The Age-of-the-Earth Debate

The controversy, which embroiled Archbishop Ussher, James Hutton, Lord Kelvin, Ernest Rutherford, Bertram Boltwood and Arthur Holmes, has "aged" the earth 4.5 billion years during the past three centuries

by Lawrence Badash

As the sun's first rays of thermonuclear light blazed across the galaxy 4.5 billion years ago, the primal earth emerged from a spinning, turbulent cloud of gas, dust and planetoids that surrounded the new star. During the next 700 million years the cloud settled into a more tranquil solar system, and the sun's third planet began to solidify.

On these figures for the age of the earth rest all of geology and evolution. Indeed, they seem to be part of humankind's permanent store of facts. Yet this chronological structure is quite new. In fact, two earlier estimates have toppled during the past 150 years as the descriptive sciences of biology and geology deferred to the more exact science of physics.

The first estimate fell during the 19th century. To the great displeasure of Charles Darwin and the geologists of the period, the physicist William Thomson (later Lord Kelvin) performed a seemingly flawless calculation to show that the earth had not existed throughout eternity, as many thought then, but had formed 100 million years ago. That chronology collapsed at the turn of the century, when the advent of radioactive dating techniques showed the earth's age to be a few billion years. After a fierce debate between geologists and physicists, radioactive dating prevailed. Above all, the age-of-the-earth controversy illustrates that emotion, intuition and vested interests can direct the course of science almost as much as logic and experimentation.

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Intuitively, one might think questions about the earth's age were as timeless as speculation about the structure of the universe and our role in it. Actually, many of the earliest civilizations treated the earth's creation as part of the question of the origin of the universe. The resulting cosmologies tended to be cyclical. The Greeks, for example, believed natural history repeated itself perpetually. The Maya recorded 3114 before the common era (B.C.E.) as the year during which the universe had been most recently re-created. In the first century of the common era, many Han Chinese held a similar view. They believed the universe was destroyed and re-created every 23,639,040 years.

The Judeo-Christian tradition also combines the earth's and the universe's birth in a single event. The story of Genesis led scholars to calculate the number of human generations since Adam and Eve. In 1654 John Lightfoot refined Archbishop Ussher's famous calculation of the moment of creation to an ultimate degree of precision: October 26, 4004 B.C.E., at nine o'clock in the morning in Mesopotamia, according to the Julian calendar.

Mikhail V. Lomonosov was one of the first scientists to suggest (in the mid-18th century) that the earth formed independently of the rest of the universe; he set the interval at hundreds of thousands of years. In 1779 the Comte de Buffon tried to determine the age of the earth experimentally. He believed the earth was slowly cooling from an initial hot state, and he estimated that the earth was 75,000 years old by creating a small globe that resembled the earth's composition and then measuring the rate at which it cooled.

Lomonosov and Buffon were virtually alone in their rigorous pursuit of the absolute age of the earth. When other 18th-century naturalists pondered the question at all, they either placed everything in the hands of the Creator or else supposed that the earth and its living things had simply taken a long time to reach their present condition. James Hutton characterized the long view in his classic *Theory of the Earth* in 1795: "We find no vestige of a beginning, no prospect of an end."

The chronology of geological periods did, however, intrigue Hutton's contemporaries. They inferred that the successive strata of rock and soil at a particular site represent the order in which the layers formed. In the 1790's William Smith built on this perception: two layers from different sites could be regarded as equivalent in age if they contained the same fossils. Extrapolating from these ideas, the naturalists began to chronicle the strata and to estimate the duration of geological periods. Their estimates varied widely, since they could only make crude guesses about the time required to build up the layers.

In 1830 Charles Lyell gave such work a theoretical boost. Lyell insisted that rock formations and other geological features took shape, eroded and re-formed at a constant rate throughout time. Virtually none of the naturalists applied Lyell's notion to calculate the age of the earth's features; the data on geological processes were just too meager. Lyell did, however, persuade many naturalists to become uniformitarians—that is, they rejected the idea that there had been catastrophic geological change or a rapidly forming, young earth. After all, evidence from stones and bones suggested that each geological period lasted for many years, perhaps even hundreds of millions of years, and the age of the earth had to be several times that.

Therefore, the naturalists were startled when Lord Kelvin (then the physicist William Thomson from Glasgow) determined in 1862 that the earth had formed somewhere between 20 and 400 million years ago. Thomson rejected uniformitarianism as unprovable. He and many other physicists of the day believed the earth was originally molten; its surface had cooled and solidified, but the core remained hot. The deeper one descends into the earth, they noted, the higher the temperature.

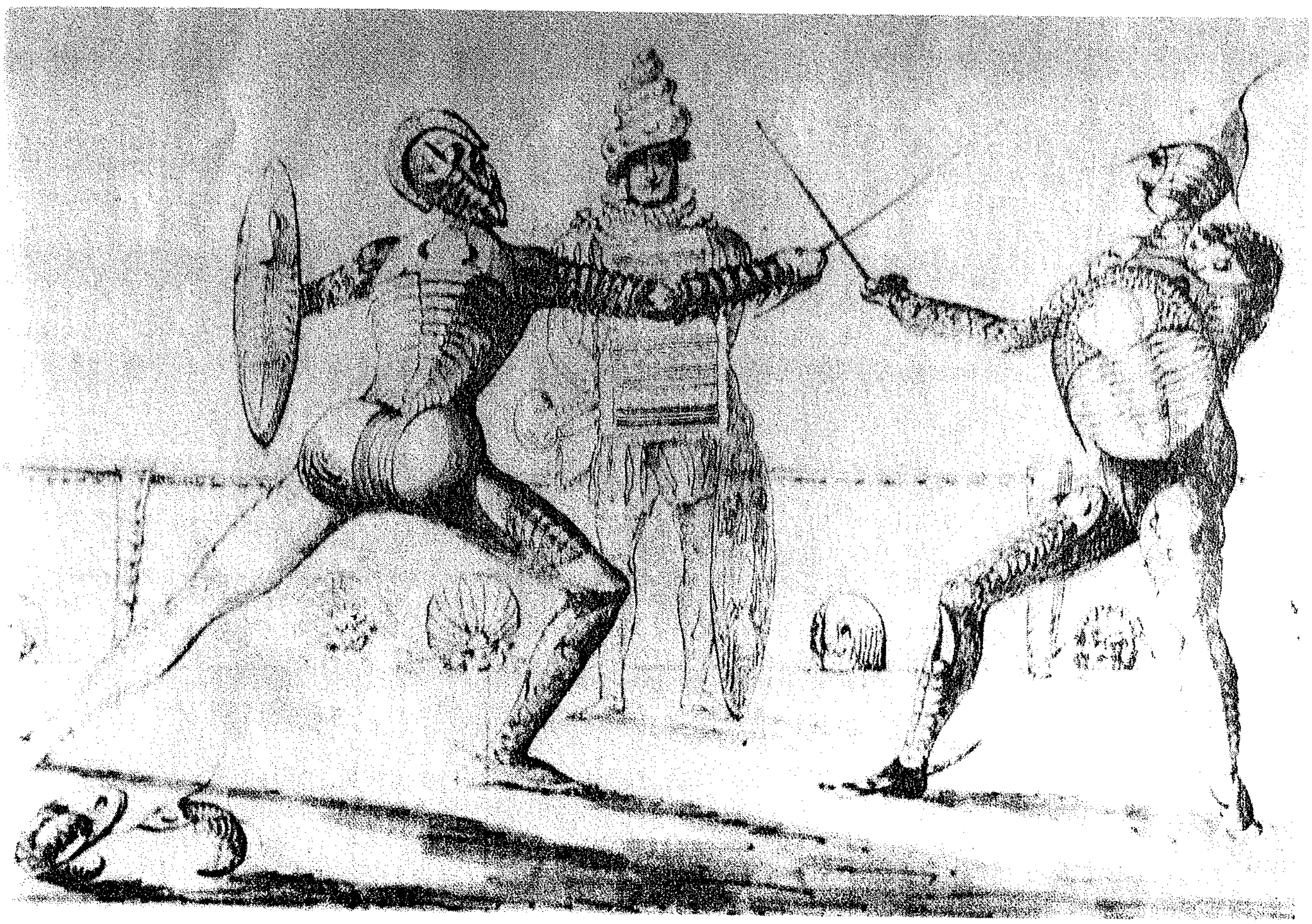
To derive the earth's age, Thomson calculated how long the earth required to cool from its primordial to its present state. He conjectured that the gravitational contraction that formed the earth had generated all of the earth's heat (except for a small contribution from the sun). Then he investigated how well the earth conducts heat and how much heat is necessary for it to melt or to raise its temperature by a certain amount. He knew that the earth had cooled steadily as energy radiated into the cold vacuum of space, according to the second law of thermodynamics. Using Jean-Baptiste-Joseph Fourier's theory of heat conduction, he predicted how the earth's temperature distribution might have evolved [see "The Fourier Transform," by Ronald N. Bracewell; SCIENTIFIC AMERICAN, June]. He corroborated his calculations by accounting for heat from the sun and the effects of tidal friction. In time he refined his estimate of geological history to from 20 to 40 million years.

Thomson's work distressed geologists, who were comfortable with the idea of unlimited time. They resented this audacious physicist who meddled in their field, but they could not fashion a counterargument, and they produced few papers on geochronology.

Thomson's calculation seemed unassailable on the grounds of logic and physics. His conclusion eventually proved to be inaccurate by a wide margin. Still, Thomson had instigated a conceptual coup d'état: qualitative geochronology was overthrown in favor of quantitative methods. Until the end of the century, Thomson's estimates were the standards against which all others were compared.

Thomson's result shocked biologists just as much as it surprised geologists. Darwin regarded Thomson as an "odious spectre" whose chronology was one of the shy naturalist's "sorest troubles." Darwin and other biologists had postulated that complex organisms would require much more than 40 million years to evolve. But neither living nor fossilized organisms offered a basis for an independent calculation of evolutionary time. The biological calendar ultimately relied on geology.

Thomas H. Huxley, a strong supporter of Darwin, attacked Thomson's most vulnerable position. Huxley's view epitomized the disdain that geologists of the late Victorian period felt for the physical sciences and the reluctant respect the workers held for quantifiable data. In his presidential address to the Geological Society of London in 1869, Huxley argued that



ARMED with Paleozoic fossils, stratigrapher Richard Griffith parries the attack by paleontologist John Phillips. The cartoon, drawn in 1843, satirizes a debate over the relative age of rock layers that contained these fossils. Such chronologies helped to establish the earth's age. Geologist Roderick Murchison referees, wearing a tabard that shows strata from the Paleozoic era.

no modern geologist would insist on absolute uniformitarianism but that its principles could be applied. Then Huxley directed his rhetoric at Thomson. The admitted "accuracy of mathematical processes [must not be permitted to] throw a wholly inadmissible appearance of authority over the results, [for] pages of formulae will not get a definite result out of loose data." Perhaps, Huxley suggested, heat radiated from the earth more slowly than Thomson supposed. Thomson thought he had estimated conservatively, but he could not be certain of his values.

Thomson no longer battled alone, however. Both the American astronomer Simon Newcomb and the German physicist Hermann von Helmholtz calculated the time needed for a nebular cloud to condense gravitationally to the present size of the sun. Their independent results of 100 million years established an upper limit for the age of the earth (presuming that the earth did not exist before the sun). George H. Darwin, son of the famous Charles and professor of astronomy at the University of Cambridge, joined the discussion. He posited that the moon broke loose from a rapidly rotating molten earth and found that Thomson's original estimates corresponded well to the time that terrestrial tidal friction would require to brake the earth to its present 24-hour period of rotation.

A few geologists concurred with Thomson's estimate of the earth's lifetime. Even before Thomson, John Phillips, Smith's nephew and pupil, had claimed that the earth must have endured for 96 million years—a result calculated from the admittedly imprecise rate of strata formation from river-derived sediment. In 1868 Archibald Geikie, director of the Geological Survey of Scotland, looked at evidence of erosion and concluded that the earth was no older than 100 million years.

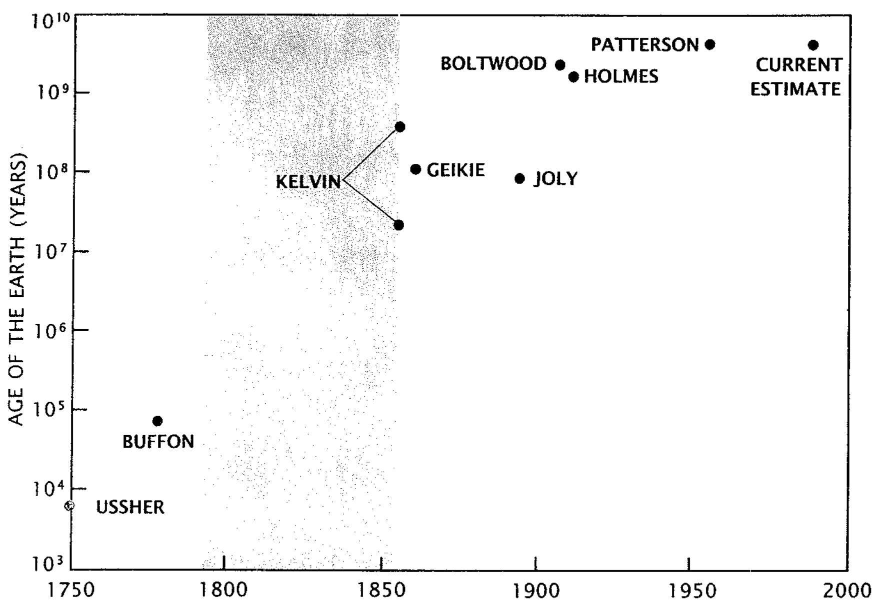
In 1899 John Joly of the University of Dublin devised the only truly new geological technique for measuring the earth's age. He maintained that all the salt in the oceans came from mineral deposits that had eroded and dissolved. He also proposed that the salt concentration in the oceans could not decline. Joly could therefore relate salinity to age. He obtained the best available figures for the quantity of water that flowed into the oceans each year and the amount of salt per volume of runoff. He then calculated the annual increment of salt. He multiplied the salinity of the ocean by its total volume and divided the product by the annual increase. Joly thus determined that the brackish sea developed over 80 to 90 million years.

At about the same time an increasing number of geologists swelled the consensus that the earth had formed less than 100 million years ago. Yet all attempts to measure the age of the earth rested on an assumption, an analogy or a best guess about the rate of change of geological processes.

Such assumptions created room for doubt. Some critics protested against the premise that only gravitational contraction explained the earth's or the sun's heat; another energy source might be possible. Some maintained that the earth had never been molten, whereas others suggested that its interior was still molten. (A liquid interior would conduct heat by convection—something that Thomson had not taken into account.) Still others questioned the data on erosion, sedimentation and salinity.

As the century drew to a close, geologists generally agreed that nearly 100 million years had passed since the earth was born. They did not, however, reconcile their differences with Thomson, who had recently been elevated to the peerage as Lord Kelvin for his scientific accomplishments. Employing his heat calculations, Kelvin was urging ever-shorter geological time scales, all the while high-handedly dismissing geological evidence.

By this time, however, geologists were wary of Kelvin's physical techniques. They had greater confidence (perhaps unwarranted) in their own methods than in the eminent physicist's collection of assumptions. After all, they had discovered several approaches to the chronology that gave concordant results. Geologists felt they had grandly completed their apprenticeship in the quantitative sciences after several decades of vigorous exploring, mapping, measuring and classifying.



GEOLOGISTS AND PHYSICISTS have advanced the earth's age from hundreds of human generations to billions of terrestrial revolutions. The red point marks the biblical estimates for the earth's age. Between 1795 and 1862 most geologists believed the earth had existed for eternity or at least a period beyond measurement.

Yet it was not long before physical scientists were once again treading on geologists' turf and calculating its age. This time the study of radioactivity gave momentum to the attack. In 1896 A. Henri Becquerel discovered the phenomenon; in 1898 Marie S. and Pierre Curie first detected the radioactive elements polonium and radium. Then in 1902 and 1903 Ernest Rutherford and Frederick Soddy explained the process of radioactivity in several papers. Radioactivity, they correctly stated, was the spontaneous transmutation of atoms of one chemical element into another.

At first, the radiation of alpha, beta and gamma rays was more important to geochronology than were the radioelements themselves. (It was later discovered that alpha particles are composed of two protons and two neutrons, just like the nucleus of a helium atom; beta particles are emitted electrons, and gamma rays are photons of electromagnetic radiation.) Earlier, in

1900, Rutherford and R. K. McClung of McGill University in Montreal showed that the various rays carry enormous amounts of energy. Their paper made little impression beyond the small community of physicists and chemists working on radioactivity.

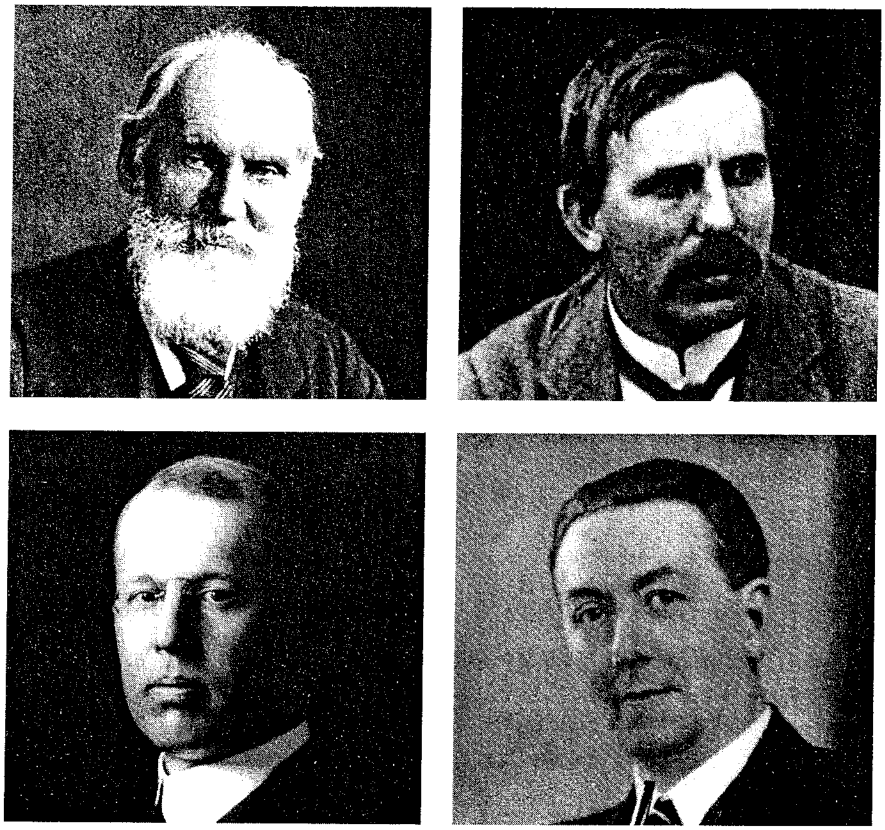
The reception was entirely different in 1903 when Pierre Curie and Albert Laborde announced that radium generates enough heat to melt more than its own weight in ice in an hour. Public interest was aroused over this apparently inexhaustible cornucopia of energy. Where did the energy come from? Rutherford and Howard T. Barnes discovered the source. They showed that the heat was proportional to the number of alpha particles radiated. These relatively massive particles were emitted at great velocity. If the particles collided with neighboring atoms, the particle's kinetic energy was transformed into heat.

Geologists immediately recognized that the relation between heat and radioactivity could significantly influence determinations of the age of the earth. Kelvin had assumed that the earth's heat came from either the sun or the original molten state of the earth. In both cases, gravitational contraction was the only source of energy. If the earth and sun contained quantities of radioactive materials sufficient to provide large amounts of heat, however, then this discovery could invalidate all chronologies that Kelvin had based on the earth's cooling.

In 1903 George Darwin and Joly were the first to make this very claim: radioactivity was at least partially responsible for the earth's and the sun's heat. But was there enough radioactive matter within the earth to make a measurable difference?

Part of the answer was at hand. Julius Elster and Hans F. Geitel, two schoolteachers in Wolfenbüttel, Germany, detected radioactivity in the air in 1901 and, soon after that, in the soil. Before long, many enthusiastic amateurs as well as professional scientists were finding radioactive rain, snow and groundwater—even radioactive mist at the base of Niagara Falls. Soon geologists had no doubt that radioactivity was widely distributed.

As for its concentration, Robert J. Strutt of the Imperial College in London found traces of radium in many rocks. Indeed, Strutt found too much radium for it to be distributed uniformly throughout the globe (without even considering the contribution from all the other radioelements). Its radioactivity alone could account for the earth's internal heat. His work



LORD KELVIN (*top left*) estimated that the earth could be a mere 20 million years old. Ernest Rutherford (*top right*) and Bertram B. Boltwood (*bottom left*) devised radioactive dating methods to determine that the earth formed more than a billion years ago. Arthur Holmes (*bottom right*) campaigned for the acceptance of these methods.

suggested that geochronology could be extended by an indefinite time. He found no vestige of a cooling, no prospect of an age.

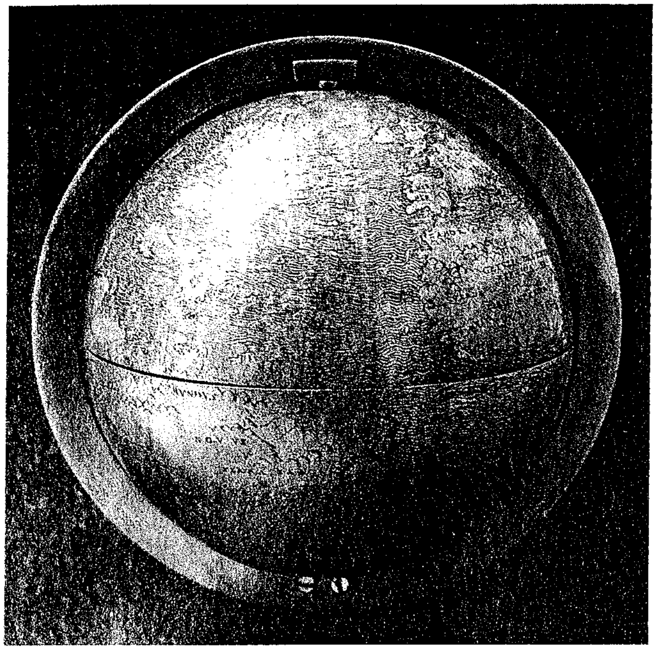
The scientific community responded with ambivalence. Joly and William J. Sollas of the University of Oxford worried that Strutt's work might overturn their own calculations demonstrating an age of about 100 million years. Kelvin's own feelings were divided: he privately acknowledged that his estimates had been superseded, but in public he remained contentious. Others were delighted to be liberated from Kelvin's earth age. It turned out that radioactivity not only loosened Kelvin's theoretical shackles but also held the key to determining the age of the earth.

During the first years of the century, scientific enthusiasm for radioelements replaced enthusiasm for radiation when Rutherford and Soddy proposed that radioactivity was actually spontaneous alchemy. A sample of a radioelement, they said, decays at a regular rate into a different chemical element. The rate of decay is expressed as a half-life: the time needed for half of the atoms of a given radioelement in a sample to change into a decay product.

Half-lives range from billions of years to millionths of a second. Uranium, thorium and radium have long half-lives and therefore exist in tangible quantities on earth, whereas those elements that have short half-lives have a transitory existence. Hence, the presence or absence of particular radioelements in rocks can imply an age; analysis of the quantities of the radioelements can reveal an absolute age.

The radioelements form distinct decay series: one radioelement decays into the next element in the series until a stable element is produced. The uranium-radium, uranium-actinium and thorium series were known or suspected in the early years of this century. The technique of radioactive dating of rocks developed from the study of radioelements and their decay series. Rutherford and the radiochemist Bertram B. Boltwood pioneered the work.

As a consulting chemist after his graduation from Yale University, Boltwood examined numerous ore samples, among them monazite, a miner-




CARTOGRAPHERS, who constructed the Hunt-Lenox Globe (*left*) in 1500, could only refer to the Bible to estimate the age of the earth. They would have miscalculated by a factor of more than 800,000. Astronauts, who photographed the earth from space (*right*), could rely on measurements of radioactive elements to date the earth's creation back 4.5 billion years.

al containing uranium and thorium. When the charismatic Rutherford lectured at Yale in 1904, Boltwood's curiosity about radioelements became a passion, and he began to document the relations among the elements in the decay series.

Later that year, Rutherford suggested a way to determine the age of the earth from measurements of helium in minerals. Rutherford then believed (and in 1908 proved) helium is not a product of any particular decay series but is formed in all the series when two electrons bond to an alpha particle. Sir William Ramsay and Soddy at University College in London had just discovered the rate at which radium produced helium. If the Ramsay-Soddy rate was accurate and no helium escaped from the mineral from the time of its formation—both great leaps of faith—the amount of helium would determine the age of the sample. Rutherford could boast an age of 40 million years for a fergusonite rock he owned.

Boltwood, on the other hand, thought to look for the end products of the decay series. The amount of an end product would increase over the years as the radioelements decayed. It was already known that radium was a product of the uranium series; in 1905 Boltwood pointed to lead as the final product. The uranium-to-lead hypothesis received additional support from Rutherford. He argued that if uranium decayed to radium and if radium (then thought to have an atomic weight of 225) and its daughter products then emitted five alpha particles (which each have an atomic weight of four), the decay would yield an element of an atomic weight of 205—not far from lead's accepted value of 206.9.

Boltwood credited Rutherford for suggesting the lead method of dating ancient rocks, but it was the chemist who demonstrated its feasibility. By the end of 1905 he had calculated ages ranging from 92 to 570 million years for 26 different mineral samples. Fortunately for the reputation of the new technique, these results remained unpublished. Boltwood's radium-to-uranium ratio was inaccurate both because Rutherford's scale for measuring quantities of radium was badly calibrated and because the half-life of radium was revised several times during 1905 and 1906. A rock's age rested critically on both these values.

When Boltwood published his work in 1907, he reported a striking constancy in the lead-to-uranium ratios for minerals from the same rock layer, which were presumably of the same geological age. He also observed that the amount of lead in a mineral increased as the relative age of the mineral increased. Minerals from which lead had apparently been leached gave lower ratios than did other minerals from the same layer. All this fit together well. Boltwood could find, however, no constancy in lead-to-thorium ratios from several minerals; the end product of thorium remained a mystery. He was inclined, therefore, to ignore lead-to-thorium ratios: an error that affected his measurements of minerals that contained both uranium and thorium.

To determine the absolute age of minerals, Boltwood examined the uranium-radium decay series. The latest value for the half-life of radium was 2,600 years, which Rutherford had deduced from the number of alpha particles emitted from radium each second. (The figure accepted today is 1,620 years.) Given that the decay of radioactive materials is exponential, the fraction of radium decaying in one year would be 270,000 parts per billion, based on Rutherford's half-life. Rutherford and Boltwood found that almost all rocks contained 380 parts of radium per billion parts of uranium. Thus, the fraction of radium decaying each year multiplied by the fraction of radium in uranium yields one part of radium decaying each year for every 10 billion parts of uranium.

Boltwood correctly assumed that the decay series of the rocks he collected were in an equilibrium state. The uranium-to-lead series, for instance, is in equilibrium when the number of uranium atoms decaying per unit of time is equal to the number of radium atoms decaying, or lead atoms forming, in that time. To maintain this equilibrium, radioelements that have long half-lives must exist in greater quantities than those that have short half-lives. (Although the supply of uranium will slowly decrease over time, Boltwood realized that the amount lost is negligible.)

Boltwood deduced that if one part of radium decays each year for every 10 billion parts of uranium, then one part of lead forms each year for every 10 billion parts of uranium. Boltwood expressed this relation in a formula: the age of the rock equals 10 billion years multiplied by the ratio of lead to uranium. He then calculated that a sample of uraninite, which had a ratio of .041, was 410 million years old and a sample of thorianite, which had a ratio of .22, had formed 2.2 billion years ago.

Actually, when the accurate value for the half-life of radium was applied, the age of Boltwood's samples was found to range from about 250 million to 1.3 billion years. Even with this correction, his thorianite measurement was invalid because the decay of thorium contributed some lead in addition to the lead that derived from uranium. Nonetheless, these results were spectacular: they demonstrated that the earth was about a billion years old.

Oddly, this enormous accomplishment was met with indifference. Although Boltwood's paper appeared in America's foremost geological journal, no one was inspired to duplicate or extend his work on the lead method. Nor did Boltwood's result sway geologists' opinion that the significance of radioactivity was overrated. They not only discounted the heating effect of radioactive decay on the earth but also "refined" their geological and physical data to show that Kelvin's range of time was correct after all!

Boltwood wrote no more on the lead dating method. He returned to the study of decay series and discovered ionium, the immediate parent of radium. Rutherford retained a light hold on the age-of-the-earth topic, publishing about one paper a decade—hardly the mark of a consuming interest. Meanwhile, Strutt refined the helium method until 1910, when he too departed for greener research pastures.

Strutt left a legacy, however. He had sparked an interest in geochronology in a young English geology student, Arthur Holmes, who kept the subject alive almost single-handedly. Indeed, Holmes ultimately forced geologists to accept radioactive dating in the course of his long career in industry and at the Universities of Durham and Edinburgh. Until 1930, however, Holmes and Joly were the only geologists who were skilled in the dating technique, and Joly, moreover, doubted its accuracy.

Holmes did not. He also considered the lead method to be more reliable than the helium technique. In 1911 he examined many rock samples and calculated that the most ancient was 1.6 billion years old. He maintained (with more faith than justification) that his samples had contained no lead when they were formed, that all the lead came from the decay of uranium and that external mechanisms had not removed or added any lead or uranium.

Two years later, however, his critics could crow in the light of two new advances. The first was the discovery of isotopes: atoms that have the same chemical properties but different atomic weights because the number of neutrons varies. Lead, for example, has a nucleus that contains 82 protons and can have an atomic weight from 195 to 214. The second advance was the discovery of the physical laws that specify the decay products of each radioelement. These laws indicated that the thorium series did after all end in a particular isotope of lead.

Although for many earth scientists these new discoveries made radioactive dating seem more difficult and unreliable, Holmes forged ahead, publishing in the years before and after World War I a steady stream of papers on geochronology. He incorporated information about isotopes into his work and sharpened his results. Although his success wore down overt resistance to radioactive dating, the method gained little support.

An exception was Joseph Barrell, a professor of geology at Yale, who in 1917 reinterpreted geological history to conform with the results of radioactive dating. Barrell emphasized that geological processes vary in intensity in a cyclical rather than a uniform fashion. Thus, current rates of geological change could not, as uniformitarians claim, be a guide to the past.

Finally, resistance began to falter. By 1921, at a meeting of the British Association for the Advancement of Science, the speakers, representing geologists, botanists, zoologists, mathematicians and physicists, seemed to agree that the earth was a few billion years old and that radioactive and geological dating techniques could be reconciled. But no plan was drafted for reconciliation. Not surprisingly, the old guard remained skeptical. Sollas would accept no age for the earth greater than 100 million years. "Geologists," he said, "are not greatly concerned over the period which physicists may concede to them; they do not much care whether it is long or—in moderation—short, but they do desire to make reasonably certain that it is one which they can safely trust before committing themselves to the reconstruction of their science, should that prove to be necessary."

The battle was won finally in 1926 when in the U.S. the National Research Council of the National Academy of Sciences appointed a committee to examine the status of the age-of-the-earth problem. Holmes, as one of the few experts on the subject, was a committee member and wrote almost 70 percent of the report. The committee agreed unanimously that radioactivity provided the only reliable geological time scale. The report presented an overwhelming amount of clear and detailed evidence. The constants of radioactivity were firmly established, lead isotopes were easily incorporated into the calculations, and the mineral samples were carefully chosen to ensure that decay products had not been lost over time. The radioactive dating methods pioneered by Rutherford and Boltwood and enhanced by Holmes had at last received the blessing of geologists. Not only had they found a vestige of a beginning, but they also had a prospect for dating all of geological history.

During the past six decades, application of the lead dating method has become more and more sophisticated, and current techniques reveal that the oldest rocks on the earth were formed as much as 3.8 billion years ago. This would date the minimum age of the earth's solid crust but not necessarily the period when the spiral cloud of gas and dust condensed to form the solar system. In 1955 Clair Patterson of the California Institute of Technology and his colleagues first determined the age of the solar system by dating meteorites. The most recent measurements of meteorites place the age of the primal earth at 4.5 billion years.

FURTHER READING

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