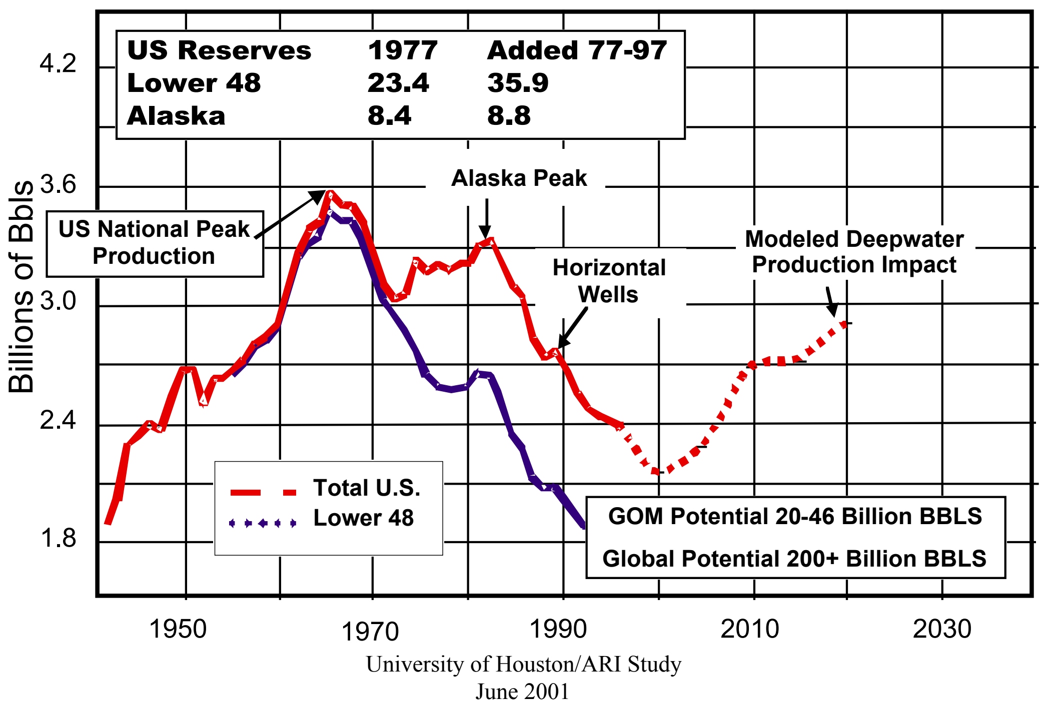

Figure 5-10. University of Houston study showing peak in United States oil production in 1965 was confined to the lower 48 states and on land. Production from the offshore Gulf of Mexico and Alaska continues to grow far into the future.

Eventually, we will run out of oil and gas (Figure 5-10). But by understanding how our planet works, we will uncover more and more exotic places to look for hydrocarbons. Before plate tectonics, it would have been heresy to suggest that oil could be found on the North Slope of Alaska. It was only after we understood that Alaska once was near the equator that the possibility that organic-rich source regions are now at the poles led us to explore above the Arctic Circle.

One outstanding problem that remains unsolved promises to lead us to further exotic terrains. By understanding what pushes and pulls the plates around, we may uncover further massive accumulations of hydrocarbons. The forces are clearly thermal, and where there is heat there is oil. To prove the point, consider the black smokers at the ridge axis. In the Gulf of California, these 350°C hot springs are covered by new sediments from the Colorado River. While exploring for metal deposits associated with these hot springs, scientists recently recovered brand new oil and gas in the surface sediments of the gulf. A core returned to the surface had diesel oil as its pore fluid. Age dating of the diesel revealed that it had been made within the last few years in the sediments above the black smokers. Where there are new heat sources, little oxygen and high concentrations of organic matter to be found, there are more hydrocarbons to be discovered as well.

Driving Force of Plate Tectonics

We now return to the one outstanding problem that we delayed discussing until the complete framework of the surface had been laid out. Even the continents, with all their complexity, are simple compared to the workings of the mantle and core. The physics and chemistry are not complex, but the detection of geological facts is more difficult the farther from the surface you venture. We depend exclusively upon geophysical and geochemical measurements made at the surface to tell us what is happening beneath the plates. We have left this to the end because an understanding of the surface does not require the deciphering of deeper processes, and because it is more complex.

What drives continents to split apart and drift halfway across the globe? Even now that seafloor spreading and plate tectonics are accepted models for how the Earth's outer shell works, Planet Earth's internal workings remain something of a puzzle. We know that somehow the surface plates respond to the pushes and pulls of mantle convection, or fluid motion of the upper mantle.

The driving force is the fundamental mechanism behind plate tectonics, and as such, an understanding of mantle convection is necessary to an understanding of how the oceanic and continental lithospheres work. The state of stress within the stable plate, deviations in depth and heat flow from that expected from the plate model, deep seismic velocity anomalies, and long-wavelength gravity anomalies measured principally by satellites are geophysical data sets that speak directly to motions deep in the mantle. In addition, our understanding of processes active in the mantle has been greatly enhanced by numerical and laboratory modelling of convection, which has been constrained by, and designed to reproduce, these observations.

Most fundamentally, mantle convection must produce the forces that account for both directions and magnitudes of plate motions. For the determination of absolute motions of the plates relative to the mantle, hot-spot trails are used. A hot spot is an anomalous volcanic center that is thought to be in a fixed location relative to the Earth's mantle, with its magma coming from deep in the mantle. Thus, as a plate moves over a hot spot, an island chain or trail of volcanic activity is left behind.

A prime example is the Hawaiian-Emperor seamount chain on the Pacific plate (Figure 5-11). Currently, the island of Hawaii sits at the hot-spot itself. To the northwest, one encounters a series of progressively older islands and seamounts. Thus, Maui is older than Hawaii, Molokai is older than Maui, Maui is older than Oahu, and so on to the northwest beyond Midway. Near Cocos Island, which is 40 million years old, a sharp bend in the chain occurs. The Emperor Islands take off to the north at an oblique angle to the Hawaiian chain (Figure 5-11), until they disappear beneath the Aleutian trench. The oldest island of the Emperor chain is just now being subducted back into the mantle, and was over the Hawaiian hot spot 90 million years ago. The direction of the Hawaiian- Emperor chain records the absolute motion of the Pacific plate relative to the mantle over the last 90 million years (Figure 5-11).

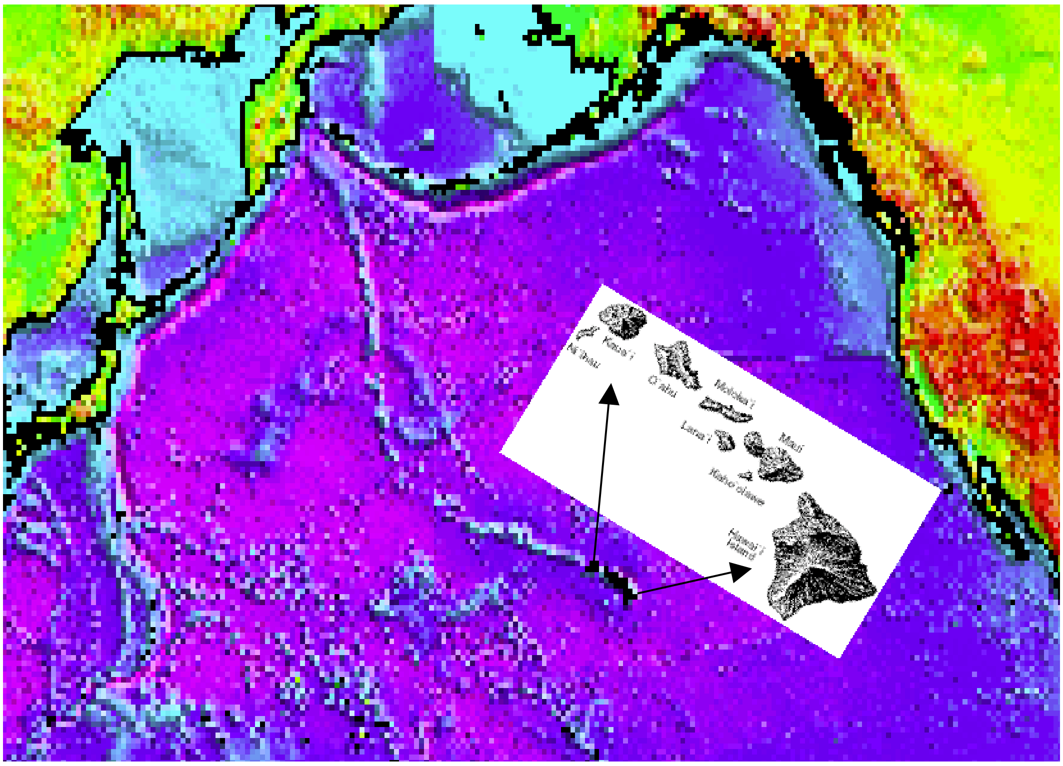

Figure 5-11. Hawaii is at the southeast end of a long string of volcanic islands and seamounts that extends to the northwest, then abruptly turn to the north and goes all the way to the Alaskan Aleutian Island subduction zone.

What then can we conclude from the sharp bend in the Hawaiian-Emperor island chain? The Pacific plate appears to have abruptly changed its direction of motion relative to the mantle 40 million years ago (the age of rocks from Cocos Island closest to the bend). Prior to that time, the plate was moving due north across the Hawaiian hot spot (Figure 5-11). Then the plate abruptly turned to the northwest. And has moved in that direction from 40 million years ago till now. Why did it change direction?

If we correctly understand the driving forces acting on the Pacific plate, then we should be able to explain such a significant pivot in motion of the largest plate on the planet. If we examine the age of volcanism along all the trenches surrounding the Pacific plate, we find the answer to this remarkable puzzle. Trench-pulling forces must be involved somehow. Volcanoes are going to exist above subduction zones whenever under-thrusting is active. The Pacific slab hanging beneath the Aleutian

Trench must exert quite a force pulling the whole Pacific plate to the north. The Aleutian Islands are a volcanic arc behind the trench with rocks at least 100 million years old found on many of the islands. The northward pull of the Pacific plate subducting slab beneath the Aleutian trench was responsible for the Emperor direction prior to 40 million years ago.

What happened then to begin pulling the Pacific to the west as well as to the north 40 million years ago? There are no volcanic rocks on Japan older than 40 million years. This fact suggests that subduction was not occurring beneath Japan prior to 40 million years ago. If subduction suddenly began then, the Pacific plate would be pulled not only to the north by the Aleutian slab, but also to the west by the Japan subducting slabs.

But why did subduction suddenly begin beneath Japan 40 million years ago? We do not really know because we have not yet discovered how to make a trench start from scratch. The primary cause of plate motion disruptions at that time is most likely the collision of India into Eurasia along the Himalayas. A chain reaction was then set off that resulted in changes in the western plate boundary configuration of the Pacific plate. China appears, for example, to be “squirting” to the east like a giant tube of toothpaste caught in the grip of the India Asia collision.

The most likely candidate for this local perturbation is that convergence between Asia and the Pacific may have eliminated a small plate in the Japan Sea. The Pacific plate then came into contact with the Asian plate being squeezed toward the Pacific by the Indian collision. But we do not know how the first piece of the edge of the Pacific plate began to sink beneath the Asian plate. No laboratory or computer model so far produced can replicate the beginnings of subduction. It obviously happened, though, and the change in direction of the Pacific plate resulted.

The Break-up of Gondwanaland

This intrigue involving the Pacific plate leads us to understand other unclear processes swept under the rug by plate tectonics. Consider the splitting of continents: What forces decided where and when seemingly solid continents split apart?

All locations of volcanism away from plate boundaries, and also some of the most prominent areas of excessive volcanism on plate boundaries, are thought to be hot spots. Consequently, there are many hot spot trails . For example, there are nine hot spots in the Atlantic Ocean (Figure 5-4). Hot-spot trails are also found propagating away from the Galapagos, Iceland, Yellowstone, the Azores, Tristan de Cuna, Easter Island, and many more volcanic centers.

Not only did the hot spots exist before the breakup of Africa from North and South America, they appear to have been located along the newly forming mid-ocean ridge all through the history of the Atlantic Ocean. Hot spots by their very nature would be excellent blow torches with which to cut the continents apart.

Further proof that this indeed happened comes from the traces of Africa and South America across the hot spots all up and down the Atlantic (Figure 5-12). Brazil was sliced off Nigeria by the St. Helena hot spot, for example.

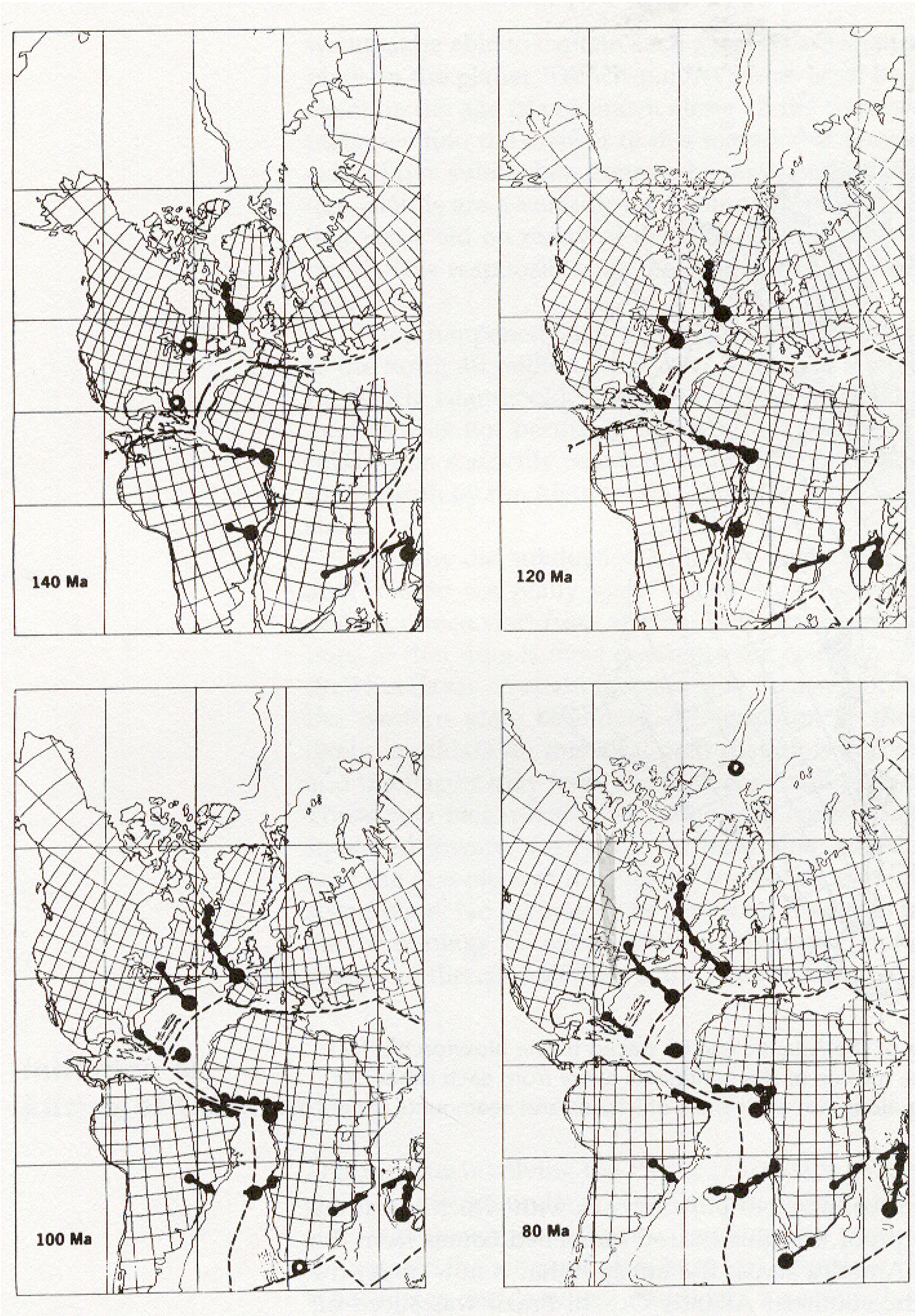

Figure 5-12 a. First 60 million years of existence of the Atlantic Ocean, with hot spot trails that cut the continents apart traced by their volcanic trails.

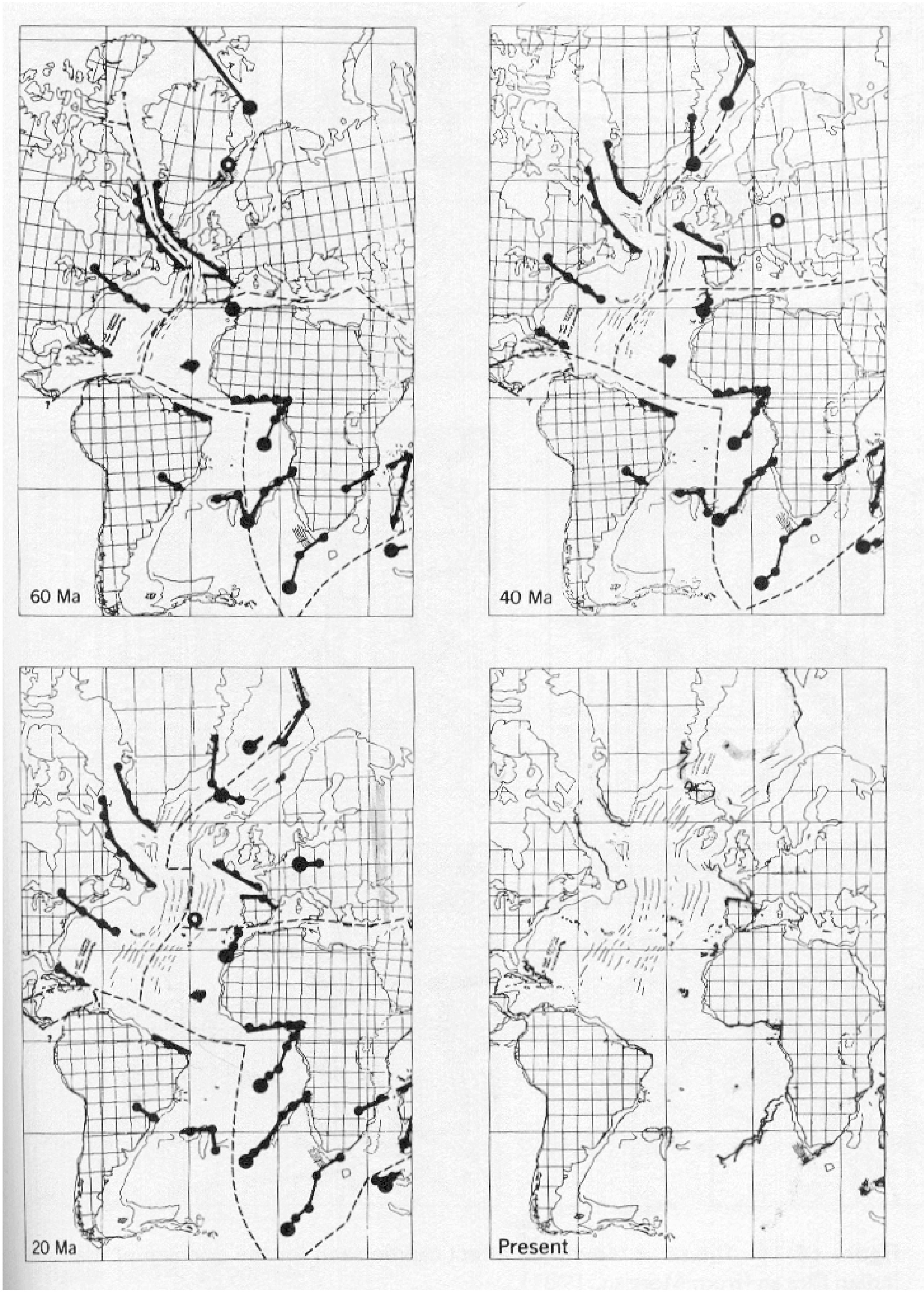

Figure 5-12 b. Last 60 million years of evolution of the Atlantic Ocean, with hot spot trails tracked by their volcanic trails.

The splitting of India, Africa, and Australia from Antarctica to create the India Ocen can be explained also by the heating and blow torch effects of hot spots now beneath Reunion, Crozet, and Kerguelen Islands in the Indian Ocean (Figure 5-13).

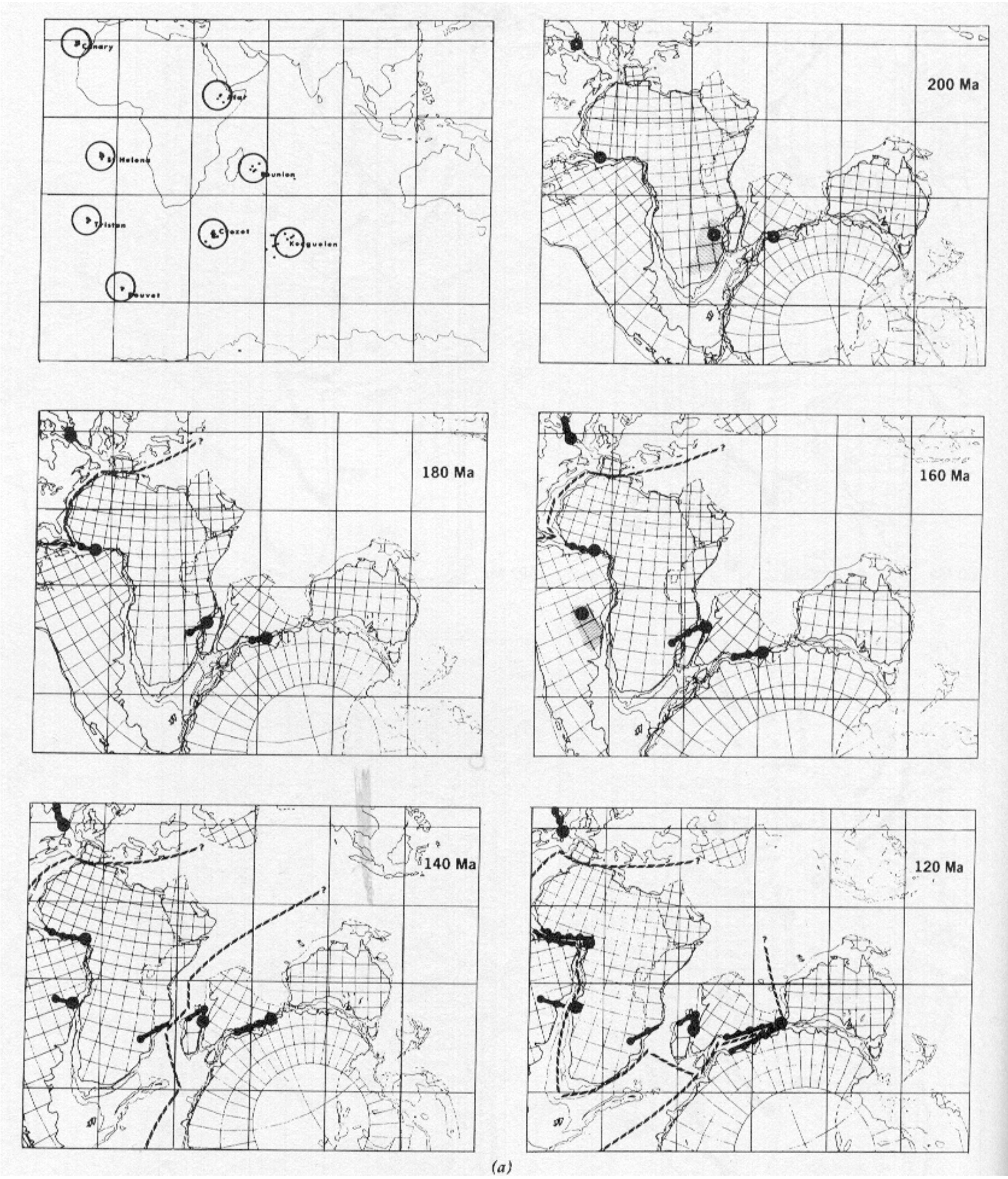

Figure 5-13 a. First 80 million years of evolution of the Indian Ocean, with hot spot trails tracked by their volcanic trails.

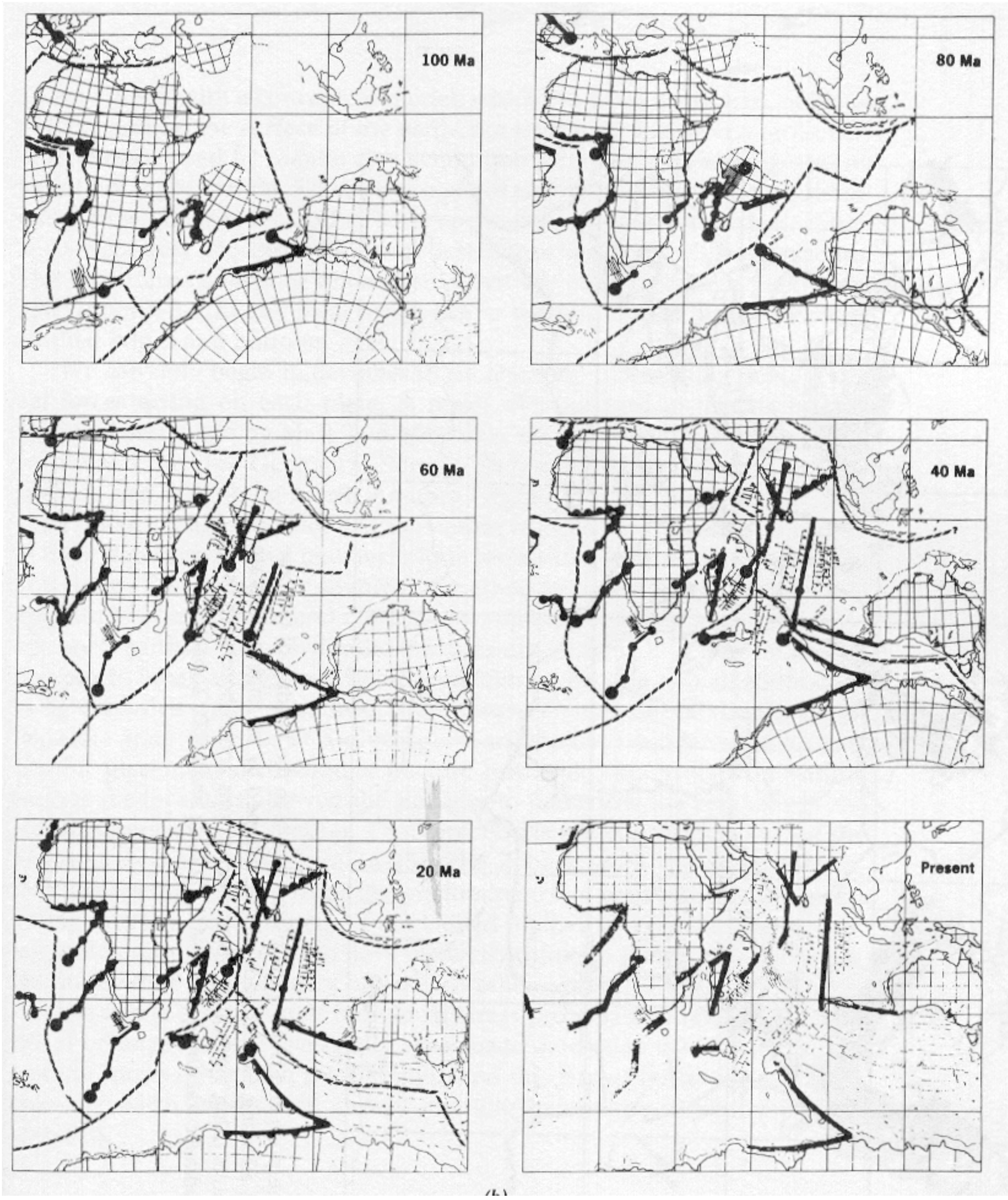

Figure 5-13 b. Last 100 million years of evolution of the Indian Ocean, with hot spot trails tracked by their volcanic trails.

Conclusion

So we are left with an all encompassing model of how the earth works with tectonic plates moving around the surface of the earth, not randomly, but driven by density differences caused by mantle convection that produces cold, heavy plates on top of hot, light mantle. Where these plates subduct back into the mantle determines in what directions and at what speeds they traverse the surface. When and where they encounter hot spots determines how they will be carved up. The important concept to remember is that the plates are large, rigid slabs that respond NOT to local forces but to the resultant of ALL forces acting on their edges and bottoms.

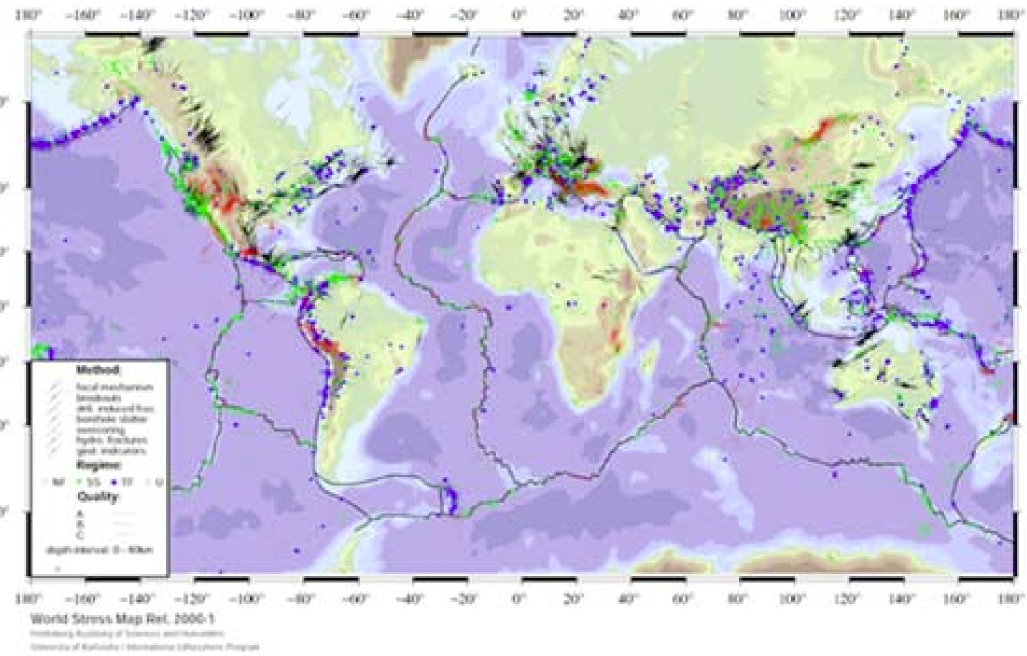

Figure 5-14. Stress map of the world shows the present day forces pushing and pulling on the plates (USGS).

We can measure these forces by determining the individual stresses acting on each plate. A major step forward in this regard has recently been made by compiling a map of the all the forces pushing and pulling on Planet Earth (Figure 5-14) using natural earthquake directions of maximum compression and directions of force determined by looking at how drill holes into the crust are deformed by this squeezing. These measurements can determine the state of stress at a given place within or at the boundaries of any plate (Figure 5-14).

The future resolution of individual stress provinces within the boundaries of plates will eventually allow us to predict when and where devastating earthquakes are about to happen and when volcanoes are about to erupt. Such discoveries may seem along way in th4e future, but never underestimate the curiosity of earth scientists to discover the unknown about Planet Earth.