Chapter 8

The Earth: A Churning Planet

As on a mountain-top the cedar shows
That keeps his leaves in spite of any storm

The Second Part of King Henry the Sixth, Act V. Scene I.
William Shakespeare (1564–1616)
The Oxford Shakespeare, 1914

Do we really have to consider how the Earth's inside works to see why it is habitable? There are numerous environments on the Earth's surface and, as Shakespeare knew, even the hostile ones teem with life. More or fewer continents or ocean basins would affect the details, but not the gross habitability. To some extent this is true, we do not need detailed daily meteorology to access habitable zones, neither do we need detailed geodynamics. Still we need to know how the Earth works dynamically to understand why it has massive oceans and a significant atmosphere. We need to know why it differs inside from the Moon, Mars, and Venus. With regard to advanced life, we want to know why the Earth's continents are near sealevel so that shallow seas exist.

Geological evidence for a changing Earth

The concept that the Earth changes dates from antiquity. In fact, Bruno and Galileo used these changes to argue that the heavens also change. As we saw in Chapter 5, the science of geology developed as a means to document changes of the Earth and its life over time. Earth scientists began to generalize in terms of natural processes in the late 1700s.

It took nearly two centuries for Earth science to move from reliable local observations to a systematic physical framework of how the Earth works. This may look like slow progress in the clear illumination of hindsight. However, geology is often quite complex when viewed on a scale of a hand-sized rock to tens of kilometers. Earth scientists could not immediately attempt to place such observations within a framework of physics. For example, Hutton realized that mountain ranges form and then are beveled to oblivion by erosion and that volcanoes face the same fate. He had little idea why mountains formed in the first place. In fact, his Earth ran on forever.

Logistics left 80% of the planet cloaked by oceans. The organization of specialties did not prove optimal. Physicists operated at a global scale and geologists quite locally. I present what may seem at first developments in disjoint fields that did not link until the 1960s. I concentrate on topics that eventually related to habitability.

Subsidence of sedimentary basins. Much of the study and debate on Earth processes before 1960 focused on the accumulation of thick piles of sedimentary rocks and their later folding into mountain ranges. Systematic observations began in 1836. The state of New York organized its geological survey. The eastern part of the state is folded and faulted rocks, the remnants of a once lofty mountain range. The more senior geologists got first crack at this interesting region. The western part of the state is nearly flat lying rocks. The survey relegated it to a junior geologist.

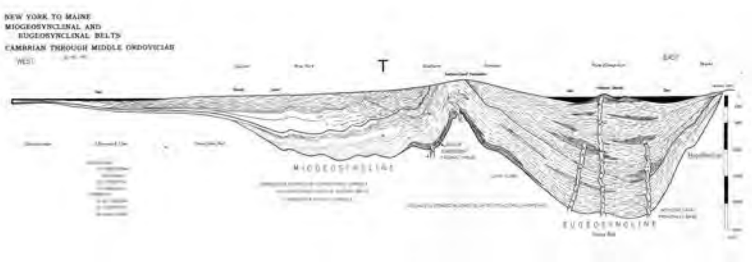


Figure 1: Marshall Kay in his 1951 book reconstructed a geological cross section of New York and New England. This is what he thought the geology looked like before intense folding began in Middle Ordovician times. The figure is typical of geosynclinal hypotheses following Hall who began the work in New York. The rocks west of “T” (my annotation) have not been extensively deformed. This part of the reconstruction is OK. In particular, these rocks accumulated in shallow water. Hence, the crust subsided more on the east than on the west to make room for them. East of “T” the reconstruction becomes increasing illusory. The rocks on the east include deep-water deposits incorrectly interpreted as forming in shallow water and rocks of a volcanic arc that latter collided with the continental margin, starting the intense folding. This arc was far away when most of the sediments on the east were deposited.

James Hall (1811-1898) went to work with the then newfangled geological time scale. He found that beds thicken toward the eastern mountains. The beds for, say, part of (what’s now) the Ordovician might be 10’s of meters thick on the west and 100’s of meters thick on the east (Figure 1). The beds consist of shallow water limestones, shales, and sandstones (Figure 2). The land subsided but more in the east than on the west. The sediment fill balanced the subsidence, keeping the sea shallow. This subsidence continued until the Appalachian Mountains formed over an extended period of time. Rivers from the mountains piled land sediments over the former shallow ocean basin.

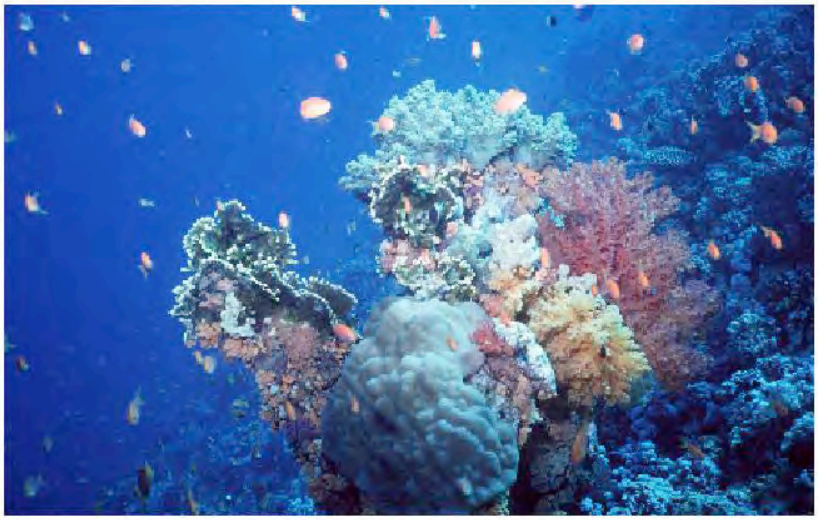


Figure 2: Modern coral reefs resemble reefs preserved in old sedimentary rocks. This allows geologists to deduce vertical motions as reefs form near sealevel. For example, old reef deposits are buried beneath kilometers of sediments beneath the Bahamas indicating subsidence and elevated kilometers in the Alps indicating uplift. Reefs indicate horizontal movements as they form in warm seas. Old reef deposits occur in the Arctic. Note that organisms with hard parts like coral are most likely to be preserved. Photo by Adina Paytan.

Hall, like many geologists until recently, considered the origin of the mountains to be the main problem. The subsidence occurred as a prelude to the mountain formation. He named the region of subsidence and subsequent mountain range a *geosyncline*. (A syncline is a fold in bedded rocks where the middle is downwarped.) The concept was useful descriptively; a similar situation was soon found to exist in numerous mountain belts like the Alps. Geologists continued to refine the concept until the 1960s.

Geosynclines, however, have serious problems as a scientific concept. First, no one knew how they worked physically. The land subsided and then became a mountain belt because it was wont to do so. Yet geosynclines were not an appeal to magic or a conscious attempt to "save the phenomenon" as in classical science. Rather, they were an admission that the complex Earth's was too poorly understood to move beyond finding patterns in the data. Likewise, doctors define a set of symptoms that typically occur together as a syndrome. They then look for a cause. For example, alert physicians recognized the acquired immune deficiency syndrome (AIDS). Scientists then sought a cause, finding human immune-deficiency virus (HIV).

Bothersomely, no geosynclines seemed to exist on the modern Earth. As we will see, information from the ocean basins swept them into history books with phlogiston in the 1960s. Until that time, the reluctance of many Earth scientists to consider physics slowed progress.

Floating continents. Mundane surveying in the 1850s provided evidence that the interior of the Earth is fluid over geological time. India was then a new part of the British Empire, the Jewel in the Crown. The British gentlemen did the same thing they did when they shot a large tiger; they measured, this time the entire country. The surveying techniques of the day were accurate, but the results did not look good. The north-south distance obtained by adding up individual sightings differed by hundreds of meters from that obtained using stars. The star method was basically the method from antiquity of determining the radius of the Earth (see Do It Yourself Box on Navigation in Chapter 2), but the radius was accurately known by then and could not be the source of the error. J. H. Pratt went to work. One look at the Himalayan Mountains indicated that they are a large mass. The survey accurately gave their elevation.

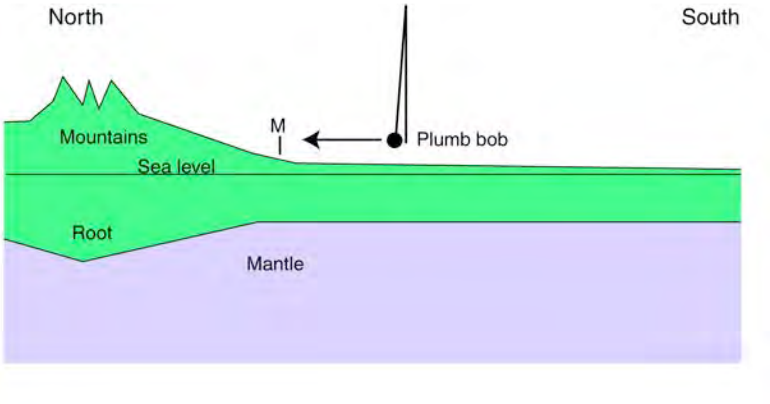


Figure 3: The mass of the Himalayan Mountains attracts a plumb bob (at point M) deflecting it slightly to the north from the expected vertical orientation. (The actual difference is too small to show to scale.) The actual deflection is less than that expected from the mass of the topography. A less dense root underlies the mountains. That is, the mountains float like an iceberg on the more-dense underlying mantle. Pratt contended that the root is hot less dense material rather than chemically less dense crust. This explanation applies to mid-oceanic ridges.

Pratt computed the gravitational effect of the mountains on the survey. Basically the horizontal attraction of the mountains causes the local vertical measured by a level or a plumb bob to differ from that of a smooth Earth (Figure 3). He had too much of a good thing. His calculated attraction was much more than the observed. A region of low density must exist in the subsurface beneath the mountains.

Pratt's result immediately piqued G. R. Airy who used the analogy of an iceberg. The crust of the Earth was then known to be less dense than its interior. Thick regions of crust float high like thick icebergs. Pratt liked the basic idea, but thought that high temperature rather than composition produced the low density. That is, a hot buoyant region (with thermal expansion) existed beneath the mountains.

The concept, soon called *isostasy*, is only a restatement that the interior of the Earth is fluid enough so that Archimedes' principle applies to floating continents. Importantly, it brought the nose of physics into the tent of regional geology.

There was no good way to resolve the conflict between Pratt and Airy until the 1960s. Both mechanisms in fact occur. Continents float higher than ocean basins, mainly because of their thicker less dense crust. Mid-oceanic ridges are elevated above the ocean basins because the rocks are hotter beneath the ridges. This concept became a pillar of plate tectonics by 1970. (By the way, earth scientists refer to the processes that form mountains, mid-ocean ridges, basins, and faults collectively as tectonics. Tectonics or tectonophysics is also the branch of science that studies these processes).

In the meantime, isostasy brought grief to geosynclines. The surface of the Earth can subside only if the density of the underlying material increases. The idea modern idea that cooling of hot subsurface material causes subsidence was in play in the late 1800s. The geologists of this era had no good way to measure absolute geological time, independently of assumptions about thermal processes. They did not know whether cooling was the aftermath of the Earth's formation or the aftermath of much later local events. By 1963 when I took freshman geology, concepts relating basin subsidence to cooling received no mention.

Post-glacial rebound. Another line of evidence soon confirmed that the interior of the Earth is fluid (Figure 4). The land around the northern Baltic Sea continually rises. This nuisance, causing harbors to dry up, was noticed by the Hanseatic League in the late Middle Ages. Rebound occurs in other regions, like much of Canada, that were covered by glacial ice 20,000 years ago. Basically the load of kilometers of ice depressed the Earth's crust like containers on the deck of a ship. Once the ice melted, the crust began to bob up. The inside of the Earth is viscous (gooey) so the process is still going on. The melt water raised sealevel and its load depresses the ocean basins.

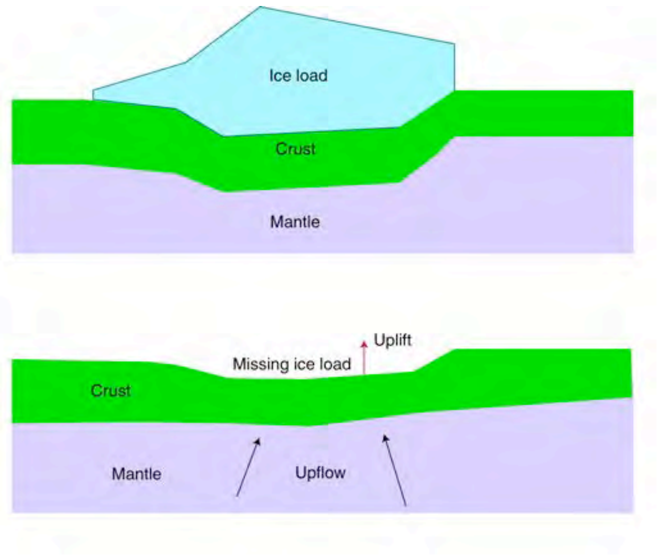


Figure 4: The weight of glacial ice depresses the surface (above). In effect the ice floats on the dense mantle of the Earth. Once the ice melts, the load is no longer present. The mantle flows upward slowly to remove the depression. The surface uplifts while this is happening. The process takes many thousands of years and is still going on in the aftermath of the last ice age. Not to scale.

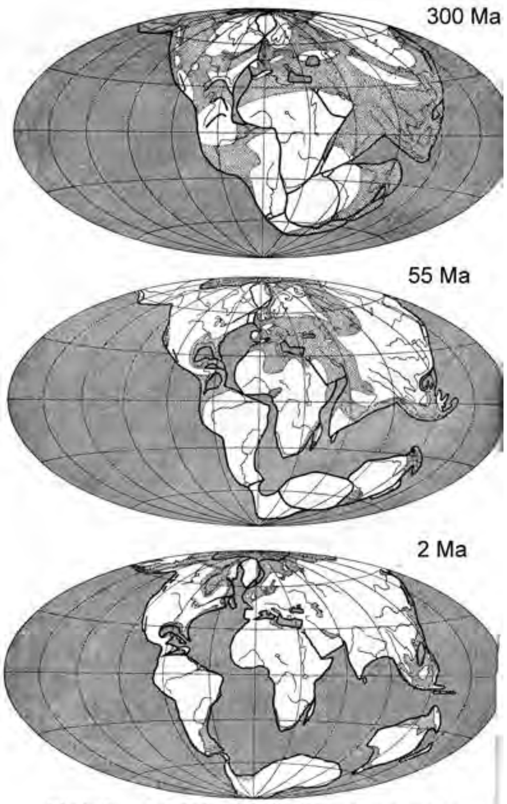
Despite this evidence that the inside of the Earth behaves like a fluid, many geodynamists until the 1960s considered that the fluidity was limited. The Earth could deform a little but not a lot. It was much like a wooden jigsaw puzzle. You can deform it a little until the pieces lock. Misleadingly, cracked rock behaves this way in the laboratory at room conditions.

Moving continents

Focused on the evidence for vertical movements, Earth scientists generally regarded continents and ocean basins as permanent fixed features of the Earth's surface. This attitude began to change in 1906.

A young meteorologist arrived in Greenland with months of harsh weather to study. He was also responsible for surveying the position of the Danish colony. There were lulls when Alfred Wegener (1880-1930) had little to do but watch the pack ice. Lanes and leads opened up. The broken blocks of ice could be fit back together like a jigsaw puzzle. This experience served him well on his return to Europe. He found a book on the identical plants and animals present on either side of the Atlantic. He started to think and looked at a globe. Europe, Africa and the Americas fit together. Greenland fits back into Baffin Island and Norway (Figure 5). Could the continents have once been joined like the broken pack ice?

Fig. 1.



Rekonstruktionen der Erdkarte nach der Verschiebungstheorie für drei Zeiten.
Schraffiert: Tiefsee; punktiert: Flachsee; heutige Konturen und Flüsse nur zum Erkennen.
Gradnetz willkürlich (das heutige von Afrika).

Figure 5: Wegener reconstructed continent positions at three times in his 1922 book. I annotate the modern values of 300 million years ago, 55 million years ago, and 2 million years ago. Earth scientitists have made considerable refinement since that work, but the figure suffices to show that the Atlantic and Indian Ocean continents were once together and then split apart.

Wegener was not the first person to note that the continental boundaries fit together; this was known from the age of exploration. He was not the first to suggest they broke apart. But he was familiar with geological and geophysical literature. He started to check his hypothesis. As frequently occurs, extensive available data bore on the concept.

Paleontology and other "soft" evidence. I go back a little to the development of the geological time scale. Paleontologists noted that there are fossil realms at different times. These realms do not make at lot of sense with modern geography. For example, Cambrian fossils in eastern Massachusetts resemble those in Britain more than those in the western part of the state. More recently, similar flora and fauna existed in South America, Africa, India, Antarctica and even Australia in the Permian. Paleontologists "solved" the problem by proposing a network of land bridges between various continents that arose and subsided at the appropriate times.

Wegener was familiar with the real Panama and Bering Strait land bridges. He knew they are made out of buoyant continental crust. They might get beveled below sealevel like the Bering Strait but because of isostasy they cannot sink out of sight. The topography of the oceans was well enough surveyed by then (from laying telegraph cables) that sunken land bridges could not have been missed. Wegener noted other anomalies, like glacial deposits in the Saharan desert that make little sense with the continents in their present position. He compiled massive evidence and published in German in 1915. His German term "Kontinentalverschiebung" was neutral, simply implying motion. The English term "continental drift" and the French term "la dérive des continents” imply that an underlying current, such as those beneath ice floes, carried the continents. This concept clouded thinking for decades.

WW I raged at the time. Wegener was wounded and then transferred to the safety of the German weather service. A new edition of his book in 1920 renewed interest. Geologists did not like speculation about global issues and they were not enamored with a meteorologist blundering into their turf, but Wegener had raised telling points. He had some support among geologists, especially in South Africa. He merited the courtesy of an open scientific debate. Other than the prejudice against big thinking, Wegener faced three issues.

First, much of his data were soft, like faunal descriptions and similarities of geology between fitting continents. Even the climatic data was open to multiple interpretations. Could the climate have been different so that glaciers occurred on the Sahara in the Ordovician? The Earth has just come out of a glacial period so climate seemed to be an erratic indicator.

Second, he was wrong in numerous details. Scientists do not often get everything right on the first try. He had Norway separating from Greenland in the Pleistocene (last million years or so), rather than starting at 60 m.y. years ago. He and his critics were confused by bad data, like the evidence for glaciers in the Boston Basin in the Permian when it should have been warm. (The deposits are glacial but actually much older.)

Search for a mechanism. Third he had no good mechanism to move the continents. Geologists asked correctly what large force is available to move continents. They did not ask what force keeps them fixed. Wegener was familiar with physics and sought a mechanism. He realized that a ridge runs down the center of the Atlantic Ocean. Could this be the site of a rising convection cell that split the continents apart? Wegener did not carry on with this idea in 1920 but instead regarded the continents as rafts drifting over a fluid mantle. His ridge was debris left by the break-up. His experience with pack ice had sent him down the wrong track.

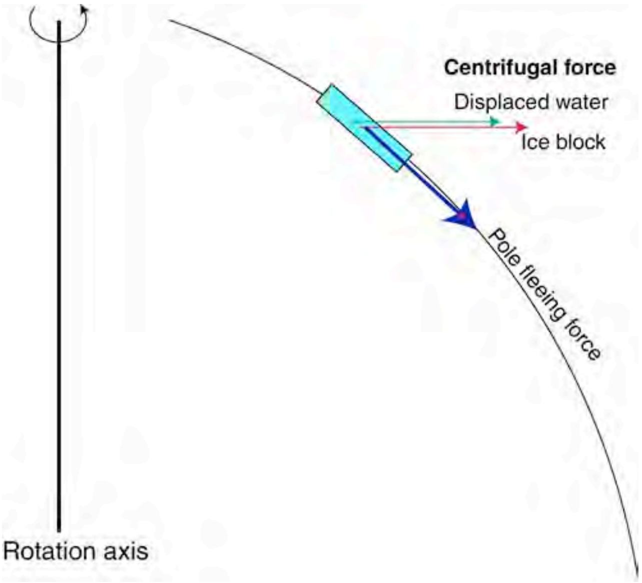


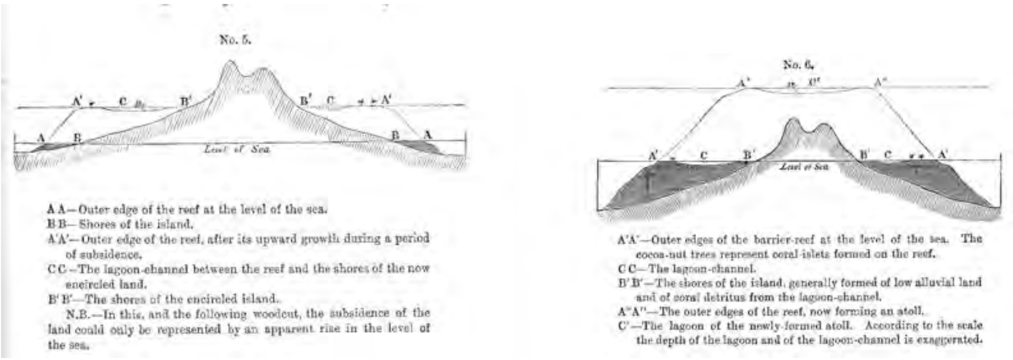
Figure 6: An ice block floats on the ocean higher than the water it displaces. That is, the block is further from the rotation axis of the Earth than the displaced water. Hence, the centrifugal force from the rotation of the Earth is higher on the block than the displaced water. This results in a component of force on the block that moves it toward the equator. This force is real but too tiny to move continents floating on the mantle.

As a meteorologist, he was quite familiar with forces associated with the Earth's rotation. A floating block, like an iceberg or a continent, rises above its surroundings (Figure 6). Its center of mass is farther from the center of the Earth than the water it displaces. The centrifugal force from the Earth's rotation is greater on the block than the displaced water. The force resolves into a vertical force that causes it to float slightly higher and a horizontal force that drives it toward the pole. The force is real; it may drive ice movement of the Jupiter satellite Europa. However, it is tiny on the Earth and proved unable to move continents around.

Wegener tried to document the movement of continents with surveying. He thought the most rapid movement was between Greenland and Norway. He died on the ice in 1930 (of a heart attack). In retrospect the motion between Greenland and Norway is relatively slow, about 2 centimeters per year. Surveying techniques did not become good enough to resolve continental drift until about 1990. By then, only a few aged holdouts doubted its existence. In analogy, the detection of parallax in 1837 provided very belated evidence that the Earth orbits the Sun.

New technology and seafloor spreading

Geodynamics, like planetary science, was driven by a great influx of new data. After Wegener's death, the world plunged into depression and then WW II. On both sides of the Atlantic, scientists labored on the war effort. They greatly improved electronic instrumentation. I begin with naval technology that provided reliable data on the seafloor.



A A—Outer edge of the reef at the level of the sea.
B B—Shores of the island.
A'A'—Outer edge of the reef, after its upward growth during a period of subsidence.
C C—The lagoon-channel between the reef and the shores of the now encircled land.
B' B'—The shores of the encircled island.
N.B.—In this, and the following woodcut, the subsidence of the land could only be represented by an apparent rise in the level of the sea.

A'A'—Outer edges of the barrier-reef at the level of the sea. The cocoa-nut trees represent coral-islets formed on the reef.
C C—The lagoon-channel.
B' B'—The shores of the island, generally formed of low alluvial land and of coral detritus from the lagoon-channel.
A''A''—The outer edges of the reef, now forming an atoll.
C''—The lagoon of the newly-formed atoll. According to the scale the depth of the lagoon and of the lagoon-channel is exaggerated.

Figure 7: Darwin's figures illustrating the evolution of a volcanic island into an atoll. For convenience, he drew rising sealevel rather that letting the base of the volcano subside. Further subsidence beneath the waves with reef growth forms a land-topped seamount called a guyot. Atolls and guyots indicate that the seafloor tends to subside over geological time.

Moonless mountains on the ocean bottom. Study of the dynamics of the deep ocean floor began in 1945, somewhere in the Pacific aboard a transport ship. A naval officer watched the echo sounder. The Pacific was not well surveyed so he had to be alert for shoals. The ship might also pass over an enemy submarine. War is "hurry up and wait." There was enough of the former when he reached Iwo Jima. There were long days and nights in deep water. The officer became curious and set the echo sounder so that it recorded all the way to the bottom. Harry Hess noticed that the ship passed over flat-topped seamounts.

Hess was a geology professor before the war. After the war, Hess returned to the Princeton Geology Department. He stayed on land with his day job but retained an acute interest in the oceans. The flat-topped features that he named *guyots* (after the geology building at Princeton University) are the remnants of volcanic islands, like Hawaii. Erosion beveled the edifices to sealevel and they then subsided below the waves. Darwin had already recognized that atolls form when coral reefs grow on subsiding edifices (Figure 7). The main point was unmistakable; the seafloor is active and prone to subsidence.

Cold war oceanography. Naval technology continued to advance after the war. The U.S. Navy needed classified information. They also needed well-trained marine scientists. To get them, they needed to open oceanographic institutions publishing open literature. The Office of Naval Research funded Lamont Oceanographic Institution in New York and Scripps Institute of Oceanography in California. These institutions went about surveying the seafloor and collecting rocks and sediment cores from the sea bottom.

A new instrument, the proton magnetometer, offered much promise. It could be towed when the ship was underway. It could record local variations in the Earth's magnetic field. For 19th century reasons, geophysicists call the variations anomalies. In this case the name seemed to apply in the common sense of the word. A graph of the anomalies looked like uninterpretable wiggles. Their interpretation in the 1960s involved diverse lines of evidence.

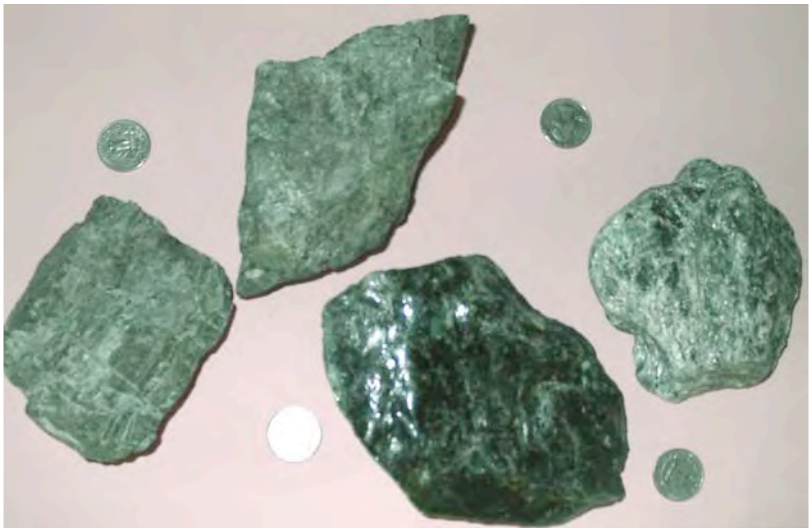


Figure 8: Samples of serpentine were collected from outcrops on land. The rock was originally part of the Earth's mantle. Uplift placed it near enough to the surface that it reacted with circulating water to become hydrous minerals. Further uplift and plate movements placed it on land. Photo by the author.

Serpentine from the seafloor. You may have seen "green marble" or "verde antique" floors or counter tops. In modern terms, this rock started out as part of the Earth's mantle as anhydrous (dry) magnesium silicates, mainly olivine. It then approached the surface and reacted with circulating water to form a hydrous magnesium silicate called *serpentine* because its fresh surfaces look like snakeskin (Figure 8). Tectonic movements then placed the rock on land where we can quarry it.

I already discussed this rock as an important prebiotic environment where ribose can form in Chapter 4. It is an interesting biological environment on the modern Earth. I thus give attention to its role in Earth processes and in the history of science.

Hess's day job as a mineralogist involved serpentine. He knew that it comes up in dredge hauls from the seafloor and occurs in rocks in the Alps that look like uplifted seafloor. He also knew that the seismic velocity of serpentine (measured by controlled explosions) is lower than that of the Earth's mantle and appropriate at 1960 resolution for oceanic crust.

Hess deduced that the oceanic crust is made of serpentine. Convection currents brought up the mantle at ridges where it became serpentine by reacting with water. The crust moved away from both sides of the ridge like a conveyor belt. Seamounts sank as the belt carried them away from the ridge. The easily deformable serpentine acted as a lubricant. Hess recognized that the serpentine forms by trapping water, CO_2, and even chlorine from the ocean. Its formation is a major global geochemical process.

Hess presented his results at a conference in 1960. The compiled volume (since the editors typically wait for the slowest author) did not come out until 1962. By then, Robert Dietz (1914-1995) of Scripps (and the Navy) reached similar conclusions and named the process, in print, "seafloor spreading." Their combined works incited the last scientific revolution.

Lodestone and missing links. I backtrack in time to the 1950s. Physicists at Cambridge University attempted to study the history of the Earth's magnetic field. They had the formidable differential equations that govern the generation of the Earth's field in its molten iron core, but they needed more than the historical record to get started.

Serious study went back only to William Gilbert, a fan of Bruno. Edmund Halley documented that the magnetic field changes so rapidly that charts need to be updated and a fluid region within the Earth generates the field. One of his day jobs was running the British navigation service.

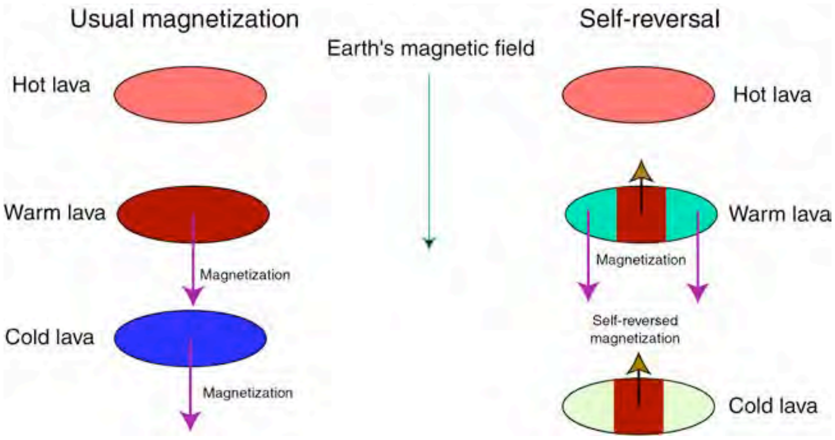


Figure 9: Lava becomes magnetized as it cools in the Earth's magnetic field. Hot lava is not magnetic. At intermediate "warm" temperatures, lava acquires magnetization. Usually the magnetization is in the direction of the Earth's magnetic field (left). The lava retains this magnetization over geological time once it has cooled to room temperature. Sometimes different parts of the grains get magnetized in opposite directions like bar magnets placed together. Here the sides of the grain are magnetized with the Earth's field and the center opposite the Earth's field. The flanks lose their magnetization as the sample cools to room temperature leaving the center magnetized opposite the Earth's field. Such self-reversal is rare in nature, but caused much confusion until it was understood.

Sensitive electronics let the Cambridge group detect the weak magnetism present in natural rocks. Crudely, minute grains of the mineral magnetite (loadstone) form when basalt and other volcanic rocks freeze. The mineral is not magnetic at the lava freezing temperature (around 1100°C) but becomes magnetic as the rock cools, below 500°C depending on the mineral's precise composition. The mineral then picks up a stable magnetization in the direction of the Earth's field. The scientists merely needed to collect oriented rock samples and measure the direction of magnetization.

The equipment worked fine but the results were in part problematic. When they measured young rocks, the direction of the magnetic field scattered about the expected pole direction much more than their precision. This scatter was due secular variation, the signal that they were after of gradual changes over time scales of 10 to 1000s of years in the local field. Some of the magnetic directions pointed in the opposite direction (Like a compass pointing south not north.) They called this reversed and the current direction normal.

If they sampled older rocks, say Triassic, they got scatter, normal and reversed, but the mean direction was not that of the present field. The modern magnetic field averaged over historic data is crudely vertical at the poles, horizontal at the equator, and tilted in between. It is a simple matter to compute the distance and direction of the magnetic pole from the sampling locality. The Cambridge scientists were familiar with the concept of continental drift. The Triassic poles of North America, Africa, Europe, and South America should coincide if we rotate the continents to their pre-drift arrangement. They do.

The paleomagnetic results convinced the choir, but seismologists regarded the data as soft. They knew that lightning can re-magnetize rocks and they were worried that collecting them with a hammer would demagnetize them. In fact some rocks do get re-magnetized from weathering, metamorphism, and lightning. The paleomagnetists were just learning to sort these out. Bad data got published with the good. When I first looked at the literature as an undergraduate in 1965, it looked like an inconsistent morass.

The reversed directions intrigued the paleomagnetists. Had they found evidence that the Earth's field reverses direction? Or do rocks sometimes get magnetized backwards. Both seemed plausible. The equations governing the magnetic field indicate that for every normally oriented solution for the magnetic field in the Earth's core there is an equivalent reversed one. Conversely, rocks can get magnetized in the reversed direction if there is more than one magnetic mineral (or magnetic lattice component in one mineral) (Figure 9). The first mineral to lock in magnetization is normal, but the second locks in the reverse direction, like one bar magnet placed next to another. If the first mineral subsequently loses its magnetization the rock retains self-reversed magnetization.

A young Japanese geomagnetist tested things for himself. There are lots of volcanoes and young volcanic rocks in Japan. Fujiyama is the most picturesque. Seiya Uyeda collected samples, measured the magnetic directions, and then heated them in the laboratory demagnetizing them. He then let them cool in a known magnetic field. Some of his samples did self-reverse. This threw in a monkey wrench into paleomagnetism. Much more careful work was needed to get the gears of the field to turn smoothly.

By the late 1950s, it was evident that very young rocks typically have normal magnetization. Somewhat older rocks may be either normal or reversed. Radioactive age-dating techniques were inadequate. The U.S. Geological Survey considered dating as an aid to mapping and there was still a worldview that young rocks were unimportant. The discovery of hominid fossils in east Africa changed this. When did these human ancestors live?

Robert Doell, Brent Dalrymple, and Allan Cox, then at the U.S. Geological Survey, got right to work. Cox was trained at Cambridge in paleomagnetism and Doell and Dalrymple in radioactive dating. They improved the potassium-argon method so that it could date young rocks. As discussed in Chapter 6, potassium (symbol K) has a rare radioactive isotope (40). It decays with a half-life of 1.3 billion years into argon (Ar-40) and calcium (Ca-40). The “branching” ratio is known and is not a problem in practice. Ca-40 is one of the most common isotopes in the Earth’s crust. It was not then practical to look for a little more of it from potassium decay in volcanic rocks. Argon is a rare gas that is usually not present within crystals. (It is 1% of the air so contamination needs to be avoided.) They measured both K-40 and Ar-40 and used the ratio and the half-life to get eruption ages. Present technology gives accuracy of 10’s of thousand years on 100 million-year-old samples.

Doell and Cox found that samples younger than about 700,000 years are normally magnetized. Ones just older than this are reversed. They established a reversal time scale back to 3 million years. Paleomagnetists continue to refine the scale. It is now reasonably determined back to 150 million years.

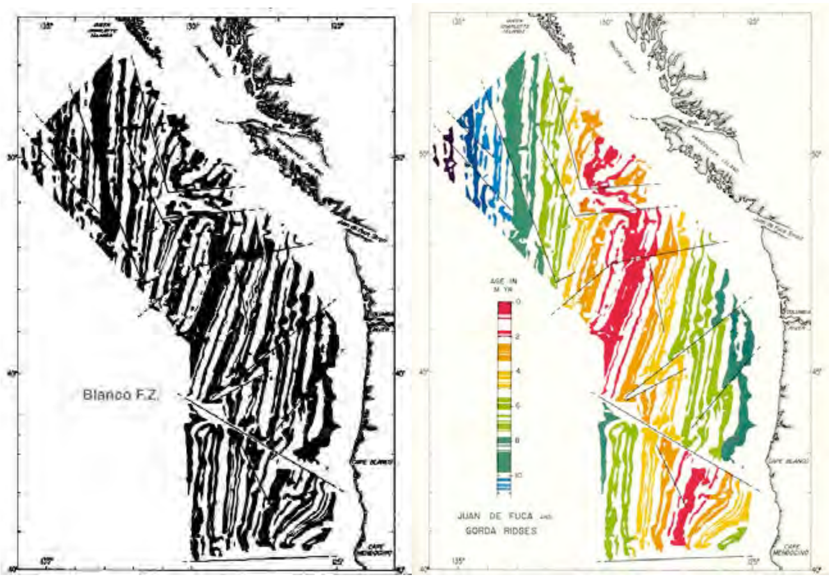


Figure 10: Mason and Raff shaded magnetic anomalies to get a zebra patterlike the map on the left. Such maps brought order out of the chaos. Fred Vine colored the anomalies to show the age of the seafloor (right). The Blanco fracture zone offsets the anomalies. Both Figures are from Vine’s paper. I converted the left panel to black and white to simulate uninterpreted data.

Marine magnetism and seafloor spreading. The penchant for measuring by marine scientists paid off. Cruises had surveyed the Pacific Ocean near the United States. Ronald Mason and Arthur Raff (1917-1999) attempted to make some sense of the chaos. They were used to contouring soundings to make bathymetric maps. They contoured the magnetic anomalies. Then for ease of presentation they made a simple map with the positive (above average) anomalies colored black and the negative anomalies white. This restored order. The map (Figure 10) looks like a zebra. The stripes line up with the topographic grain. The anomalies look symmetric around the topographic axes of an undersea ridge. They are cut by great topographic faults, like the Mendocino fracture zone off northern California. The stripes match when several hundred kilometers of slip is restored. Weirdly, there seemed to be no evidence of such slip on land.

The ridge axis is a positive anomaly. The same situation exists at the Mid-Atlantic ridge. This observation got a Canadian mining geologist thinking. He was familiar with the work on magnetic reversals. He knew how to interpret magnetic anomalies in terms of magnetized rocks from his day job. Lawrence Morley knew that erupting basalt becomes magnetized when it cools. He put all this together. Basalt erupts at the ridge axis, freezes and becomes magnetized. Seafloor spreading then carries it in both directions away from the axis (See Figure 11). The young region near the axis is normal and reversed and normal stripes lie further out on the belts. Positive magnetic anomalies lie over normal stripes and negative ones over reversed stripes.

New concepts like the Sun being a star upset the organization of science. The people, who were nominally the most qualified, Aristotelian astronomers in the case of Bruno, lacked the necessary skills. Worse yet, they were fixed in their ways and unwelcoming to outsiders.

Morley faced this situation. His idea got the welcome of a pig at a Bar Mitzvah. He submitted to the British journal *Nature*. This was and still is a highly prestigious place to publish. To maintain this reputation, the journal sends submitted manuscripts to well-known scientists in the field. The *Nature* reviewers and editors treated Morley as a nut. Being from a former colony did not help any.

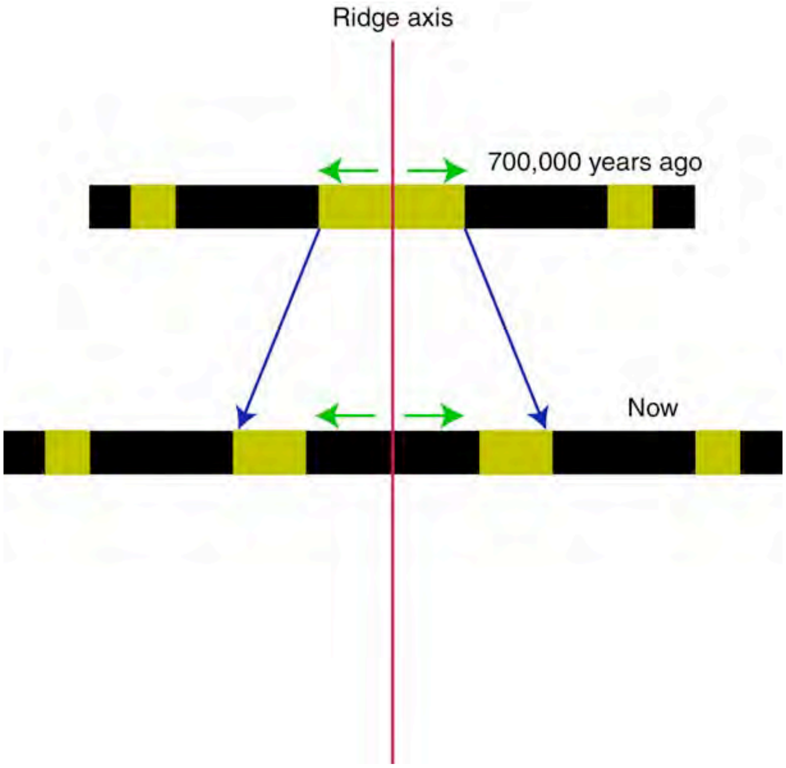


Figure 11: Lawrence Morley's combined magnetic reversal of the Earth's magnetic field with seafloor spreading. The seafloor moves away from the ridge axis forming a symmetric pattern. The black-shaded crust formed during times that the field was in its present (normal) direction and the brown-shaped bands formed when it was in the opposite (reversed) direction. For the ridges familiar to Morley, the observed magnetic field is slightly higher above the normal stripes than the reversed stripes. The last reversal was around 700,000 years ago. The geometry is analogous to a magnetic tape recorder with tapes running both ways from the ridge.

He did no better with the *Journal of Geophysical Research*. At that time, the journal operated at Lamont. The marine geologists were in no mood to look at the ignorant musings of a miner, and they were trained like most American geologists to avoid big thoughts. Morley gave up his futile attempts to publish. This situation at Lamont with the journal persisted until the early 1970s. I was at the Toronto meeting of the American Geophysical Union in 1980. Morley received an award related to his day job. By then the story of his paper's rejection was common knowledge. Several other scientists who got awards, including me, had had early plate tectonic papers rejected by the journal.

Back at Cambridge University, a graduate student reached the same conclusions as Morley. Fred Vine went to his advisor Drummond Matthews who was at first skeptical. Vine used the new reversal time scale to make calculations. The fit to the real anomalies was good. They submitted to *Nature* and got the warm welcome accorded to Cantabridgians. The cat was out of the bag.

Testing seafloor spreading. At Lamont, Maurice (Doc) Ewing (1906-1974) was troubled by seafloor spreading. The idea went against all his geologic training that the ocean basins were permanent features of the Earth. To boot, the magnetic anomalies on the Mid-Atlantic ridge (the one nearest his office) are not all that regular. As director, he mobilized a full effort to collect new data and compile old to rid the world of seafloor spreading. The endeavor did just the opposite. The final coffin nail came when Walter Pitman, then a graduate student, returned from a cruise in the South Pacific. The ridge there is spreading faster than the Mid-Atlantic Ridge, like an ideal conveyor belt. The anomalies are symmetric about the axis. Pitman plotted the anomalies on transparent paper to overlay the flipped profile on the data. Ewing was not immediately comfortable with seafloor spreading, but time was of the essence. Lamont had esquireled away magnetic data for much of the ocean as had Scripps. By 1968, there were reasonable global constructions of seafloor spreading.

Plate tectonics

By 1965, the concept of seafloor spreading was in place but not really linked to the rest of the planet. The large fracture zones on the seafloor did not make much sense. For example, fracture zones cross the Atlantic in several places. The Mendocino and Blanco fracture zones lie off the coast of California. Yet these features do not come on shore. In fact, they go against the training of field geologists from the time of Steno. The Atlantic fracture zones offset the Mid-Atlantic Ridge so they must be younger than it. These fracture zones are deeply buried by sediments, especially near the coast, so they must have been active a long time ago. Yet the paleomagneticists contended that seafloor spreading is presently occurring at the ridge axis.

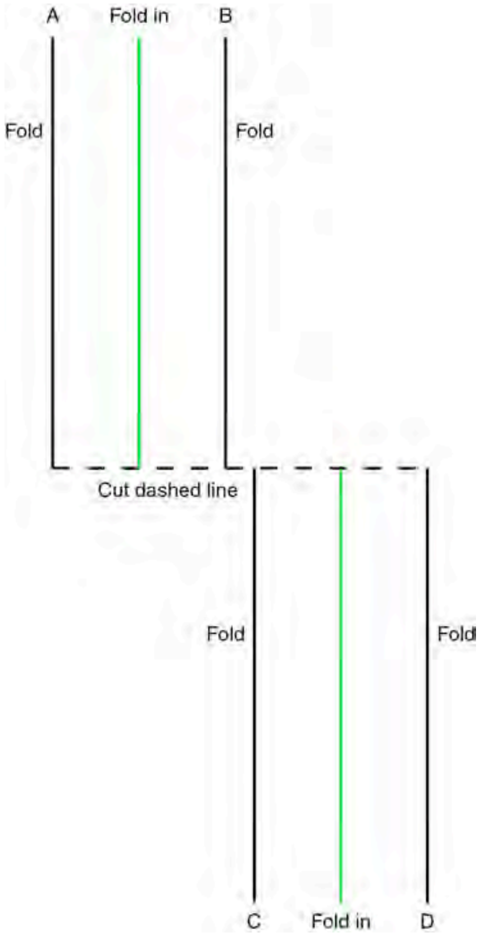


Figure 12: For many years, J. Tuzo Wilson carried transform fault kits to scientific meetings. Cut along the dotted line to make the active part of the transform fault. Fold the green lines inward so that the black lines come into contact. The black lines then represent a band of crust formed at the ridge axis at one time. Pull the folds apart to restore the flat map. Now the green lines are the ridge axis and the black lines are age bands of crust away from the axis.

Transform faults. A Canadian geophysicist started to think. Could only the part of the fracture zone between the two ridge segments be active? J. Tuzo Wilson made a cutout on a piece of paper. (See Wilson kit in Figure 12). He carried these to meetings for several years until the concept was common knowledge. The two ridge segments spread at the same rate. Only the fracture zone between the two fault segments slips. Wilson got the idea just from thinking about the geometry. If you look, similar features exist where sidewalk cracks and igneous dikes jog. They also exist between leads in pack ice.

Wilson was familiar with both dikes and pack ice. (He was the last person to discover an island in Hudson Bay.) Remarkably, dikes and pack ice did not enter his mind at the time. He quickly published his idea.

Nuclear tests and modern seismology. I again jump back into the 1950s. The nuclear arms race benefited seismology. Both the Soviets and Americans recognized the dangers of radioactive fall-out. A ban on above-ground tests was politically feasible since the fall-out makes violations easy to detect. Easy detection did not apply to underground tests. In 1958, seismology was in a state of extreme neglect. There were good seismologists at Lamont and CalTech and Jesuit Schools, including the University of St. Louis. There were few working seismographs and these were not standardized. A seismologist had to write every observatory in the world and wait months to years for hard records to arrive just to study one earthquake. Seismologists were able to locate earthquakes, but not precisely. Neither did they have good ways to tell earthquakes from explosions.

The United States was unwilling to sign an underground test ban that could not be verified and unwilling to risk a confrontation with the Soviet Union on the word of ill equipped, slow-moving, and poorly trained seismologists. The planners recognized that open institutions and open data were necessary to have well trained seismologists. Like the Navy, they also maintained classified research.

The United States deployed the World-Wide Standardized Seismograph Network starting in 1961. As the name implied, the seismographs were the same. One could quickly compare arrivals at various stations and from various events. The seismographs recorded on film that was photographically reproduced, making distribution efficient. When I arrived at MIT in 1967, canisters of rolled microfilm already filled part of a laboratory. The seismic stations all sent picks of arrival times to central agencies in the U.S. and Britain. They published reasonably accurate earthquake locations from these data.

Wilson's idea of transform faults did not please the seismologists at Lamont. A graduate student, Lynn Sykes, saw that it is a testable hypothesis. A transform fault slips in the opposite direction of a "transcurrent" fault offsetting the entire ridge and ocean basin. It is easy to tell the difference as the first motion on a seismogram (Figure 13). He had catalogs of earthquakes to find events along fracture zones. The new WWSSN seismograms helped greatly. He could do an event in a few days. He studied several events and all had the slip direction of a transform fault.

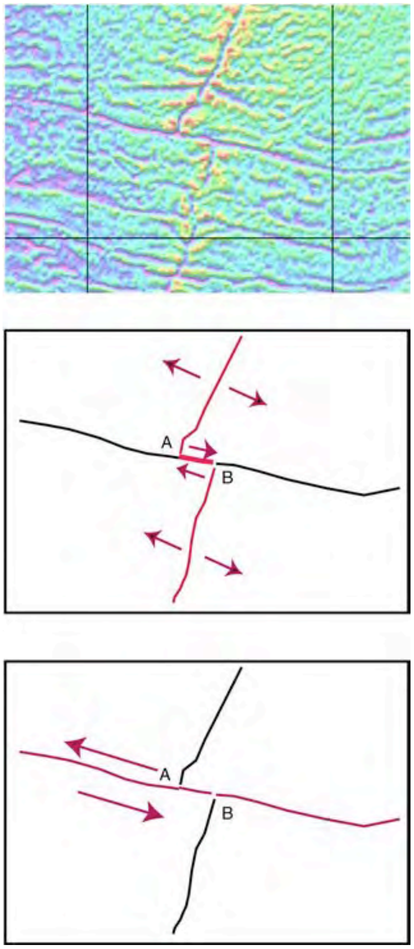


Figure 13: Oceanographers had mapped the larger fracture zones in the Atlantic by 1960. Smaller fracture zones and much of the detail on the modern map were not evident. The large fracture zone running east west appears to offset the north-south ridge axis. In plate tectonics, the ridge axis spreads apart and the transform fault between the ridge segments slips, here with the north side moving east. The rest of the fracture zone is not active. Lynn Sykes found this to be the case. If the fracture zone offset on older ridge, the slip would be north side to the west and the whole fracture zone would be active. Map from Smith and Sandwell.

In addition, the fracture zone should be active only between the two ridge segments. Earthquakes, in fact, occur there rather than on the inactive fracture zone away from the ridge segments. The fit, in retrospect, was too good. The maker of Lamont bathymetric maps, Bruce Heezen, had already noted the correlation and correctly used it to put fracture zones into unsurveyed areas of his maps.

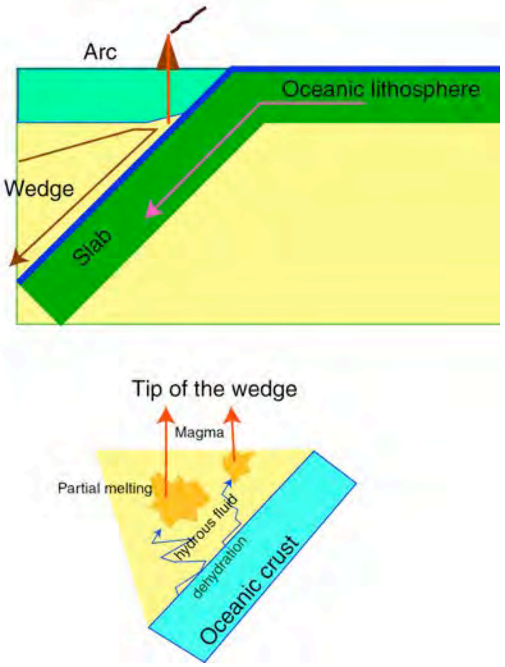


Figure 14: Subduction carries hydrous oceanic crust (thick blue line top) into the mantle. The crust heats up and dehydrates when it comes in contact with the hot mantle wedge above the slab. In detail (below), the hydrous (water-rich) fluid leaving the oceanic crust diffuses and vents into the overlying how mantle. This lowers the melting temperature. Molten rock (magma) forms by partial melting and ascends to feed the volcanoes of the island arc

(photo Dave Scholl) **Subduction: Cold fog and hot volcanic ash.** The ultimate fate of the oceanic crust formed at ridges came from practical considerations. During World War II, the United States retook the Aleutian Islands and built airstrips. Volcanic eruptions sometimes blanketed the strips with volcanic ash. Ash getting sucked into plane engines was also a problem that still threatens commercial jets. The military summoned a geologist to study the volcanic nuisance.

Robert Coates studied ancient as well has modern lavas for over a decade. (The islands were important bases in the cold war.) He was aware that earthquakes occur deep beneath the arc. He knew that arc volcanoes are hydrous and explode like a boiler when the steam within the lava expands while approaching the surface. He put all this together. In modern terms, a slab carries oceanic crust and sediments down into the mantle (Figure 14). At around 100-km depth, the material dehydrates and the water moves upper into overlying hot mantle. The “wedge” melts under hydrous conditions (hydrous rocks melt at lower temperatures than anhydrous ones). The melt then ascends to form arc volcanoes. The idea caught on only when seafloor spreading did. The “subduction” of crust at island arcs balances that produced at ridges. The smoking gun came later. Julie Morris detected the short-lived isotope berylium-10 in arc volcanics. It forms from cosmic rays hitting the upper atmosphere and then falls to the surface. It can only enter the lavas via subducted sediments.

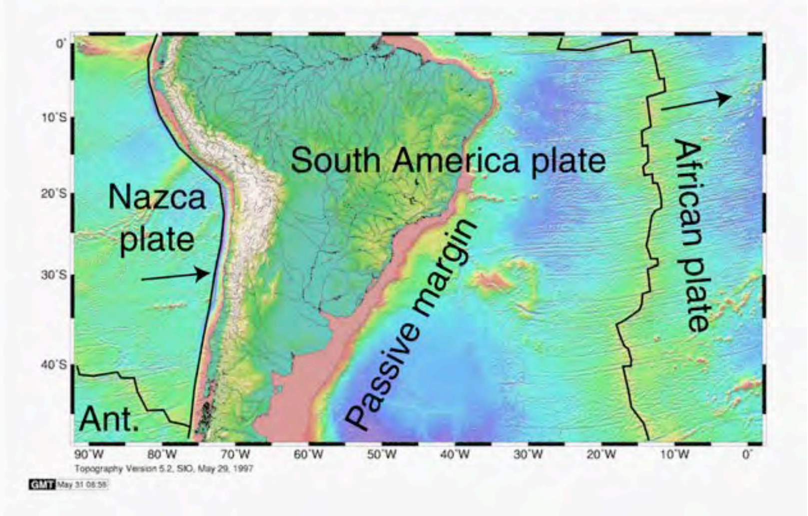


Figure 15: The South America plate extends from the ridge axis west to the Chile trench. Oceanic crust of the Nazca plate subducts beneath South America. The Africa plate moves away as new crust forms at the ridge axis. Part of Antarctic plate occupies the southwest corner of the figure. Base map from Smith and Sandwell.

Global tectonics. The Lamont seismologists went on a crash program to integrate seafloor spreading, transform faults, and subduction. Their earthquake slip directions resolved the convergent motion of subduction and the opening of ridges. They realized that intermediate and deep focus earthquakes (below 70 km) occur within the cold brittle subducted slab. We now call the unified geometrical theory "plate tectonics." The continental and oceanic crust rides on more or less rigid plates (Figure 15). In modern terms, crust and mantle within the plates are called *lithosphere*. Subducted slabs are lithosphere that has re-entered the deep fluid part of the mantle.

Still some seismologists were not convinced. The cold war drove home the last lance. By 1965, the United States wished to test large nuclear weapons underground. The Nevada test site was too near Las Vegas. They tested in the Aleutian Islands. The arrivals from the first test were bothersome. Their computer program located it (with the assumption that it is an earthquake with an unknown origin time and position) tens of kilometers north of the site and tens of kilometers deep. They had inadvertently discovered the cold downgoing slab beneath the arc where Coates formulated subduction. Seismic waves went (north) faster through the colder slab than through ordinary mantle and arrived earlier than expected. Waves going south missed the slab and arrived at the expected time. The location program for earthquakes placed the event to the north and down into the slab so that both north-going and south-going waves arrive at the expected time for a symmetric earth model. I did my thesis on these data, finishing in 1973. By then the task was to resolve the details of the slab, not to confirm its existence.

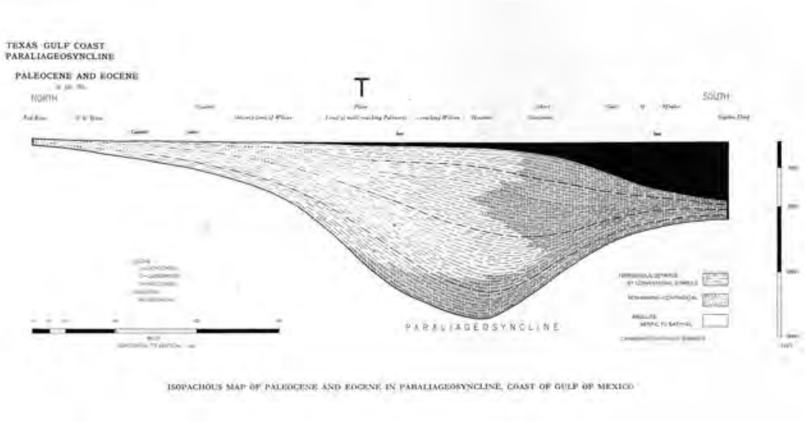


Figure 16: Reconstructed cross section of the coast of the Gulf of Mexico from Kay's 1951 book show the basic structure of a passive margin. Kay at the time did not fully recognize the similarity between these rocks and ancient geosynclines. The reasons for this were that the deep-water rocks off the modern coast were properly recognized but the analogous deep-water rocks in geosynclines are highly deformed and were considered shallow water deposits. Another problem is that Kay plotted only part of the sedimentary sequence of the Gulf, rather than the full package from Jurassic to recent. The region north of "T" (my annotation) is analogous to the region of flat-lying sediments in western New York in the Figure 1. The region seaward of "T" will be highly deformed when the oceanic crust of the Gulf eventually subducts beneath an island arc.

Passive margins as bumper cars. Plate tectonics provided a simple explanation for geosynclines, this issue that started the study of Earth processes. Seafloor spreading breaks continents apart, like Africa and North America. The crust near the break-up stretches like taffy and becomes thin. This reduces its buoyancy (a thin board floats lower than a thick board) causing subsidence. This region and the adjacent oceanic lithosphere are also hot. The lithosphere cools slowly. The slow subsidence on these margins allows sediments to accumulate at sealevel. Geologists call continental margins formed by break-up either Atlantic margins (after the examples formed by the break-up of Greenland, Europe, North America, South America, and Africa), passive margins (to contrast them with active subduction and fault margins), or just break-up margins.

My bit part in the matter illustrates that the necessary expertise shifts as concepts shift. I was in a student in a seminar at MIT in 1968 on the Appalachian Mountains. The geology faculty were interested in applying (what became) plate tectonics to continental geology. I picked the present continental margin of the East Coast because it seemed simple and because I had the last presentation of the semester, as the topics ran geochronologically. I was already familiar with the concept that oceanic lithosphere cools and subsides as it spreads away from the ridge. The ridge is high because its lithosphere has just come up from the deep mantle and has not yet had time to cool. I applied this concept to the subsidence of the East Coast as recorded in wells. It worked fine. The professors were not expecting my presentation to be a new concept. It lasted much longer than scheduled.

I attempted to publish in the *Journal of Geophysical Research*, which rejected my paper as extremely amateurish. The senior scientists studying passive margins were well trained at using seismology from controlled explosions and local variations (again called anomalies) of the acceleration of gravity to study the deep structure. Much of their expertise involved equipment design and maintenance. They were not trained in heat and mass transfer. They had been trained to avoid thinking about dynamic processes until (at a minimum) one at spent many years collecting data.

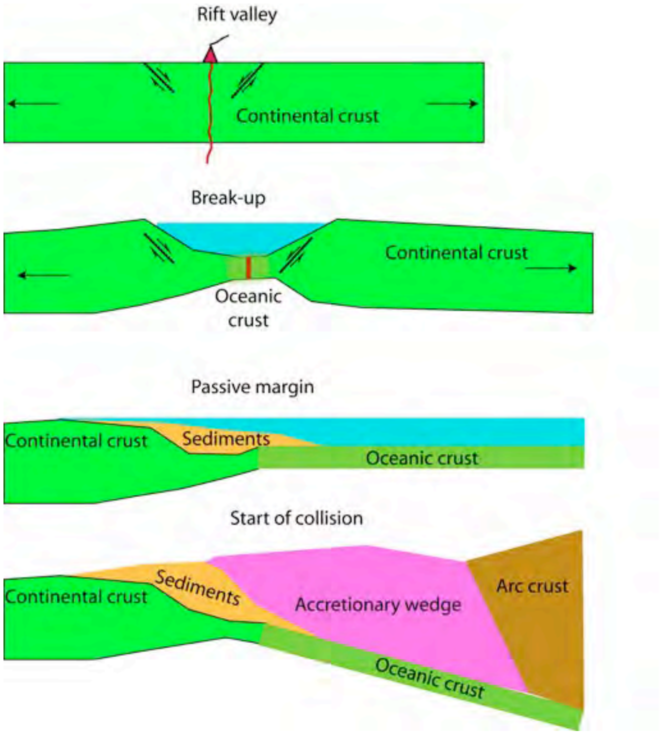


Figure 17: History of a passive margin. (Top) A continent begins to rift apart. Faults cut the upper crust. There is often volcanism. The Ethiopian and east Atrican rift systems is in the stage. The Mississippi River follows a rift valley that did not become an ocean basin. (Second) The continental crust necks like taffy. Oceanic crust begins to form at a new ridge axis. The Red Sea is in this stage. (Third) Sediments begin to accumulate along a passive margin. Thermal contraction from the cooling of the underlying lithosphere and the load of the sediments on the seafloor drive subsidence. The East Coast of the United States is in this stage. (Bottom) The passive margin begins to subduct beneath an island or continental arc. The accretionary wedge of the arc overrides and deforms the sediments beginning mountain building. The north coast of Australia has been colliding with parts of the Java and New Guinea arc for several million years.

My situation also illustrated that excessive compartmentalization of science leads to problems. The passive margin is as far away as one can get from the mid-ocean ridge axis and still be in the Atlantic Ocean. The reviewers did not consider recent developments at the ridge axis to be particularly relevant to their field area. One reviewer rejected plate tectonics altogether. The other thought the margin formed in the Permian too long ago for the lithosphere to still be cooling significantly. Ironically, Lamont (the home of the reviewers) rests on the Palisades sill, an early Jurassic igneous body associated with the continental break-up!

Like Morley, I gave up publication as futile. I resumed work in late 1969 when the military draft was blowing my way. I was in a panic to get PhD thesis done so that I would be employable if I survived military service. The Moon program was in full swing, taking the geophysics faculty with it. My plan was to do a thesis and then look for an advisor. I did quantify my results, but I did not have enough for a full thesis. I published in the *Geophysical Journal of the Royal Astronomic Society* in early 1971. By then I was doing a thesis on subducted slabs. In retrospect, my big mistake was missing the importance of stretching of the crust during break-up. I thought that the crust broke much like rigid blocks. (Just like Wegener's analogy to blocks of floating ice.) Erosion by rain and rivers at the surface then beveled the landscape to sealevel, as with Hutton in Scotland. The erosional surface later subsided, much like an atoll. Dan McKenzie of Cambridge recognized the importance of stretching in 1978 and produced a viable theory.

I realized when I presented my seminar talk that passive margins became geosynclines when they were eventually partly subducted beneath arcs or active continental margins (Figures 16 and 17). The initial subsidence of geosynclines does not cause mountain building. Merely the margins of continents, like the bumpers of cars, get into collisions. I did not know enough land geology to carry through with linking passive margins to geosynclines. I also knew, from my first rejection, to avoid this sensitive topic. I did not return openly to it until the late 1970s when it was common knowledge and the term geosyncline was quaint. Robert Speed, a colleague at Northwestern, was studying an ancient passive margin in Nevada that was partly subducted by an arc in the Paleozoic. I investigated the subsidence inboard (east) of the collision.

Rock cycle and habitable global geochemistry

Plate tectonics provide an easy explanation for the rock cycle observed by land geologists since the time of Hutton and why the Earth stays habitable. Sedimentary deposits in the ocean basins and continental margins are short lived. In tens of million to a few 100 million years, they enter into subduction zones. Some material gets uplifted to form mountains, other material is carried to crustal depths where it is metamorphosed or even melts. Later uplift exposes some of these new hard rocks to erosion. Some of the sediments subduct into the deep mantle along with the oceanic crust. Volcanism brings mantle-derived material and recycled crustal material to the surface. There are always fresh rocks eroding somewhere on Earth. There is always hydrothermal activity, metamorphism, sedimentation, and volcanism.

Serpentine and oxygen. Many Earth scientists did not immediately recognize the importance of hydrothermal processes on the seafloor to planetary habitability. Harry Hess was an exception. He knew that the formation of serpentine takes up vast quantities of water, carbon dioxide, and chlorine. The rock reacts with water to form hydrogen gas and ferric iron. In terms of chemistry, iron is a transition element with both a partly filled inner shell and outer shell. Ferrous iron behaves like magnesium with two outer shell electrons (See Chapter 4). It gives 2 electrons to an oxygen atom to form FeO, which acts like MgO. Ferric iron has 3 electrons to share like aluminum. Two iron atoms share electrons with 3 oxygen atoms forming Fe_2O_3. Magnetite Fe_3O_4 is one part ferric and one part ferrous.

Natural olivine is a solid solution of Mg_2SiO_4 and Fe_2SiO_4 (with ferrous iron) along with trace components including Ca_2SiO_4 (involved in ribose formation in Chapter 4). In terms of chemistry, a simple reaction is

$3FeO$ (in olivine or serpentine) + H_2O (water) → Fe_3O_4 (magnetite) + H_2 (in water solution or gas)

This is a net oxygen sink as the hydrogen later reacts with dissolved oxygen in the ocean.

$2H_2$ (hydrogen in solution) + O_2 (oxygen in solution) → H_2O

This reaction is good food for microbes. I used this as an example reaction in Chapter 4.

Figure 18: Hydrogen from reaction of serpentine with water collects in a bag (10 cm across) in a streambed in the Cedars area of California. Microbes living in the ground water have already reacted some of the hydrogen with CO_2 to make methane. Other microbes react the hydrogen with atmospheric oxygen near the surface. Photo by the author.

Hess was correct about the chemistry, but only about 10% of the oceanic crust is serpentine. Hess studied samples dredged at fracture zones and exposures in the Alps where serpentine is over-represented. Hess encouraged Robert Speed's work in Nevada on chlorine-rich altered rocks that led to his interest in the Paleozoic passive margin and my involvement at Northwestern.

Figure 19: Serpentine rusts during weathering forming red soil. This process is a sink for the oxygen in the air. Cedars area of California. Photo by the author.

I earlier became interested in serpentine during my attendance of geological seminars at MIT. One time, I got the topic of serpentine as the material forming the oceanic crust. There are actually several slightly different serpentine minerals. Their crystal structures seemed complicated (they are) and I looked for something easier to present. Roger Hart had talked earlier about hydrothermal seawater altering the crust at the midoceanic ridge axes. The correct idea that most of the oceanic crust is basalt not serpentine was becoming prevalent. I made the simple calculation that making the entire 5 km (6 is modern average) of the oceanic crust out of serpentine would use up the oxygen in the air by the reactions discussed above.

I did not do anything immediately with it because I thought I would kick a dead horse. In retrospect, seismic work was biased against finding serpentine. The seismic studies that showed oceanic crust to be basaltic were placed away from the complications of fracture zones. Very slowly spreading ridges covered by serpentine turn out to be in hard to reach places like the Arctic. Henry Dick, in 2003, showed that a significant fraction

(10%) of the ocean is covered by serpentine crust, typically 2-km thick. In general, scientists try to pay attention to such sampling biases.

Geochemistry of ridge axes.

Scene: deck of a nameless oceanographic ship late 1960s. The scientists have just recovered a dredge haul.

Ignacio (the petrologist): Damn! All we got is the squirrelly greenstone again. This rock is so altered that we will not be able to determine its original composition. The rest of the rock has weathered to rust.

Ortholitho (the chief scientist): Weathering is a recent, unimportant process. Remember when we first looked at outcrops on a field trip. The professors kept our eyes on the fresh rock. Recent volcanism can be important on the seafloor but we need fresh rocks to study it. All this weathering and alteration is royal pain.

Ignacio: We need to get the dredge down again. What should we do with these wretched rocks?

Ortholitho: Over the side! They are not worth cataloging and bringing back to the lab.

In 1970, many geologists tended to view recent processes as unimportant, particularly those that screwed up fresh rocks. A minority of geochemists were well aware of the chemical aspects of the rock cycle on land and quick to grasp the importance of plate tectonics as a driver. They were eager to constrain the chemical processes at the midoceanic ridge axis. There are plenty of places where plate tectonics has placed oceanic crust on land where it can be easily viewed and sampled. It was obvious that hot water circulated through the oceanic crust, forming the despised greenstone dredged by Ignacio's worldview.

I tiptoed onto this part of the stage in 1974 as a young assistant professor at Northwestern. Robert Garrels and Fred Mackenzie led a program in geochemical cycles. They were committed to plate tectonics and scrambling to include it in their work. Thomas Wolery, a new graduate student, wanted to study the oxygen cycle. He asked me and I remembered my calculations at MIT. I suggested that he investigate the ridge axis. Garrels independently suggested the same topic the same day.

Scientists check what other scientists are doing before starting major projects. We found that other groups were already doing laboratory experiments of the reaction of basalt and hot seawater. Wolery concentrated on developing thermodynamic codes from which we calculated what went on during the reactions and on constraining the global balances of elements in the ocean. I concentrated on thermal models that yield the volume of water passing through hydrothermal vents.

Hot hydrothermal vents. Hydrothermal circulation quickly became an observable seafloor process. Scientists aboard the submersible Alvin soon discovered cool vents at the Galapagos spreading center. Chemical analyses showed that hot 350°C water had mixed with seawater. Black smoker 350°C vents soon followed. The "smoke" is really sulfide compounds. The vents teem with microbial life that eats the sulfides along with dissolved methane and hydrogen gas. Some of the microbes grow at high temperatures, the current record is 122°C. Diverse animals live off the microbial bounty. Before the ship reached shore, the scientists considered vents to be a possible site for the origin of life. I get back to this later.

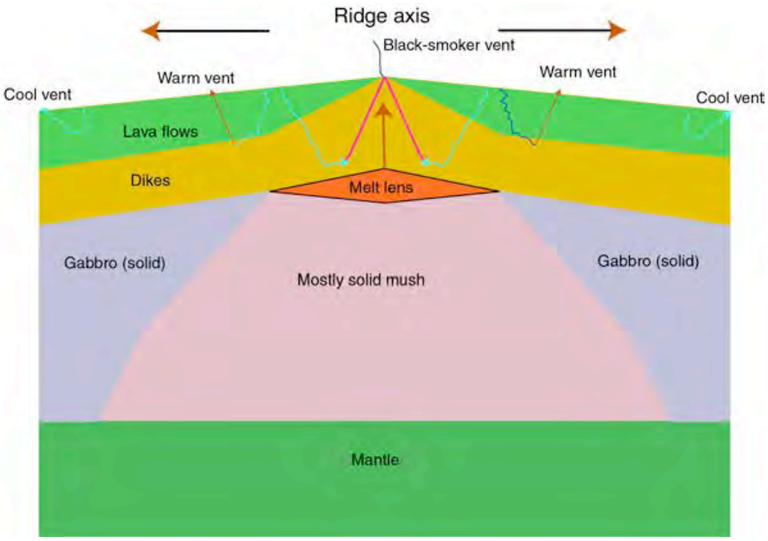


Figure 20: Oceanic crust forms at the ridge axis. Lava flows form the shallow part of the crust. The next deepest layer consists of dikes. A thin lens of melt exists at the axis. Beneath it the material is mostly solid. This "mush" freezes as it spreads away from the ridge to form a coarsely crystalline rock of basaltic composition called gabbro. The mantle underlies the crust. Hydrothermal circulation alters the rock at depth and exchanges chemicals between the water and the rock. The hot circulation vents at black smokers along the axis. Warm and cold circulation exist further away from the axis. Their effects have been less extensively studied. CO_2 in the ocean gets sequestered into the crust by the warm hydrothermal circulation.

It was not hard to constrain the global volume of hydrothermal flow. It is merely a matter of conservation of energy between the vent fluids and the heat in the oceanic crust and mantle (Figure 20). The entire ocean passes through hot vents about every 60 m.y. years. It goes through warm 20-60°C vents close to but not on the ridge axis every few million years. It circulates through the shallow porous crust at a few degrees Celsius a few times in a million years. Hydrothermal circulation buffers the acidity of the ocean.

Hydrothermal circulation is a major source of calcium to the ocean. It is a sink for magnesium, free oxygen, water, and CO_2.

Fresh air and churning rock. Tectonics keeps water, CO_2, and nutrients from getting permanently sequestered in the subsurface. CO_2 is particularly important to climate as we saw in the last chapter. Overall, weathering and hydrothermal activity keep atmospheric CO_2 in check. Volcanoes and metamorphism keep it all from being sequestered in the surface. In detail, the warm circulation removes dissolved CO_2 that forms carbonates in the basaltic crust. I give the reactions, as we will need to keep track of CO_2.

CO_2 (dissolved) + $CaSiO_3$ (calcium silicate in rock) -->

$CaCO_3$ (calcium carbonate in rock) + SiO_2 (quartz in rock and solution)

For those with more chemistry, there is also magnesium and ferrous iron silicate in the rock. These form magnesium and ferrous iron carbonates. Degassing at the ridge and at island arcs above subduction zones balance the flux into the oceanic crust. If no other sinks were present, CO_2 would build up in seawater until the amount carried into the oceanic crust by warm hydrothermal flow balanced the sources.

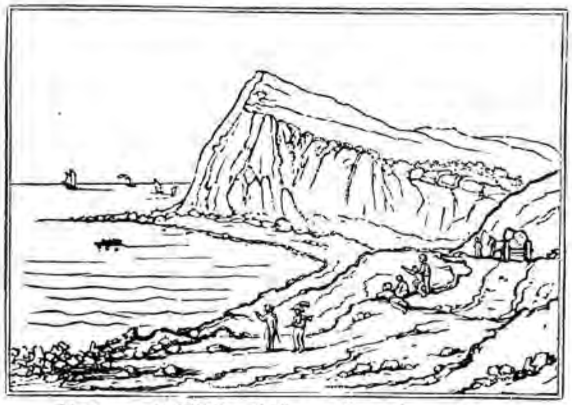
At present, the formation of carbonates (limestones) in shallow seas (Figure 22) and by pelagic (suspended) organisms in shallow water in the deep oceans are larger sinks. Greenhouse CO_2 builds up in the air until it adjusts the surface to a clement climate where weathering can occur. The weathering rate depends on the CO_2 content in the air because chemical reactions go faster at high temperatures and because dissolved CO_2 is a weak acid

CO_2 (gas) + H_2O (rain water) -->

H^+ (hydrogen ion dissolved) + HCO_3^- (bicarbonate ion dissolved)

Rocks tend to weather faster in an acid solution. An atmosphere with significant CO_2 has the potential of extending the habitable zone for an earth-sized planet out beyond the orbit of Mars as discussed in the last chapter.

Fig. 55.



Shakspeare's Cliff in 1836, seen from the north-east.

Figure 21: Chalk outcrops along the south coast of England contain calcium carbonate deposited from the ocean in shallow water. Today the white cliffs of Dover are eroding. Some of calcium carbonate in the cliffs eventually ends up on the deep seafloor. Charles Lyell illustrated active coastal erosion of Shakespeare's Hill in his 1872 book. Early geologists overestimated the effects of coastal erosion. Globally, hill and stream erosion is more important volumetrically. Streams carry calcium carbonate, the ingredient of chalk, in solution into the oceans.

The early Earth may not have behaved in this way as warm hydrothermal circulation at the ridge axes is a significant sink that depends on the CO_2 concentration in the oceans and hence its concentration in the air. (The air and the ocean are in dynamic equilibrium with most of the CO_2 reservoir in the ocean.) The hydrothermal sink balances the volcanic sources when the concentration in the ocean is several times the present one. This probably kept CO_2 low enough on the early Earth that it alone could not maintain a clement greenhouse. Methane provided a potent greenhouse gas once life evolved.

Global water budget. In contrast to CO_2, the ocean collects the water that the crust and mantle reject. There is no sufficient crustal place to store an ocean of water, including sediments. Burial of water as hydrated minerals in one place results through tectonics and metamorphism with expulsion of water from another. Subduction carries vast quantities of water down beneath island arcs - the whole ocean every few billion years. The subducted oceanic crust heats up, as Coates said, and dehydrates. The water moves upward into the hot mantle wedge that partially melts. The molten rock then ascends to arc volcanoes, like Fujiyama and Mount St. Helens, where it degasses its water, often explosively.

Thou sayest well, and it holds well too;

for the fortune of us that are the moon's men doth ebb and flow

like the sea, being governed as the sea is, by the moon.

The First Part of King Henry the Fourth, Act I. Scene II.

William Shakespeare (1564–1616)

The Oxford Shakespeare, 1914

Ebb and flow of water from the continents. Seafarers and shore folk saw the ebb and flow of tides in the surrounding shallow seas. The association of tides with the Moon was much more evident to them than it was to Galileo in the Mediterranean. Shakespeare did not understand the cause of tides. Neither did anyone appreciate that the rocks under their feet in the south of England indicated the ebbs and flow of the sea on a geological time scale.

Much of the development of geology involved the study of these sedimentary rocks deposited in shallow seas over vast continental platforms. Deposition is a record-producing process, hence the term “rock record” for the bedded deposits. Widespread flat-lying thin layers, as in southern England, make it easy to apply Steno’s law that the younger rock is on top. For example, the chalk of the White Cliffs of Dover covers much of southern England, the Channel, and parts of the continent. The Ordovician Saint Peter sandstone extends from Minnesota to the southern United States and east-west from the Appalachians to Nevada. Younger sediments cover it over most of this region. Geologists starting with Smith developed much of the paleontological time scale by studying flat-lying rocks.

Geologists, beginning with Hall, recognized that the platform sediments were deposited near sealevel. The deposits of a given age range, say Ordovician, are thicker in some places than others. This implies that the crust in the thick regions subsided relative to the crust in the thin regions. In addition, the sea came in and out many times, as first recognized by Da Vinci. Sometimes, like today, North America between the Appalachians and the Rockies was dry land. At other times shallow seas covered this region.

The flat-lying sedimentary rocks on the continent, like those studied by Hall in western New York provide evidence of the long-term water cycle on the Earth. The south of England has similar though younger rocks. However, platforms are so common that there is a tendency to regard them as the natural state of affairs, not requiring any explanation. We have already seen that Hall relegated the area of thick beds and rapid subsidence, his geosyncline, to a prelude to the important process of mountain building. I encountered these attitudes in the 1970s when I was actively working on the physics of subsidence of platform basins.

For an example of this worldview, I attended a Geological Society of American Penrose Conference on continental interiors in 1975. Such conferences typically have a limited number of attendees, around 100, and schedule talks by active researchers in the field. They are held within the geological region of the conference topic if this is possible. The Geological Society officers clearly thought that the topic was trifling. They scheduled it at a San Diego hotel complex at a semi-rural freeway interchange so that their staff could prepare for the annual meeting to be held at the site the next year. This was about as far as one could get from the continental interior without going to Hawaii. The conference organizers jettisoned the published schedule on the listed topic and gave the podium to anyone who wanted to rant against plate tectonics. I was trapped in an endless series of presentations that just as well could have advocated a flat Earth. I had wasted over a month of my pay to attend this idiocy.

Back to science, one must winnow out the reasons that platforms exist. The simple parts are erosion and deposition. As Herodotus recognized, streams drop their loads of sediment when they enter the sea. As Hutton recognized, erosion bevels the land to a sealevel base level. Over time, the net effect is to produce a widespread surface near sealevel that gets covered each time the ocean rises and exposed each time it ebbs.

The difficult part involves tectonics. Continental crust is buoyant. It would flow out over the dense rocks in the ocean basins, like oil over water, if it were fluid. Plate tectonic forces need to overcome the tendency of continental crust to spread in order to thicken the crust in the first place. Regions with exceptionally thick continental crust, like the Himalayas, occur where plate tectonics have recently thickened the crust. Parts of this region are already starting to spread, again like oil on water.

Over time continental platforms are both compressed, thickening the crust, and extended, thinning the crust. Over hundreds of millions of years, these processes balance out. That is, plate tectonic forces on average tend to maintain an average elevation near sealevel. The combined efforts of plate forces and erosion/deposition tune the platform elevation toward sealevel.

We have just the right amount of water in the ocean for this coincidence. The Earth erratically accreted and lost water as it formed from the impacts of planet-sized bodies. See Chapter 6. It could have easily ended up with more or less. We could have ended up with *Waterworld* or a dry planet like Mars.

Life on a water-covered planet. The shallow seas on the actual Earth provided a vast arena for evolution. Children (including me) growing up in platform regions eagerly collect fossils. In more detail, the marshy land at the edge of the shallow seas was a nice transition for marine to land life. But is there any serious problem with life on a water-covered planet?

Phosphorus, needed for DNA, may be a real limitation. Biochemists have not found a good alternative as discussed in Chapter 4. On the Earth, the seafloor is a phosphorus sink. Biologically active phosphorus comes from erosion on land. This process is inefficient. Only about 1/10 of the available phosphorus gets mobilized for biota. It is not evident how life would get phosphorus on a water-covered planet. Like porcupines mating, this difficulty may be only our lack of imagination. For example, some microbes are adept at freeing phosphate trapped by ferric iron (rust) in sediments and soils.

Life history of planets

Geodynamists understand the present Earth well enough that they can productively discuss the history of its interior over geological time. They attempt to extrapolate to other planets.

The Earth's interior is squandering the heat to drive plate tectonics faster than radioactivity regenerates it. This imbalance from conservation of energy causes the Earth's insides to cool. Earth scientists know this from several lines of inquiry. They compute the current heat loss from the Earth from plate tectonics and add in the minor contribution that comes through continents. They have a good idea of what the radioactivity inside the Earth is like from samples. They also have a good idea on how much radioactive material accreted with the Earth from the meteorites. Neutrino detectors give the internal radioactivity directly. Petrologists see the cooling of the Earth's interior directly from the eruption temperatures of ancient versus modern volcanic rocks. Currently the Earth's interior cools at between 50 to 100 degrees Celsius per billion years.

As Lord Kelvin suspected, the Earth will run out of internal heat. Within a half billion to a billion years the Earth will be too cool for basalt to melt at midoceanic ridges. Plate tectonics will grind to a halt, dying with a whimper. We can see the harbingers of this doom. A region of cold mantle already exists south of Australia. The mantle is too cold for much basalt to melt on the spreading Antarctic ridge.

Mars. Active tectonics died on Mars a few billion years ago (Figure 22). It is unclear whether there ever were plate tectonics. The tectonic difference between Mars and the Earth results because Mars is smaller. The physics are simple, akin to a child getting cold faster than an adult does because she has more surface area per mass. The surface area to mass of Mars is 2.5 times that of the Earth. The heat generation per mass and the amount of original heat per mass in the two planets is similar. (We know this from studies of Mars rocks.) The heat flow (energy lost per area per time) is similar on both planets when they had active tectonics. Mars lost its original heat quickly. A thick lid of lithosphere covered the planet. Subsequent activity was quite sluggish.

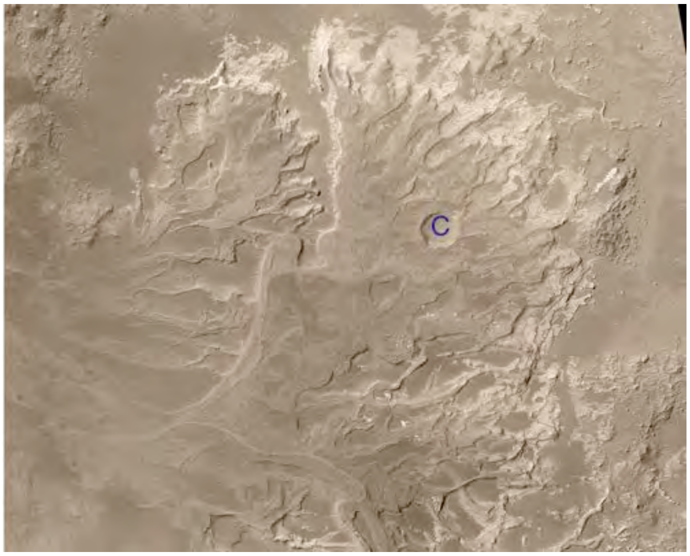


Figure 22: This delta is an uncommon product of stream erosion and deposition on Mars. It is a few billion years old. It has been dissected some by wind erosion and hit by an asteroid forming a small crater "C". Otherwise little has happened. The Earth is far more active geologically. Anything of the age would have been eroded, buried and metamorphosed, subducted, or deformed by tectonics. The photo is 20 kilometers across. http://www.nasa.gov/multimedia/imagegallery/image_feature_98.html

Space photos show that Mars is nearly geologically dead. There may be rare attempts at feeble volcanism and there is likely to be some metamorphism at depth. The net effect is that only tiny amounts of CO_2 and water reach the surface. The climate buffers with enough CO_2 in the air that liquid water drops occasionally form in favored locations. The water reacts with basalt to form hydrous minerals and the CO_2 reacts to form carbonates. Metamorphism rarely liberates these volatiles once they are sequestered in the basalts. There were shallow seas and lakes on early Mars. Vigorous tectonics and volcanism then returned volatiles to the surface, analogous to the modern Earth.

Mars may have started out with much less water per surface area than the Earth. Planets do not efficiently accrete water. For example, the Earth lost water equivalent to several ocean masses during its accretion. Mars, being smaller and having only 40% of the Earth's gravity, was less apt at retaining its water. Martian meteorites have some hydrous minerals but are not extensively hydrated. Mars had enough water to form shallow seas and lakes, but not enough to turn the crust into hydrous minerals.

Future Earth. The fate of the Earth is more complex than Mars because it has a surfeit of water and because the Sun will start to become too luminous at about the time tectonics fails. If the Earth still has a substantial ocean when tectonics dies, erosion will take over. Mountain belts will be beveled in 10s of millions of years and dry land in a couple of hundred million years. Only a few volcanoes may stick up. We will have the set for *Waterworld*. Sediments will sequester the CO_2 and nutrients needed for life. Life will persist on the scraps of current bounty.

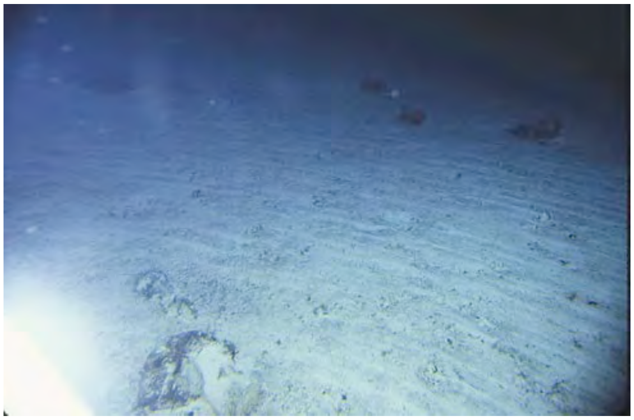


Figure 23: Calcium carbonate shells accumulate on the seafloor near the midoceanic ridge. These photosynthetic organisms lived near the surface before they died and sank. Seafloor currents formed ripples. The shells may eventually get subducted sequestering the material in the mantle. This process did not remove the calcium carbonate on Venus. Photo by the author.

Alternatively the Earth, or more likely a planet with less surface water to begin with, may lock it in the mantle and jettison it to space. The Earth's interior will cool to the point that it is too cold for basalt to melt at mid-oceanic ridges. It will also become too cold for melting to occur beneath island arcs, ending the return of water to the surface. Conceivably, sluggish plate tectonics last a long time. (We do not know. We have not yet studied any examples.) The oceanic crust will then be serpentine, like on the modern Arctic ridge. Serpentine contains a lot of water, 45% by volume compared with 10% by volume for hydrated basalt. Still it will take over a billion years to subduct our oceans in the absence of a recharge from volcanism.

It is unlikely that the dying stage of plate tectonics will last this long. Our life-giving oceans will become the curse of the runaway greenhouse unless the remaining water can escape out of the top of the atmosphere. A planet with less water to begin with than the Earth might escape the runaway and become *Dune*.

Venus. Venus is nearer to the Sun than the Earth. It has been tectonically dead for 700 million years. It has almost no water in its atmosphere. The surface is too hot for hydrous minerals to form. The atmosphere has 90 bars of CO_2, more than all the limestones on the Earth.

In analogy to Mars, the inactive surface is partly that Venus is a little smaller than the Earth so that it squandered its internal heat a little sooner. Unlike the future Earth, Venus had active tectonics when the greenhouse ran away. After that, the hot surface made the lithosphere less resistant to flow leading to more vigorous plate tectonics. The liquid water escaped to space during the runaway greenhouse.

Why all the CO_2? The planet had to start out with both it and water. The early Sun was not luminous enough to put Venus into a runaway greenhouse. As long as liquid water was present, CO_2 entered carbonates. The location of these carbonates is critical. If they got subducted into the mantle, like those within oceanic basalt on the Earth, they were in the mantle and out of the way when the runaway greenhouse started. In contrast, limestones on the continents released their CO_2 once a runaway water greenhouse approached the temperature of molten rocks. Where was it? Probably in exposed carbonates. Where will it be on a typical planet? We do not know. The amount of available CO_2 at the time the greenhouse runs away is a complicated function of previous tectonics and biological evolution, if any. A thick Venus atmosphere is not the inevitable aftermath of a runaway water greenhouse. The planet, once it has jettisoned its accessible water to space, may emerge as a sterile but habitable version of *Dune*.

Take the Earth for an example, carbonates accumulated on the continents before 100 million years ago. The calcium to form these limestones came from hydrothermal circulation at ridge axes over time. Right now, rainwater dissolves the continental carbonates. The acidity of dissolved CO_2 does this

CO_2 (dissolved in rain water) + H_2O + $CaCO_3$ (limestone) →

Ca^{++} (dissolved calcium ion) + $2HCO_3^-$ (bicarbonate ion)

The dissolved CO_2 and calcium enter the ocean where the reaction reverses. Some of the calcium carbonate forms reefs that become more continental limestone. The net effect is just to move carbonate from one place to another. Some calcium carbonate precipitates within the oceanic crust. (The fluid then supplies the CO_2 and the rock supplies some calcium.) A significant fraction becomes the shells of single celled organisms in the deep ocean (Figure 23). The shells sink to the bottom when the organisms die, especially in relatively shallow water near ridge axes. The process has not been going on long enough for these sediments to get subducted in quantity. It is conceivable that most of the present continental limestones will erode and get subducted in this way before our greenhouse gets too out of hand. That is, biology controls whether CO_2 ends put in continental limestones or in the mantle.

Executive summary

The Earth has vigorous tectonic processes that form mountains, sedimentary basins, and ocean basins. These features were evident by the 1830s, but the modern concept of plate tectonics did not arise until the 1960s. Part of the difficulty was logistic. Good marine and seismic data were not available into the 1950s and 1960s. The worldviews of geologists and physicists did not mesh. Geologists viewed processes on scales that they could walk in a day. They were reluctant to apply physical concepts and often untrained in the mathematics required to do this. Physicists tended to view the Earth as a planet-sized object. They did well understanding tides, but found the local detail of geology confusing. Both groups now focus on the actual scale of plate tectonics.

The oceanic data and the earthquake data that established plate tectonics came from “big” science. The concepts of seafloor spreading and subduction came from individual researchers away from the major oceanographic institutions. Still, the oceanographic institutions switched from collecting data for future use to collecting data focused on plate tectonics in the few years after 1965. Residual dogmatism by marine scientists at the major oceanographic institutions briefly retarded the careers of some young scientists including myself. It did not crush us or the concept of plate tectonics as the management of science was quite diffuse outside of the former Soviet Union. It was not hard for me to find that Northwestern welcomed study of the physics and chemistry of Earth processes.

With regard to biological results, tectonics maintains a myriad of environments on the Earth from mountaintops to deep ocean trenches. As Bruno and Galileo realized, the Earth's surface is in a constant state of change. Tectonic, volcanic, erosional, and sedimentary processes continually renew the surface, giving the illusion of a (human) historically young planet. I discuss evolution in the next chapter. The changing Earth and its many environments encourage continual biological change. With regard to intelligent life, a changing landscape often favors a learned and thought out response rather than a programmed one.

With regard to the chemical basis of life, the Earth's surface keeps nutrients, water, and CO_2 in play. Rocks containing this bounty are repeatedly buried and exhumed as Hutton recognized in the late 1700s. Hydrothermal circulation supplies chemical disequilibria that provide food for microbial life. Life may have well originated around hydrothermal systems. Serpentine is a particularly attractive venue where ribose can form.

The interior of planets evolves on the same time scale as sunlike stars, billions of years. The Earth's tectonics are running down and may last only another billion years. Over much of its history, the Earth has had the right amount of water for shallow seas to episodically cover continental interiors.

Mars and Venus are tectonically dead. The surface of Venus is too hot for life. Its CO_2 is in the atmosphere. The surface of Mars is cold. Tectonic processes and volcanism are too sluggish to maintain a thick clement atmosphere. The Earth will eventually suffer from a runaway greenhouse unless civilization intervenes. It may cease to be tectonically active before then.

We understand the Earth and Mars well enough that we can export our knowledge to similar extrasolar planets that are heated by radioactivity. Small planets cool fast and become tectonically dead. Earth-size planets stay active for billions of years but not forever. They are a more auspicious venue for multicellular life.

Notes

Numerous scientists have written personal accounts of their experiences at the advent of plate tectonics. The topic has piqued professional historians of sciences. A good place to start is “Plate Tectonics; An Insider’s history of the Modern Theory of the Earth” edited by Naomi Oreskes, Westview Press, 2001. Dr. Oreskes is also author of “The Rejection of Continental Drift: Theory and Method in American Earth Science (Oxford University Press, 1999 where she recounts the early part of this history.

Many senior scientists including Marshall Kay accepted plate tectonics and sought to apply it to geological observations. Holdouts were a vocal minority. There is some sampling bias here. Previously distinguished older holdouts got noticed. Young holdouts were unsuccessful in obtaining good academic positions or even completing degrees. I cannot even think of any examples.

You may wish to compare the works by the Scripps scientist H. W. (Bill) Menard. He wrote “Marine geology of the Pacific” (McGraw-Hill, 1964) just before the advent of plate tectonics. His memoir is “The ocean of truth: a personal history of global tectonics” (Scientific American Library, 1986).

Exercises

The 1962 and 1970 editions of “The Structure of Scientific Revolutions” by Thomas S. Kuhn were available when plate tectonics became established. Neither these editions nor the final 1996 edition discuss plate tectonics. Many earth scientists were aware of Kuhn’s work by 1970. This had the positive effect that people avoided becoming holdouts. A workable essay project would focus on scientific papers during the 1963-1973 transition in a subfield. You will not find lots of them because few people then worked on “big” problems and see if Kuhn’s generalizations hold. Abstracts presented at the American Geophysical Union often snapshots on what the scientist was thinking a couple of months before the meeting. You can also monitor the transition from description to explanation. Note that plate terminology did not become standardized until 1973. You can also check out abstracts for Geological Society of America meetings to see when land geologists became involved.

Many colleges retain copies of their old course catalogues but not those of other universities. You can check out the transition until the 1980s on when and how plate tectonics come into course descriptions. If you have friends at other colleges you can compare notes.

A related project is to compare how and when plates come into beginning level college texts. You can compare physical geology and historical geology texts. You can do the same with introductory biology texts. Libraries often retain old additions in compact storage.