19th and 20th Century Earth Sciences

The rise of geophysics, dating the earth, radioactivity and plate tectonics

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History of Modern Earth and Life Sciences

Geology and earth sciences

In the late 19th and early 20th century geology when through a massive change both theoretically and methodologically. The older methods of the naturalist engaged in field work came to be supplemented, and in some ways overruled, by the methods of physics and chemistry. Many historians of science have discussed this as part of a larger trend of “colonization” of the life sciences by the physical sciences that took place in the 19th century.

The 19th century debate between naturalists and mathematical physicists about the age of the earth was eventually settled in the first few decades of the 20th century by applying new discoveries of radioactivity and chemical isotopes to dating minerals. In the 1960s, the new science of geophysics, using new techniques of data collection, created a synthetic theory of the formation of continents and oceans, which include the modern understanding of the age of the earth.

Physical considerations in the age of the earth

19th century naturalist studies made it clear that the earth was *old*, and that it had gone through various phases of change, but it was not evident how we could say anything more precise than this. In fact, some naturalists argued that it was hopeless to look for more precision.

In the 1860s, however, a number of physicists – particularly Lord Kelvin – argued that it should be possible to use the laws of the new science of *thermodynamics* to come up with an actual age for the earth. In fact, their initial efforts turned out to be wrong, for reasons that they could not have anticipated. In the 20th century, the discovery of radioactivity lead to physical studies of the earth and the promise of an accurate, and precise, geological timescale. This also gave rise to the discipline of geophysics.

In many ways, these disputes can be regarded as a sort of jurisdictional conflict between naturalists and physicists.

Kelvin on the age of the earth

William Thomson, Lord Kelvin (1824–1907), was a Scottish mathematical prodigy who became one of the most famous natural philosophers of 19th century Britain, and who's opinions and theories carried great weight.

Through his work on thermodynamics he was integral in cementing the Victorian cosmological outlook: (a) the universe is well ordered through the effects of real and universal laws, (b) the sun and solar system formed from a gaseous nebula, (c) the universe is slowly cooling and will eventually die out.

He believed that the theories of uniformitarianism and natural selection were contrary to physical law and developed a number of arguments against them.

The sun's heat

In the 1860s, Kelvin advanced three arguments against the timespan for the age of the earth introduced by Lyell.

[1.] In "On the Age of the Sun's Heat," 1862, he set out to describe how the sun could maintain its heat given the then-known physical laws, and from this to deduce how long this process could go on. He claimed that the sun's heat must either be caused by a chemical reaction, or gravity – in the form of meteors constantly falling onto its surface.

Hence, he developed the meteoric theory – which had been put forward by Kant, and von Helmholtz – and went on to calculate the total energy released through these processes, stating that it is probable that the sun has not illuminated the earth for 100m years (10^8y) and, that it has been certainly less than 500m years (5×10^8y). (We now believe it to be $\approx$ 4.6b years (4.6×10^9y).)

A cooling earth

[2.] The next year, in "On the Secular Cooling of the Earth," 1863, Thompson set out what was to become his most important argument for a limited time scale for the age of the earth.

Postulating that the earth had originally been a hot molten ball and had slowly cooled to its present state, and making various assumptions about thermal conductivity, he derived a set of equations to describe the overall process of cooling. This allowed him to make measurements of temperature near the surface to try to estimate the temperature in the center.

Although he acknowledged that there were many unproven and interconnected assumptions in his approach, he still calculated that the earth was around 98m years old – or between 20m and 400m, to allow for the uncertainties involved.

Tidal friction

[3.] In an address to the Geological Society of Glasgow, "On Geological Time," 1868, he set out another argument against uniformitarianism.

Since the tides lag behind their theoretically ideal positions based on the motion of the moon, it should be possible to roughly calculate the friction in the water – both viscosity and surface drag – and to calculate how much energy is lost in this process. This energy loss should then come at the expense of slowing the rotation of the earth.

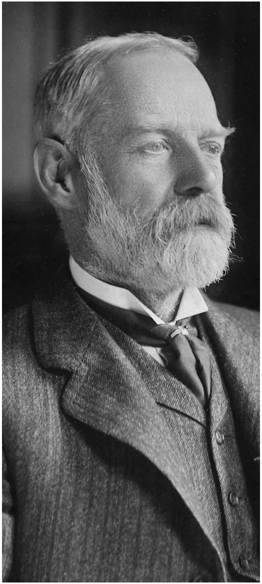
Although the numbers and durations involved in these considerations were even more vague than those for [1.] and [2.], the overall point was that Kelvin was confident that it was possible for physics to set a limit to the age of the earth.

A limited time frame

Over the next two decades Kelvin, and his colleagues, repeatedly returned to these arguments and came up with an increasingly restricted limit: 100m, 50m, 20–50m, 20–40m, and 24m years. His colleague P.G. Tait (1831–1901), another mathematical physicist, computed 10m years.

Although geologists and biologists balked at these extreme lower limits, they generally accepted the upper limit of 100m years. Hence, although there were a few, including C. Darwin, who continued to push for greater limits, the second half of the 19th century saw a turn away from uniformitarianism towards a geology set in the framework of 100m years. Indeed, a number of geologists carried out their own computations based on the erosion of land and river valleys and the gradual increase in the salt content of the oceans and confirmed numbers in the range of 100m years.

The objections of George Darwin (1845–1912)



G. Darwin – the son of the famous naturalist – was a Cambridge trained mathematician who carried out a long research project on the origin of the moon and the speed of the earth's rotation. He argued against the restricted time frames of the physicists and dismantled the argument on tidal friction.

His contribution made clear the many unconfirmed assumptions in Kelvin's work.

G. Darwin, "BAAS Address," 1886

"At present our knowledge of a definite limit to geological time has so little precision that we should do wrong to summarily reject any theories which appear to demand longer periods of time."

Perry's objections

Following an 1894 BAAS address by the Marquis of Salisbury, in which he criticized the theory of natural selection on the basis of Kelvin's objections, John Perry (1850–1920), one of Kelvin's collaborators, offered a new critique of Kelvin's methods.

Perry focused on the theory of cooling, and pointed out that if different assumptions were made, such as differences in conductivity at different points on the surface or at different depths, the results would be quite different. He then turned to the theories of solar heat and tidal friction and again showed that different assumptions gave quite different results.

Perry, Personal correspondence, 1894

"Surely, Lord Kelvin's case is lost, as soon as one shows that there are *possible* conditions as to the internal state of the earth which will give many times the age which is … his limit."

A *fin de siècle* address

In 1900, William Sollas (1849–1936), a British geologist and anthropologist, gave a plenary address to the British Association for the Advancement of Science (BAAS), summarizing everything that was then known about the age of the earth and all of the methods that had been used to reach the various figures in circulation at that time.

He argued that Kelvin's 24m years should be raised by better measurements of surface temperature, and that the geologists' estimates from strata and the oceans should be revised down by making various different assumptions. He accepted as unquestioned fact, G. Dawin's *minimum* of 50m years for separation of the moon and the earth.

In this way, by making various adjustments to the different methods he brought them all into agreement, stating that the stratified deposits were 20m years old, and the total age of the earth was 50–60m years (5 or 6×10^7y).

General Assembly of the BAAS

Address to the The British Association for the Advancement of Science

The discovery of radiation and its heat

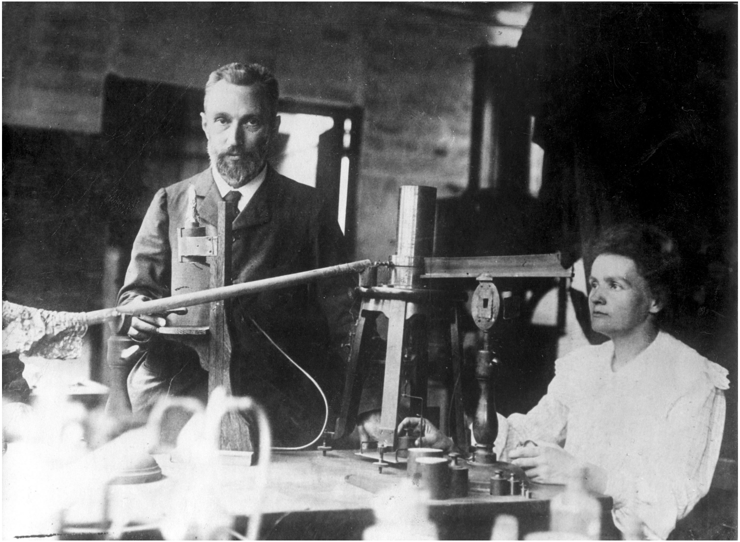
In 1896, Becquerel discovered radiation from uranium salts. Marie Curie named this activity *radiation* and, with her husband Pierre, discovered polonium and radium. In 1903, P. Curie and Laborde announced that radium salts spontaneously release heat. Immediately it was realized that this would have implications for the age of the earth.

Ernst Rutherford and Barnes studied the relation between heat release and alpha particles (He^{2+}). Rutherford announced his results publicly to an audience that included Lord Kelvin.

Rutherford, Friday Evening Lecture, Royal Institute, 1904

"The discovery of radio-active elements, which in their disintegration librate enormous amounts of energy, thus increases the possible limit of the duration of life on this planet, and allows the time claimed by the geologist and biologist for the process of evolution."

The Curies in their laboratory



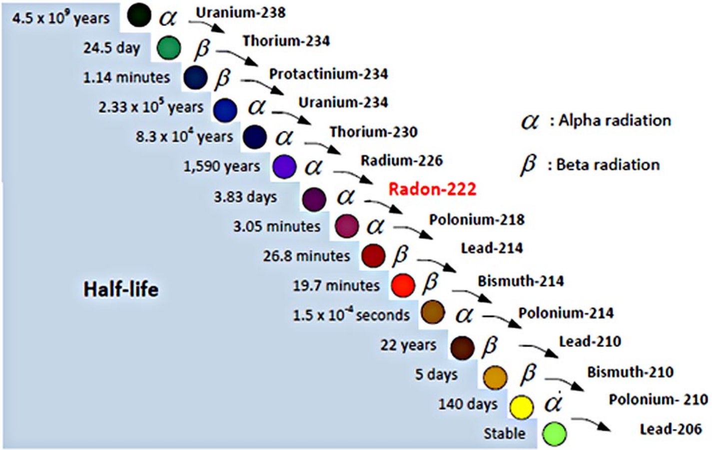
Pierre and Marie Skłodowska Curie in the lab where they discovered radium

The law of radioactive decay and decay products

Rutherford and Frederick Soddy studied the decay process of radioactive elements, pointing out as an aside that this might be used for *dating*. This is based on the principle that although it is impossible to predict when any individual atom will decay, a sample of material has such a large number of atoms that it can be predicted with great accuracy when half of it will have decayed – its half-life. Then, this remaining half will be again halved in the same time, and so on, as a sort of inverse of an exponential function. Hence, the final decay product will increase in a well-defined function as well.

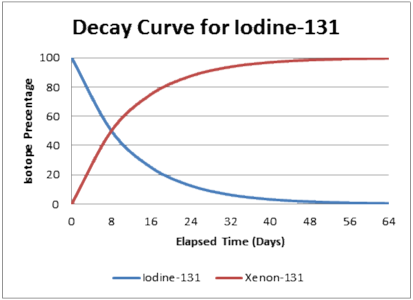
Thus, the principle for dating is simple: one finds the time necessary to produce a unit amount of the *end product*, using the logarithm. Then one multiplies the *ratio* of *end product* to *original element (or isotope)* by the time to get the age. Proposals were put forward for working with uranium to radium, thorium and helium, but there were difficulties with all of them.

A Radioactive Decay Chain, Uranium 238



The complete decay chain of uranium-238

Radioactive dating and the geologist's reaction



A simple decay relation between radioactive element and product

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Because of their experience with the fiasco of the 19th century physicists, for the time being, most geologists were now reluctant to simply take the physicists at their word, and the times that they were computing were now much greater than the geologists had become accustomed to thinking about.

Arthur Holmes (1890–1965)

- Born to the family of a cabinet-maker.
- Studied physics and geology at Imperial College London (ICL), under Robert Strutt and William Watts.
- Prospected in Mozambique and worked for an oil company in Burma (Myanmar).
- Head of Geology at Durham; Chair of Geology at Edinburgh.
- Pioneered the uranium-lead dating method; proposed the idea that convection currents are moving the continents.
- Wrote *The Age of the Earth* (1911–37), and *Principles of Physical Geology* (1940).

The uranium-lead dating techniques

When Holmes was young, the methods of uranium-radium dating was worked out by Soddy, 1909, and that of helium dating was worked out by Strutt – one of Holmes' teachers – 1908–1910. But, radium was difficult to isolate and weigh, and helium was known to have escaped through other processes.

In 1908, at the suggestion of Strutt, Holmes began a careful investigation of a rock from Norway, which contained some 17 different types of radioactive materials, using the newly developed uranium-lead technique. He developed various chemical techniques to separate these elements and to weigh them. After once discarding all his data and starting over from scratch, he carefully completed his research before the Mozambique expedition – finding the Norwegian rock to be 370m years old (3.7×10^8y) – as well as recalculating various figures in the published literature.

The age of the earth's strata

After catching malaria in Mozambique, Holmes returned to a position at ICL, where he continued to work on dating methods. Around this time, Soddy came up with the term *isotope* to denote varieties of an element that were chemically the same, but had different atomic weights. Holmes immediately began to incorporate the study of isotopes into his work, by collaborating with his colleagues in Vienna and his friend Bob Lawson to determine the atomic weights of the isotopes of lead. This pushed the age of the oldest rocks from Mozambique back to 1.5b years (1.5×10^9y).

When he returned from Burma, he was appointed professor of geology at Durham University. Here, he continued to work on dating the earth, collating the work that was being done in various labs to date different rocks and the geological strata in which they originated. In the 1930s and 40s, the radioactive dating methods were gradually accepted as the most reliable.

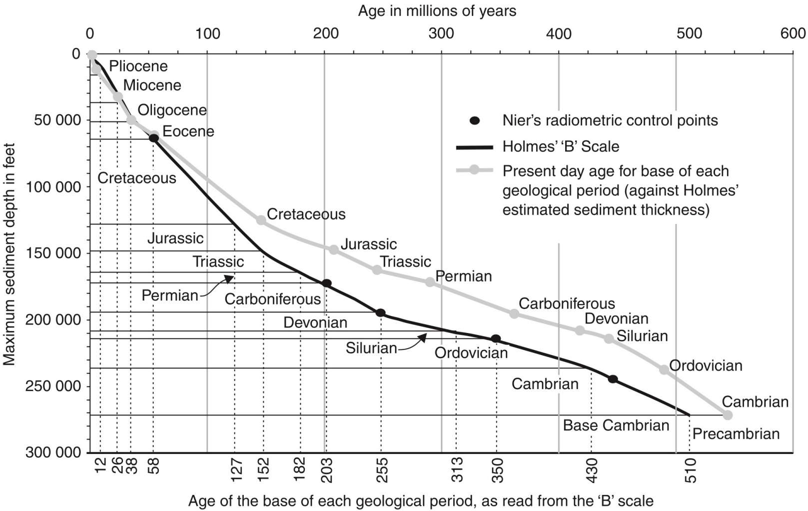
The geologists gradually come around

Throughout the 1910s and 20s, geologists continued to date the earth, using their old methods, to some 100s of millions of years ($n \times 10^8$y). They remained skeptical of the new methods from radioactive decay for some time. Over the next few decades, as the methods of radioactive decay became more developed, they began to come around to the new methods. They began to understand that the rates of erosion, and the quantities of salt in the oceans were not constant, and had increased over time.

When Holmes delivered his inaugural address at Edinburgh University, he calculated that the age of the earth was 1.5–2b years old (now 4.54b, 4.54×10^9y). Although few geologists could competently contest this range, it was older than what astronomers calculated for the age of the universe. After the lecture, a professor of biology remarked: "it is highly satisfactory that the Earth is older than the Universe!"

In the following decades these methods continued to improve.

A geological timescale



Using the ratio of original lead to end product lead, in 1947 Holmes created a timescale for the history of the earth.

Continental drift and plate tectonics

The theory of continental drift is another example – like the theory of unit factors in genetics – of a theory that was put forward well before it was taken up into mainstream scientific thinking. The theory had been muted a number of times throughout history, but it was first developed in detail by Alfred Wegener (1880–1930) in the 1910s on purely geological grounds. Nevertheless, the reasons for opposing the theory were too strong for it to be taken seriously until half a century later.

Although a few geologists agreed with Wegener most did not, until the 1960s, when the theory was redeveloped, supported by further evidence, and incorporating the new concept of the *tectonic plate*. The development of plate tectonics in the 1960s took place in the context of the new geophysics and is a classic example of a synthetic theory, which incorporates elements from a wide variety of studies.

Alfred Wegener (1880–1930)

- Wegener was the youngest son of a Berlin family. His father was a theologian and gymnasium classics teacher.
- He studied physics, astronomy and meteorology in Berlin, Heidelberg and Innsbruck, with a PhD in astronomy from Friedrich Wilhelms University.
- He was wounded on the front line in WWI, and then served in the army weather service.
- He made four expeditions to Greenland – publishing extensively on meteorology and polar ice and air circulation. On the fourth expedition he died of heart failure, due to the strenuous conditions of the arctic winter.
- Wegener first published his continental drift hypothesis in 1912. He fleshed his ideas out in *Die Entstehung der Kontinente und Ozeane* (1915, 1920, 1922, 1929).

Wegener on his final Greenland expedition

Wegener's Pangea

Wegener began from a purely geological perspective. He noticed that the present-day coastlines of Africa and the Americas seem to be complementary to one another, and searched the literature for geological evidence of similarity in the ancient flora and fauna.

He found that the Hercynian chain (in Europe) and the Appalacian range (in North America) were related, as well as the South African chains and those around Buenos Aires, Argentina. He read that the same organisms had populated both South America and Africa, on the one hand, and North America and Europe, on the other, up until sometime in the Mesozoic period, and then began to diverge.

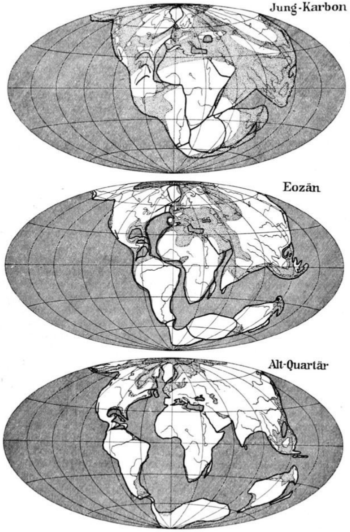
He argued that all of this was evidence for a single ancient continent, which he called *Pangea*.

Wegener’s continents

Wegener argued that the continents were made of a lighter rock (*sial*) that floated on a denser layer below (*sima*).

Although it was difficult to come up with a physical mechanism that could cause this movement, he advanced a number of different ideas: (1) the crust is a sort of semi-solid liquid, like a resin, (2) there is a centrifugal force driving the continents away from the poles, and (3) there is a westward pressure caused by tides.

Abb. 4.

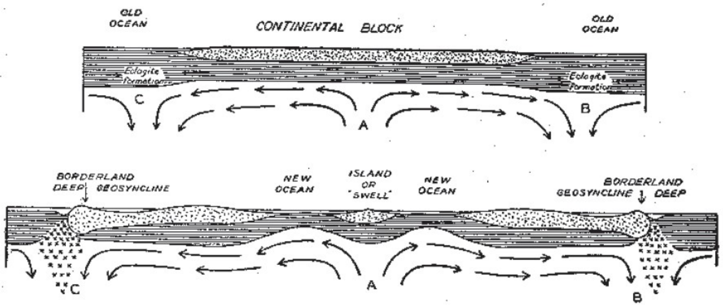


Rekonstruktionen der Erdkarte nach der Verschiebungstheorie für drei Zeiten.

Schraffiert: Tiefsee; punktiert: Flachsee; heutige Konturen und Flüsse nur zum Erkennen. Gradnetz willkürlich (das heutige von Afrika).

Holmes' convection currents

In 1927, Holmes read a paper to the Edinburgh Geological Society in which he proposed that the continents are moved by underlying convection currents generated by the swirling heat of a glass-like, moving core.



Figs. 2 and 3.

Holme's 1931 publication on convection currents

Resistance to drift

Although there were some – like Holmes – who agreed with the theory and took it seriously, for the most part it was not accepted, especially in the English-speaking world. At a 1926 meeting of the American Association of Petroleum Geology, the majority opinion was that drift was impossible.

Geophysicists pointed out that the mechanisms developed by Wegener were insufficient to move continents and that proposed by Holmes was pure speculation. Geologists for the most part held on to the old idea of sunken land bridges to explain the similar ancient flora and fauna across the continents.

Some geologists, however, did take the theory seriously, such as the South African Alexander du Toit (1878–1948), who proposed that there had been two ancient continents: *Laurasia* and *Gondawana*.

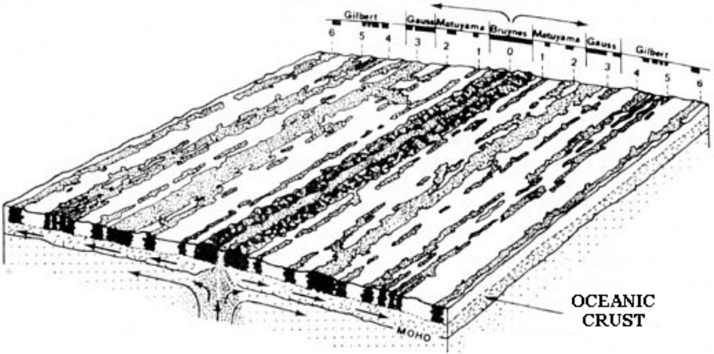
Seafloor spreading

In 1954, Jean-Pierre Rothé (1906–1991), at Strasbourg, published a paper arguing that the system of midceanic ridges running down the Atlantic and Pacific Oceans formed active seismic belts, or rifts – which were then studied extensively in the late 1950s.

In 1962, Harry Hess, at Princeton, put forward the theory that the ocean floor is continuously being produced in the rifts by rising magma, which then cools and solidifies on the ocean floor – a theory which was called *seafloor spreading*.

Support for this theory came from studies of the earth's magnetic core. During the 1950s, it was realized that the magnetic field of metallic ores seemed to indicate that the earth's magnetic pole was moving around, and shifting polarity. Especially around the oceanic rifts, there appeared to be bands of oppositely orientated magnetic fields.

Fossil magnetism



In 1963, Lawrence Morley (1920–2013), Fred Vine (1939–), and Drummond Matthews (1931–1997), proposed that these reversals of the magnetic field were produced by lava outflows during periods of switching orientation of the earth's magnetic pole.

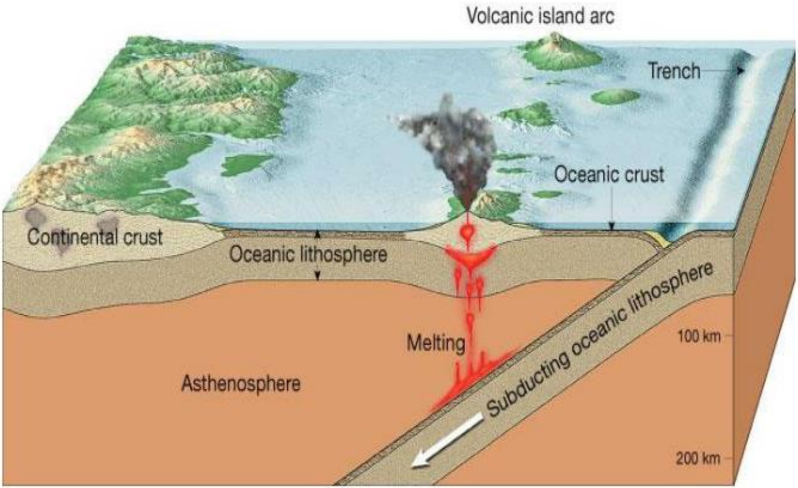
Subduction

In 1925, Kiyoo Wadati (和達 清夫, 1902–1995), of the Central Meteorological Observatory, Japan, had studied the differences between surface and deep earthquakes in Japan, and proposed that the ocean floor of the Pacific is being driven below the Japanese archipelago – a phenomena known as *subduction*.

In the 1940s, Victor Benioff (1899–1968), at Caltech, had continued this investigation by studying the phenomena of subduction more broadly in the Pacific and observed that there are many such subduction zones.

It was hypothesized that subduction was caused by an upper layer of the mantle, the *lithosphere*, being driven down into a lower layer of the mantle, the *asthenosphere*, creating a zone of deep earthquakes, now know as a *Wadati-Benioff zone*.

A Wadati-Benioff zone



A textbook image of a Wadati-Benioff zone.

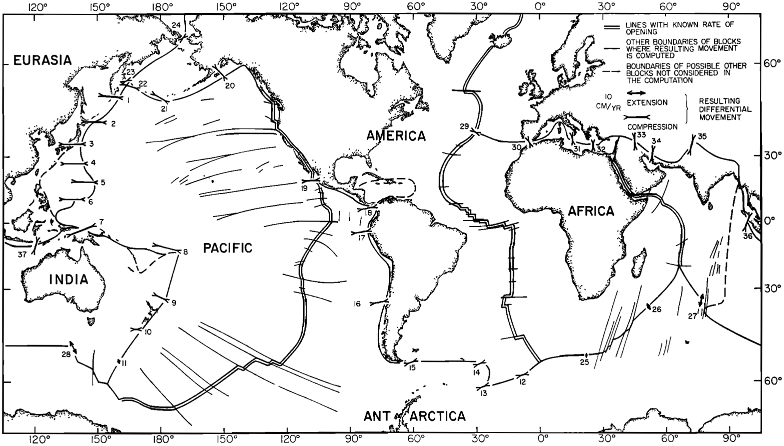
Plate tectonics

In the late 1960s, all of this was then put together into a new synthetic theory, known as the theory of *plate tectonics*. The main players were W. Jason Morgan (1935–), at Princeton, Dan McKenzie (1945–), at Cambridge and Xavier Le Pichon (1937–), at Lamont.

The theory proposes that the earth's crust is divided up into originally six (or 12, now some 15) solid plates that are moving against each other – either away from each other, towards each other, or laterally.

Where they move away from each other, there are *mid-oceanic rifts*, where new crust is being formed. Where they move towards each other, the lithosphere is driven down in a Wadati-Benioff zone, a *subduction* creating earthquakes and volcanos. Where they move laterally against each other, there are earthquake zones that have comparatively fewer volcanos.

Tectonic plates



From Le Pichon, “Sea-floor Spreading and Continental Drift,” 1968.
(The labels name the plates – hence, “India” appears in the middle of Australia.)

Overview

- We have examined the rise of the new disciple of geophysics and its use in trying to address the questions of the age of the earth and the formation of the continents.
- We saw that the methods of 19th-century thermodynamics were not successful in dating the earth, whereas the new science of radioactive decay was remarkably so.
- We saw another example of way in which a correct idea, such as that of continental drift, must be introduced in the right context to be accepted.
- We have seen in this material yet another example of the expansion of the concepts and methods of the physical sciences into the earth and life sciences.