k9 The geologic column is transformed into a geologic time scale < Holmes, the ‘Father’ of geological timescales—AI >

> In Victorian times, geology had been a favourite among the sciences, but by the 1930s ... devotees grumbled about a press that no longer reported their activities. ... when I became an undergraduate in 1950 I discovered that three pillars of my first-year reading-list—Rutley’s *Elements of Mineralogy*, Watts’s *Geology for Beginners*, and Woods’s *Palaeontology*—were all written the previous century. —Gordon L. Herries Davies.[1] (but, not to worry, available succeeding editions had been much updated by additional authors. —HR)

Arthur Holmes was the major contributor to pioneering efforts to transform the geologic column (with relative time-stratigraphic divisions) into a geologic time scale (with absolute time divisions as later in Felix Gradstein, Jim Ogg and Alan Smith, 2004).[2] Inspired by Boltwood’s radiometric method, and at the age of twenty one, unfazed by the carpings of geochemists that the basic analyses were suspect, and in the year of 1911 that Horace Bolingbroke Woodward glumly ended his historical geology book with: “We may safely regard the period of geological time is vast, but the reckoning of geological ages into any exact number of years is beyond our ken,”[3] Holmes published: *The association of lead with uranium in rock-minerals, and its application to the measurement of geologic time*.[4] In retrospect, all that he later published that embellished upon the ideas in this paper and which established him as the most eminent geologist of his day, was fraught with clumsy methodology. Yet, his findings were never far off the mark. Lawrence Rickard (Bill) Wager (1904-1965) (of Skaergaard Intrusion fame) suggested that was so because “Holmes’s handling of the sketchy early data was done with great geological insight.”[5] More likely, it was his resolute use of a principle, long held by geologists and formerly stated in 1878 by Samuel Haughton (1821-1897), that “the proper relative measure of geological periods is the maximum thickness of strata formed during those periods.”[6] In other words, an incrementally cumulative function is monotonic increasing. The temptation is to use the average slope of a monotonic increasing curve of some quantity plotted against time as being close to the actual rate of some process when its only use can be as an upper or lower bound to constrain an hypothesis. Early estimates of Earth’s age fell into this trap of assuming that rates of geological processes hold over long durations. Holmes dubbed these “hour-glass” methods and unfortunately did not stamp out the purported image of its “constant flow” (an illusion at best, and also an hourglass cannot be read to know say minutes) when he had himself learned how misleading it could be.

Arthur Holmes (1890-1965) pioneered the use of radiometric dating to construct a geologic time-scale.[1]

For example, John Joly’s famous estimate in 1899 of Earth’s age from chemical analyses of river waters and seawater salinities (realizing Edmund Halley’s 1715 suggestion)[7] assumed: 1) no significant amount of salt originally in the ocean (which, to quote C. Gordon Winder: “made the method spurious” [8]), 2) that salt losses as salt deposits in sedimentary rocks have been negligible (but for long periods this is not so), and 3) the time required for ocean to reach its present salinity is knowable from the amount of salt added each year by all the rivers of the world (nonsense as geographies have changed). Calculation (***Footnote k9.1***) “points to a period of between 80 and 90 millions of years having elapsed since water condensed upon the Earth.”[9] Truth is, the ocean has changed little in volume and salinity (fluctuating to possibly twice as salty)[10] in the course of geologic time, and calculations as Joly’s address the residence time in seawater of ions such as Na^+.

Estimates based on hourglass rates of sedimentation had even less reasonableness. The time taken for the deposition of a stratigraphical sequence can only be known directly if the layers contain a running clock such as varves that record seasonal variations. Otherwise, the time taken for the deposition of a stratigraphical sequence must be estimated indirectly. Rates of weathering, to the degree of accuracy to which these can be measured, place an upper limit on continental denudation rates. From an area of supply, basins of sedimentation fill at a rate inversely proportional to their area. However, the size of areas of deposition at any time is proven to be essentially unknowable.

Given the extreme variability of the thickness of stratigraphically defined intervals, only the maximum known thickness of each system has the right bias for physically indicating the time represented. But, as John D. Hudson has pointed out "new sections are continually being discovered that exceed the previous known maxima." In his book *The Age of the Earth,* 1913,[11] Holmes reviewed various nineteenth-century attempts and settled on an estimate by William Johnson Sollas (1849-1936) of a rate of deposition of 1 foot per hundred years as a tolerable initial hourglass approximation. Sollas himself had seen no reason to change this rate for his calculation in 1883 of 26 million years for Earth's age even as the reported maximum thickness of sedimentary rocks increased from 164,000 feet in 1895, to 265,000 feet in 1900,[12] to 335,000 feet in 1909.[13]

What Homes demonstrated tentatively in 1913, and thereafter with increasing confidence, was that a simple correspondence can be sketched between the *thickness of sediments* of the geologic column measured down to any geologic age and the *time measured radiometrically* that has elapsed since the sediments began to accumulate.

Reasonably, as Joseph Barrell (1869-1919) in his instant classic, *Rhythms and the measurements of geologic time,* 1917, pointed out, most of the sedimentary record is missing and that to know the age of strata, radiometiric dates, newly becoming available, should be used.[14] Earlier estimates by Sollas of the length of geologic time using just sedimentary thickness were seen, in the light of radiometric dating, to be to short by an order of magnitude. Numerous diastems (year to decade long cessations in the deposition of a stratum that are too short to be evidenced by weathering of bed surfaces) must therefore add to lengthy unrecorded durations. The physical rate at which a succession of beds accumulates is not contingent on the rate at which any of its beds has.

The relationship between cumulative sedimentary thickness and time measured radiometrically is consistent with a radiometric decay rate that is either a constant (true—but not known to be so when Joly discussed it in 1909)[15] or is an increasing function with respect to time (false—as is now known). Holmes favored the first possibility and argued against the latter by using his graph (***Figure k9.1***) (curve A) to persuade (falsely, it is seen in retrospect) that in the earlier part of the stratigraphic column, rates of accumulation were slower (false) and since then have increased geometrically (false). Confirmation that he had (without good reason) chosen correctly had to await advances in isotope chemistry and mass spectrometry which also brought about a quiet revolution (1935-1950) in methods of geochronology.

In 1947, Alfred ("Al" to all who knew him) Otto Carl Nier's (1911-1994) newly designed mass spectrometer could distinguish between different lead isotopes.[16] Holmes had found that age determinations of old samples using hydrogen accumulation are unreliable. He therefore shifted his reliance to five radiometric dates calculated from U/Pb and Th/Pb isotopic data. Using these, he recalibrated the world-maximum thickness of Phanerozoic strata and interpolated between them to find the age of the geologic period boundaries. The distinctly logarithmic curve Holmes sketched (***Figure k9.2***) though the radiometric date points shows that to link maximum thickness of sediments and age, real measurements took precedence over an hourglass model.

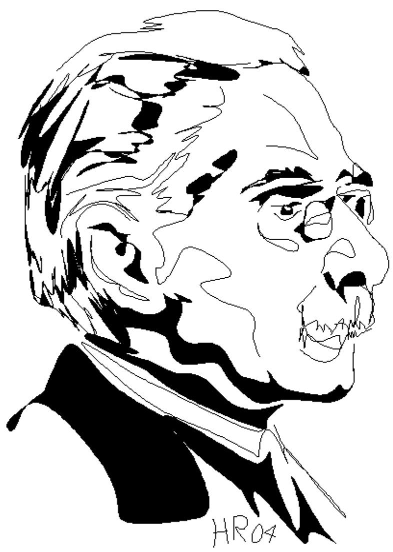
A new set of values for world-maximum sedimentary thickness published by Marshall Kay in 1955,[17] and a wealth of reliable radiometric data, prompted Holmes to publish a revised geologic time scale in 1959.[18]

A refinement (ongoing) is exampled by the geologic time scale constructed by John Laurence (Larry) Kulp (1921-2006) in 1961 in which the need to interpolate using sedimentary thickness is to be replaced by accurate radiometric dates obtained for numerous strata.[19] The resolving power of radiometric dating of Precambrian events has been not better than 20 to 30 million years for most methods used. However, refinements in the U/Pb zircon method (***Footnote k9.2***) now make routine a resolution of 1 million years for the Phanerozoic and 1 to 5 million years for the Precambrian.

To celebrate its founding in 1888, the Geological Society of America (GSA) in 1980 resolved to issue a multi-volume cyclopedia of North American geology. For use with this, the GSA in 1983 published a *Geologic Time Scale*.

Phanerozoic global chronostratigraphic boundaries are formally defined by a Global Standard Stratotype Section and Point (GSSP).[20] A GSSP interval of time is physically, and ideally, the global record of an event such as: a volcanic eruption, a fossil appearance or disappearance, a meteorite impact, a mass extinction, a magnetic reversal, an isotope excursion. A GSSP interval and its base, which must be a fixed point in a measured *and* accessible section, is called a "golden spike."[21]

Precambrian chronostratigraphic boundaries are formally defined in terms of absolute ages: Global Standard Stratigraphic Age (GSSA).[22] ❑



Footnote k9.1 **John Joly** (1857-1933) premised, "That the ocean began its history as a vast freshwater envelope of the Globe is a view which accords with the evidence for the primitive high temperature of the Earth. Geological history opened with the condensation of an atmosphere of immense extent, which, after long fluctuations between the states of steam and water, finally settled upon the surface, almost free of matter in solution: an ocean of distilled water."[23] But this thought is made moot by Earth's exceedingly greater age than Joly could imagine. For also, the nuclear source of Sun's prodigious energy output was unknown when Joly noted: "The duration in the past of Solar heat is necessarily bound up with the geological age. There is no known means (outside speculative science [read geology]) of accounting for more than about 30 million years of the existing solar temperature in the past. In this direction the age seems certainly limited to 100 million years. See a review of the question by Dr. [Frederick Alexander] Lindemann [1886-1957] in *Nature*, April 5th, 1915."

Footnote k9.2 **The Science of Zircon Dating < 1982 >**

Uranium has of its many isotopes two that are long-lived. These are ^{238}U (with a half-life of 4470 million years) and ^{235}U (with a half-life of 704 million years). As these occur together in any crystal that contains uranium, the change of their relative abundance and the accumulation of their different end-daughter products (^{206}Pb and ^{207}Pb, respectively) makes uranium particularly useful for precise dating of ancient rocks. The mineral of choice that contains uranium is zircon. In acidic igneous rocks, zircon crystallizes early from magma as it solidifies in the continental crust. The zircons occur in the rock as hard, inert, accessory mineral grains that look like tiny diamonds under a microscope. As zircons crystalize from the magma, they take in uranium from the melt but exclude any lead present in the melt. Each newly formed zircon thus has uranium sealed in and any lead originally present in the cooling magma, is sealed out to become part of the surrounding rock. However, lead is found in old zircons. The best explanation for its presence, as B. B. Boltwood in 1905 originally explained, is that as the uranium (which is radioactive) in the crystal decays to lead (which is not radioactive) that stays trapped in the place where it came to be.[24] Diffusion of the lead out of, or into, the crystal structure of the zircon does not occur. This bottling in of original uranium and, later, the daughter product of its decay, which is lead, allows for precise dating. In the whole rock, outside the zircons, uranium is easily oxidized and dissolved out at the conditions of temperature and pressure near Earth's surface. So U-Pb ages on whole rocks are usually unreliable.

In laboratory preparations for dating zircons, the crystals are separated from a few kilograms of crushed rock using magnetic fields and dense organic liquids that float off most of the other minerals. In practice, the outer part of zircons are often found to have suffered crystal-structure damage and so leakage of uranium and lead over time. Fortunately, geochronologists can easily identify results from leaky zircons because the ages given by their two U-Pb decay systems do not agree. The first challenge is to isolate undamaged zircon crystals or parts of crystals. The solution, introduced by Tom Krogh in 1982 is to microscopically identify and select zircons with no visible damage, and then abrade off the outsides of the grains in a small compressed air chamber.[25] This, revolutionized the field of U/Pb geochronology as it enabled geochronologists for the first time to work routinely with undamaged zircon. The Jack Satterly Geochronology Laboratory of the Royal Ontario Museum (now relocated to the Department of Geology, University of Toronto),[26] wrote:

> ... zircons in Precambrian rocks [are mostly] too altered to be dated with accuracy. It is necessary to recognize and extract the tiniest unaltered portion, the part that retains an accurate memory of the age. A second challenge is to analyze these tiny grains without contaminating the sample. The lead in a single zircon may amount to only a few millionths of a microgram, so analyses must be done under ultra-clean conditions.
>
> Because the ROM lab has always had the lowest contamination levels in the world—less than half a picogram of lead (one picogram is a millionth of a millionth of a gram)—we have been able to date samples that could not be effectively worked on anywhere else.
>
> These methods give us very accurate ages (to within 1 million years) on Precambrian rocks.

Figure k9.1 Holmes's plot in 1913 of radiometric ages against maximum thickness of sediments[27]

For Cenozoic time, Holmes used Strutt's helium-method to obtained data which indicated that the Eocene began 30 million years ago. For the Paleozoic, he plotted U-Pb dates for: a uraninite occurring in the pre-Triassic post-Early Carboniferous Portland granite, Connecticut, that Boltwood had dated at 340 million years old; the age (believed to be Devonian) of the igneous activity of Oslo igneous rocks for which he obtained in 1911 a weighted average of 370 million years old; and, a uraninite occurring in the probably Ordovician, Brancheville granite, Connecticut, that Boltwood had dated at 430 million years old. The two Precambrian ages were data from Boltwood. The base of the sediments was the maximum thickness known in 1909 to which Sollas had applied his rate of deposit of 1 foot per hundred years.[11] The right-hand part of the figure would exist if Precambrian rates of sedimentation were the same as those for Phanerozoic time established by the radiometric dates for the Carboniferous, Devonian, and Ordovician.

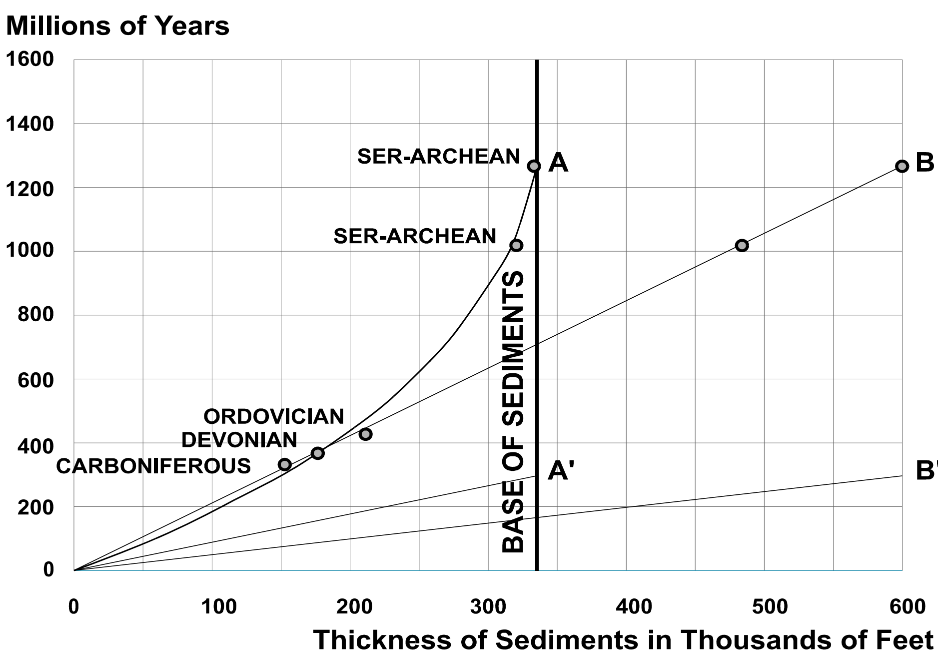


Figure k9.2 [28] Holmes plot in 1947 [29] of five U-Pb ages (three shown as double points)

At the time, Holmes had little reason to doubt the accuracy of the U-Pb ages he calculated [30] using his hour-glass formula, Pb/U • 8200 x 10^6, but the stratigraphic position of the three youngest were each in some doubt. For this reason he plotted an upper curve through points placed at what was then thought to be their youngest stratigraphic positions, and a lower curve through points placed at what was then thought to be their oldest stratigraphic positions. The stratigraphic position of the oldest U-Pb age, which was for kolm (organically rich material that occurs as pods in black shale of Bi Uingen region, southern Sweden) was not in doubt because of the presence of the Late Cambrian trilobite *Peltura scarabaeoides*. Holmes recommended the use of the lower curve for interpolation to obtain the period boundary ages. His results were the basis for the standard geologic time scale used by geologists for the next ten years. Interestingly, the U-Pb ages Holmes had relied on were later found to be individually poorly constrained and using data from David Raup, Bernhard Kummel illustrated in his textbook *History of the Earth*, 1961, how these should have been plotted, not as points, but as areas (pale gray in the half-scale inset). However, collectively the five points constrain the median age curve (dashed line) very well and indeed little change to the ages of the geological period boundaries was required as new radiometric data accumulated. The superposition of the median age curve on Holmes's plot, in retrospect, recommends the upper curve (dashed line).

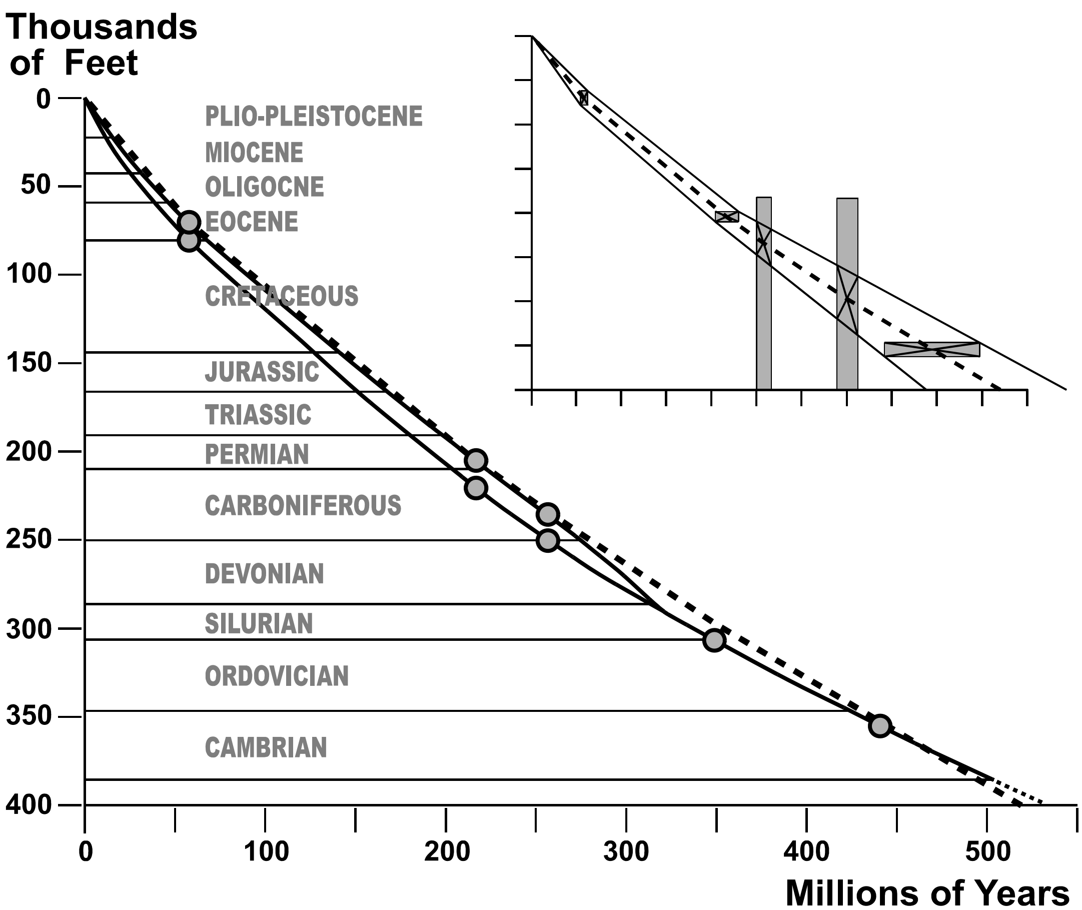


Figure k9.3 [31] J. Laurence Kulp's 1961 radiometric data for Late Paleozoic time. The vertical lines show the possible ranges of the specimens in the stratigraphical column of maximum thicknesses of sediments. Estimated errors in the ages are given in millions of years. As a first approximation straight lines are drawn between the estimated best positions of the radiometric ages to interpolate to the age of period and epoch boundaries. (cont.)