PART 1
Earth/history

I.I

Introduction

The age of the Earth has been one of the most controversial numbers in science since the 17th century. The currently accepted value – about 4.55 billion years – is a fundamental datum of science and thus of considerable interest for its own sake. Yet, much of its significance lies in its relation to other scientific facts and theories, such as geological time periods, biological evolution, and cosmology. Most earth science and astronomy books mention the figure of 4.55 billion years. But they miss the opportunity to show these connections between different sciences, as well as fail to explain how that age was actually determined. For example, more than 30 years ago, scientists developed ultraprecise techniques for measuring small amounts of lead in order to estimate the Earth's antiquity. Geochemist Clair C. Patterson, who succeeded in establishing the currently accepted figure, subsequently applied similar methods to study the distribution of potentially harmful lead in our environment. He found that human activities, especially the burning of leaded gasoline, were rapidly increasing our exposure to lead poisoning. A campaign in which Patterson's results played an important role eventually led to federal regulations forcing automobile manufacturers to switch to engines using unleaded fuel.

In an earlier approach to the problem of estimating the age of the Earth, nearly 200 years ago, scientists thought that the Earth had originally been formed as a hot fluid sphere and believed they needed a mathematical theory of heat conduction in order to calculate how long it would have taken for the Earth to cool to its present temperature. Joseph Fourier was the first to develop a successful theory for this purpose. In order to apply his theory, he had to work with functions that were much more irregular than those previously used by mathematicians: They might have sharp corners or discontinuities. Fourier's work led others to redefine functions in terms of sets, ultimately bringing about a major reformation of mathematical analysis. Set theory ultimately worked its way into all levels of education, reaching American elementary schools in the 1960s as part of the "new math."

1.1.1 Genesis and geology

Problems of environmental pollution and discontinuous functions were not major concerns for the first scientists who tried to find a reasonable timetable for the formation and development of the Earth. Instead, they had to contend with religious doctrines that postulated the creation of the world only a few thousand years ago. Even if they did not insist on the precise date – Saturday evening, 22 October 4004 B.C. – proposed by Bishop Ussher in 1658, many theologians as late as the 18th century regarded as sacrilegious any suggestion that the Earth (or the universe) was much more than 6000 years old. Thus when the French diplomat-scientist Benoît de Maillet (1656–1738) wrote a book arguing that continents had been emerging as a result of the gradual diminution of the ocean over a period of more than two billion years, the priest to whom he entrusted the manuscript deleted or reduced the longest time estimates. Thus the book, when published posthumously in 1748, sacrificed scientific integrity in order not to offend Christian belief. Similarly when Buffon estimated the time required for the Earth to cool down from a hot initial state, he withheld from publication his best value of three million years and claimed only that the Earth is about 75,000 years old. Even this figure was considered heretical and Buffon was ordered by the theological faculty of the Sorbonne to revise his theories.[1]

By the middle of the 19th century, the problem of the Earth's age had ceased to be a major battleground for the conflict between science and religion. The study of fossils and geological formations had convinced even the most pious scientists that the Earth's surface must have existed for much longer than the biblical six millennia. Theologians decided that the "days" of creation in Genesis should be interpreted metaphorically rather than literally – each representing a geological period of thousands or millions of years. Stellar astronomy produced strong evidence that most stars are at least a million light years away from us, hence must have existed a million years ago. (Modern "creationists" answer this argument by maintaining that God created the light in space to make it *look* like the stars were already there before the actual creation of the universe!)

But British geologists, especially the followers of the "Uniformitarian" doctrine of Charles Lyell, were headed for a new conflict over their use of long time periods. Lyell, in his *Principles of Geology* (1830–3), argued that the only scientific way to reconstruct the Earth's history was to invoke just those causes or forces that could now be seen in operation – erosion, uplift, and occasional earthquakes and volcanic eruptions. Enormous catastrophes such as worldwide floods were not allowed, although some of the effects formerly attributed to such a Flood were later ascribed to extensive glaciation as proposed in the "Ice Age" theory of Louis Agassiz. Lyell's Uniformitarianism not only forbade the use of causes qualitatively different from those now operating, but also assumed that familiar forces were not much more intense in the past. In particular, he rejected the hypothesis that the Earth was cooling down

1 Maillet (1748/1968). Haber (1959). Albritton (1980). Dean (1981). Brice (1982). Rossi (1984). See also the works of Buffon cited in *Nebulous Earth*, Chapter 1.1, notes 12 and 17.

from a much hotter state, and asserted that the surface temperature had been more or less the same (apart from the cooler "Ice Age") during the entire period of geological history. This period had no definite time limit; Lyell and his followers assumed that they could invoke whatever amount of time was needed to accomplish geological processes at present rates, whether it be a million or a billion years.

1.1.2 Darwin and Kelvin

Charles Darwin, one of the followers of Lyell, suggested in his *Origin of Species* (1859) that periods of the order of 300 million years, estimated from the rate of geological processes, might be available for the slow process of evolution by natural selection. That was a nearly fatal mistake. William Thomson, later known as Lord Kelvin, used Fourier's heat conduction theory to show that Darwin's estimate was impossibly high: The entire Earth was hotter than the melting point of any rock only 100 million years ago. Fourier himself had obtained a similar result, but it seemed to have no significance at a time when geological periods were measured in thousands rather than millions of years; only after Lyell encouraged geologists to "think old" did 100 million years seem like a short time.

The late-19th-century controversy over the age of the Earth has often been described as a dispute between physics and biology. But Kelvin's real target was Lyell, not Darwin. He complained that Uniformitarianism not only assumed unreasonably long periods for geological time, but directly violated the Second Law of Thermodynamics. The latter charge was in fact correct. Lyell had postulated that the Earth's surface, though continually radiating energy into space, could remain at the same temperature indefinitely by means of a thermoelectric energy conversion cycle in the interior. Lyell had proposed this mechanism *before* Rudolf Clausius and Kelvin established the Second Law of Thermodynamics, but he never conceded the validity of Kelvin's argument on this point.

As for evolution, Darwin's theory did not itself require any particular time period; he could just as well have estimated a time of 30 million years and then there would have been no direct conflict with Kelvin's calculations. Kelvin was willing to accept the general principle of biological evolution, but he disliked the apparent randomness of Darwin's natural selection mechanism and preferred to invoke some kind of divine guidance. Kelvin's restriction on the age of the Earth did not refute evolution, but it did encourage biologists to propose Lamarckian and other influences that would make it go faster.

[Aside from the time-scale problem there is no fundamental inconsistency between Darwin's theory of evolution and the Second Law of Thermodynamics. In particular, evolution as a change from simple to complex systems is not forbidden by some tendency for entropy or disorder to increase. This is a favorite but completely fallacious argument of creationists. Ludwig Boltzmann, one of the founders of statistical thermodynamics, pointed out that Darwinian natural selection is actually predicted by the Second Law. The reason is that molecular reactions are governed by energy (E) as well as entropy (S). At a given temperature (T) a system will go to the state of lowest "free energy" (F) defined as $F = E - TS$. At high temperatures this means that states of high entropy (e.g., a disordered gaseous state) are favored, whereas at low temperatures states of low entropy (solids bound together by intermolecular attractive forces) will prevail despite their low entropy. Thus water vapor condenses into highly ordered snowflakes as the temperature drops – a process completely in accord with the Second Law of Thermodynamics even though it involves an increase in entropy. Similarly, complicated molecules can be built up step by step because of the action of attractive interatomic forces that favor bonds and reduce energy.]

Kelvin and other physicists reduced their estimate of the age of the Earth to only 24 million years by the end of the 19th century. An independent line of reasoning developed by Hermann von Helmholtz and by Lord Kelvin indicated that if the Sun's energy is derived from gravitational contraction, its age would be about the same order of magnitude. Geological estimates, based on processes such as the transport of salt by rivers into the oceans or the deposition of sediments, gave ages of 90 or 100 million years. But most geologists seemed to be unwilling to challenge Kelvin's basic assumption that physics is a more reliable source of knowledge than geology. Physics had become the most "fundamental" science; all other sciences should be consistent with – and ultimately reducible to – physics.

The major exception to this submissive attitude was the American geologist Thomas Chrowder Chamberlin.[2] Chamberlin rejected the assumption, shared by Kelvin and most other scientists in the 19th century, that the Earth began as a molten globe. He proposed instead that it was formed by the accumulation of cold solid particles, which he called "planetesimals" (infinitesimal planets). (Later he proposed, in a theory worked out with the help of the astronomer F. R. Moulton, that the planetesimals themselves had condensed from gases pulled out of the Sun by the tidal force of a passing star.) As the planetesimals fell into the growing Earth their kinetic energy of motion would be converted into heat, but if the process was slow enough most of this heat would be radiated into space and the Earth would remain solid. Kelvin's time limit would no longer apply and there would be plenty of time for geological and biological evolution. As for the Sun, Chamberlin suggested (in 1899, before such ideas were fashionable) that its life might be prolonged by previously unknown intraatomic sources of energy.

After the isolation of radium by Marie and Pierre Curie in 1902, it was generally recognized that Kelvin's estimate of the Earth's age was much too

2 Chamberlin's cosmogony is briefly summarized in *Nebulous Earth*, Chapter 1.9; for further details and references see *Fruitful Encounters*, Chapter 1.2.

low. There was apparently enough radium in the Earth's crust alone to generate more heat than was lost by radiation into space, so there was no longer any good reason to believe that the Earth is cooling down.

1.1.3 Radiometric dating

Radioactivity itself provided a clock to measure the ages of rocks, if one could establish the nature of the transmutations of radium and other elements.[3] For example, if the helium trapped in a rock had been produced by radioactive decay at a known rate, one could determine how long the rock had been solid. The leader in this new field was Ernest Rutherford. At the St. Louis Congress of Arts and Sciences in 1904, Rutherford announced that a sample of fergusonite was 40 million years old; he soon revised this figure to 140 million years and then to 500 million years. The British physicist R. J. Strutt (later known as the fourth Lord Rayleigh) published in 1905 an estimate of 2400 million years for a specimen of thorianite, but he admitted that this age was uncertain since some of the helium might have come from the decay of thorium.

Helium analysis could not give reliable ages since an unknown amount of helium leaked out over a long period of time. A better method was to measure the amount of lead, assuming it was produced by the decay of uranium (through radium as an intermediate stage). The American chemist Bertram Boltwood developed this method and reported an age of 2200 million years for a sample of Ceylonese thorianite in 1907; this was later found to be too large because some of the lead came from thorium.

After the discovery of isotopes in 1913, the various radioactive decay series were sorted out, and corrections for the amount of thorium-generated lead isotope could be made. The Scottish geologist Arthur Holmes was the leading authority on this and other methods of radiometric dating during the next three decades. By 1920 he and other scientists had established that the oldest minerals were about 1600 million years old, and that the age of the Earth's crust is probably about 2000 million years.

The geologists were put in an awkward position by the rapid development of radiometric dating. At first they were relieved to be rid of Kelvin's extremely short time limits; it seemed that geology had been right and physics wrong about the age of the Earth. But they found it hard to adjust their thinking to the vastly expanded time scale provided by the new physics. Traditional geological methods, based on the accumulation of sodium in the ocean and deposition of strata, still gave figures of only a hundred million years or so. Accepting the radiometric dates would imply that geology was still subordinate to physics as a source of knowledge about the Earth's past.

Chamberlin was again the exception that proved the rule. He was familiar

3 For further details and references see Chapter 2.2.

enough with the methods of geology to see their weaknesses, and secure enough in his own position as an innovative global theorist to be willing to expose those weaknesses to the scientific community. After all, he was the one who had first defied Kelvin and then persuaded the astronomers to abandon the theory of the Earth's origin (the Nebular Hypothesis) that had been accepted throughout the 19th century. So in 1920 Chamberlin again broke the unwritten rules of scientific protocol and declared that the way to determine the age of the Earth was to put *biological* considerations first. Rather than force evolution to race through its course in the limited time allowed by physics, he proposed to use evolutionary theory in combination with radiometric dating and his own planetesimal hypothesis to find out how long the Earth must have existed. Since biologists estimated that about one tenth of the total evolutionary process had taken place since the early Paleozoic, and since radiometric dating had placed this epoch about 400 million years ago, Chamberlin concluded that life began on earth 4000 million years ago. Another 260 million years were needed to collect planetesimals and reach the conditions suitable for life to begin, making the age of the Earth 4.26 billion years. Chamberlin showed that there was nothing in the geological evidence inconsistent with this result. On the other hand he notified the physicists that it was now their duty to find an energy source rich enough to allow the Sun and stars to fulfill their functions of providing light and heat for at least 10 billion years.

By 1936 it was understood that two isotopes of lead – 206 and 207 – are the stable products of radioactive decay series starting with ^{238}U and ^{235}U, respectively. Another isotope, ^{208}Pb, comes from a thorium isotope. The fourth stable isotope, ^{204}Pb, is not produced by any such process and is therefore called "nonradiogenic." Using a mass spectroscope, Alfred Nier at Harvard (later at the University of Minnesota) found that these isotopes do not occur in the same proportions in all rocks, even though the atomic weight (the average of the isotopic mixture) is about the same. If one knew their relative abundance at some initial time – the "primeval abundances" – one could compare the amounts of the isotopes generated by the decay of uranium after a certain time *t*. Since the initial amounts of the parent uranium isotopes are not equal, one has to compare the ratios of the radiogenic components of the lead isotopes (present minus primordial) to the initial abundances of the parents. In order to explain the observed fact that different rocks have different relative abundances of ^{206}Pb and ^{207}Pb, Nier proposed that each rock has a different mixture of primeval and radiogenic lead. At the time of its formation, each rock contained a certain amount of primeval lead and a certain amount of uranium and thorium which later decayed to produce the radiogenic components of the lead isotopes. If the primeval abundances were known and the present abundances of all four isotopes are measured, then the time since the formation of the rock could be calculated. (This assumes that all the decay rates or half-lives are known and are constant through time.) The problem is then reduced to estimating the primeval abundances of the lead isotopes.

Nier and his colleagues assumed that the closest approximation to primeval lead would be a rock that has the highest proportion of ^{204}Pb, since all of that isotope is primeval. This happened to be a galena from Ivigtut, Greenland, for which the abundances of isotopes 204, 206, 207, 208 were in the ratios 1 : 14.54 : 14.60 : 34.45. The oldest rock sample, Huran Claim Monazite, then gave an age of 2570 million years.

In 1946 Holmes and Fritz Houtermans independently pointed out that Nier's method can be extended to give not only the ages of particular rocks but the age of the Earth itself. Before the Earth's solid crust was formed, it may have been in a fluid state; in any small portion of matter, the proportions of elements such as uranium and lead might be subject to change in unpredictable ways, so dating methods based on the uranium/lead ratio could not be applied to this pregeological epoch. But physicochemical processes have very little effect on the proportions of isotopes of heavy elements; these proportions change only because their parent isotopes decay at different rates. A group of samples solidified at the same time but with different proportions of primeval and radiogenic lead should have different abundances of the two isotopes ^{206}Pb and ^{207}Pb relative to ^{204}Pb, but if one plots the amount of isotope 207 against the amount of isotope 206 one should get a straight line. Houtermans called this line an "isochrone" since it displays the variations in isotopic composition for rocks formed from varying amounts of uranium and thorium at the same time. From the slope and intercept of the line, together with an estimate of the primeval abundances of the lead isotopes, one can calculate the time when the Earth was formed with those abundances.

Holmes based his calculations on Nier's isotopic data, but lack of adequate computing facilities delayed him for several years. In 1946 he announced that the Earth's age is 2900 million years, and Houtermans reached the same conclusion at this time. Holmes revised his value to 3350 million years in 1947.

In 1953 a group of scientists at the University of Chicago and the California Institute of Technology reported that the abundances of the radiogenic lead isotopes in some meteorites were significantly lower than the figures previously considered primeval in estimating the age of the Earth. The ratio for the four isotopes was found to be 1: 9.4 : 10.3 : 29.2. Moreover, the ratio of uranium to lead in these meteorites was extremely low, so little if any of the present abundance of ^{206}Pb and ^{207}Pb could be attributed to decay of uranium since the formation of the meteorite. It seemed reasonable to suppose that this material was much less affected by chemical differentiation processes than minerals found in the Earth's crust, so that these values were the most appropriate ones to use for the abundance at the time of formation of the Earth.

The group originally consisted of Clair Patterson, Harrison Brown, George Tilton, and Mark Inghram. Brown was the senior member, who provided resources and suggested the general direction of research; Inghram developed the mass spectrometer that made it possible to measure isotopic abundances. Tilton worked with Patterson in measuring the abundances of uranium and thorium in various minerals, and later verified the meteorite lead measurements. Patterson developed an isotopic dilution method and contamination control techniques that allowed him to make much more accurate measurements of trace amounts of lead isotopes than had been possible before, and thus to discover a new value for the age of the Earth.

In September 1953 Patterson announced at a meeting in Williams Bay, Wisconsin, that the age of the Earth is at least 4.5 billion years, on the assumption that the primeval lead isotopic abundances were the same as those found in meteorites. After Patterson, Tilton and Inghram discussed their results at another meeting in November 1953, the heading of a report in *Chemical and Engineering News* boldly proclaimed: "Earth's Age: 4.6 Billion Years." Houtermans, using the data obtained by the American group, published his own estimate in the same year: The age of the Earth is 4.5 ± 0.3 billion years.

During the next three years the new value was confirmed by other analyses of lead isotope data and by completely independent estimates of meteorite ages based on two other radiometric dating techniques.

In 1956 Patterson thought that enough data were now available to clinch the argument for the 4.5-billion-year age. The meteorites used in the calculation had been found to have the same age by three independent radiometric methods, within the known limits of accuracy of each method: lead/uranium, potassium/argon, and strontium/rubidium. The most accurate method, based on the $^{207}Pb/^{206}Pb$ ratio, gave an age of 4.55 ± 0.07 billion years. Several terrestrial minerals were found to contain lead isotope ratios that fell on the same 4.55-billion-year isochrone as do the meteorites. Patterson concluded that the age of the Earth is the same as that of the meteorites: "we should now admit that the age of the Earth is known as accurately and with about as much confidence as the concentration of aluminium is known in the Westerly, Rhode Island granite."

During the two decades after Patterson first announced his result, the earth sciences underwent a major revolution that changed much of what we thought was known about the Earth's past. It is remarkable that the most fundamental parameter, the age of the Earth, has remained fixed; its current value is within the error limits given 40 years ago.

1.1.4 Geology as a science

At the 1904 Scientific Congress in St. Louis, Robert S. Woodward asserted: "If we agree with Laplace that astronomy is entitled to the highest rank among the physical sciences, we can accord nothing short of second place to the sciences of the earth" (Woodward 1904/1986: 86). But few outside the community of geologists would have agreed with him. Even though geologists "won" the battle with the physicists over the age of the Earth, the prestige of geology among scientists declined substantially after the late 19th century. In part this was because advances in atomic physics, relativity, and quantum theory attracted so much attention that geology by comparison seemed to be making little progress. But geologists themselves went along with the premise that physical methods are more reliable than geological methods; this can be seen in the fact that the results of radiometric dating were originally recognized to give the most accurate ages for geological events (including the age of the Earth), and that continental drift was accepted (as "plate tectonics") when backed up by physical measurements though it had earlier been rejected as unsupported by geological evidence.

The picture of "science" as a body of fundamental laws and mathematical theories confirmed by laboratory experiments – a picture painted by philosophers and popular-science writers in the 20th century – did not seem to leave a place for the qualitative/observational/historical research characteristic of geology. It also reinforced the idea that the sciences and the humanities are radically different kinds of knowledge-seeking enterprises. Conversely, the revival of "historical sciences" – evolutionary biology as well as planetary science – in the late 20th century has broadened our conception of the nature of science and somewhat narrowed the gap between the sciences and humanities. In particular, it is reasonable to compare styles of research on the history of the Earth with styles of research on the history of human society. The comparison allows us to develop another perspective on 19th-century geology.