The ChronoZoom Time Atlas of Earth History and Big History

by

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Introduction to *The ChronoZoom Time Atlas of Earth History and Big History*

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"History" is commonly thought of as the written record of human activities, but in the last few decades, *scientific* historians have discovered an enormous amount of information about the past, before the appearance of writing. Geologists and paleontologists have been very successful in documenting Earth and life history in great detail, and much information is now available also from archaeology, molecular biology, astronomy, and cosmology. "Big History" is the currently active effort to bring together in a unified way all of the information about the past, both humanistic and scientific.

Founded by David Christian[1] and Fred Spier,[2] Big History aims to break out of the specialization characteristic of most historical writing and see the past as a unified field of study. It is now taught at a number of high schools, colleges and universities, and has a growing literature, an International Big History Association, and a *Journal of Big History*. The Big History Project of David Christian and Bill Gates is developing Big History as the centerpiece for 9th-grade education, to take advantage of the intense excitement this approach to history brings to students, which all who have taught it have observed. Among the present authors, Walter and David definitely observed this excitement while teaching Big History at Berkeley.

One of the problems for anyone teaching Earth history or Big History is how to get the students to comprehend the time scales. Students soon come to understand that Earth history, back to about 5,000 million years ago, is about a million times longer than written human history, going back to about 5,000 years ago, so that the basic time unit for geologists is "million-years." But it is much more difficult for them to wrap their minds around the *concept* of a million years, or 5,000 million years. In fact, it is probably impossible for *anyone* to do thisl, given our lifetimes of not much more than a century. Diagrams do not help much, for on a linear diagram, human history is invisibly brief, while a logarithmic scale, although expanding human history, distorts the time scale so much as to make it completely misleading.

After a discussion of this problem in the Berkeley Big History class in 2009, Roland, then one of the students, suggested portraying deep time using computer-zoom technology. His initial proof of concept, presented to the class, was so successful that he began working with Walter and David, leading the effort to develop what came to be called ChronoZoom. Microsoft got interested in the project, supporting the Berkeley design team and developing the code. A first version, ChronoZoom-1, was developed by Microsoft Live Labs, and a second version, ChronoZoom-2, by Microsoft Research, with Roland leading the design work. This third version, ChronoZoom-3, uses panels drawn by Walter, and was tested in a course in History and Evolution of Planet Earth (EPS 102) taught by Mark, with Alexis and Roland responsible for much of the design and coding.

ChronoZoom-1, prepared quickly for a public lecture,[3] simply included graphic information relevant to the lecture. The second version had a different goal — it was intended to be crowd sourced like Wikipedia, to be populated with information by anyone who wanted to participate, and is available on-line for interested users.[4] The current version, ChronoZoom-3, is designed to be a teaching and reference tool, so the graphical information has been selected to convey a clear picture of major features of Earth history and Big History.

The first two versions of ChronoZoom were designed for continuous zooming; this new one is based on about a dozen graphical Panels, each of which can be examined individually, but which can also be thought of as a zoomable sequence. Having the zoom segmented by the panels helps the user avoid getting lost in what seems a wilderness of time. The panels cover intervals of time that differ by about a factor of ten, but rather than rigid, order-of-magnitude separations, each panel begins at a significant date in history. Since many significant dates in Big History begin approximately with the number "5," this is taken as roughly the beginning the date for the start of each panel. The main exception is the Cosmos panel, beginning at the Big Bang, 13.8 billion years ago.

The plan for the panels is shown on the right of the next page, as a graphical index. It is drawn on a logarithmic scale, for only in that way can all the panels be shown. However, all but one of the panels are presented on linear time scales, which is the whole point of ChronoZoom — to give an undistorted graphical representation of the past. The only exception to the linear panels is Panel 0, which portrays the Big Bang, and in fact, all of Big History. The Big Bang covers time back to 10^{-43} seconds after "the beginning," and to show that many orders of magnitude on linear panels would require a very large number of mostly-empty drawings; a log plot is the only reasonable solution. Conveniently, after the Cosmos panel, there are three panels that show Earth and life history, three more covering pre-literate human history, and then three more since the invention of writing. For the last three panels, covering literate human history, only some background information about human population and natural disasters is shown. Human history is too complicated and detailed to be portrayed here, so users may wish to print out the panels and draw in the history that interests them.

Finally, there is a coda of two more panels, not showing much of historical interest, but included in order to take the zoom all the way down to one day, again for personal use. From one day to the entire duration of the Universe is a zoom factor of 5 trillion. The last two text pages are devoted to a kind of summary, first discussing the origin of the dating that lies behind the historical synthesis presented in ChronoZoom, and then considering the nature of history, and how its character might be understood.

Each panel is accompanied by a page of text, discussing the historical features shown in the panel. The layout of this version of ChronoZoom was inspired by the historical atlases of Colin McEvedy,[5] and following his design, may be best viewed on a computer and external monitor, placed side by side. The full PDF of the ChronoZoom Time Atlas can also be printed out in book form.

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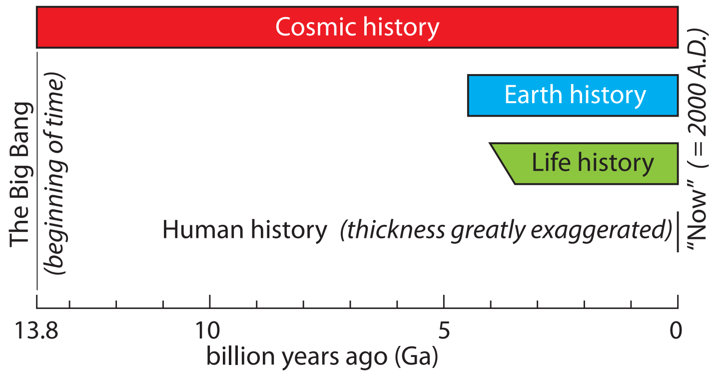
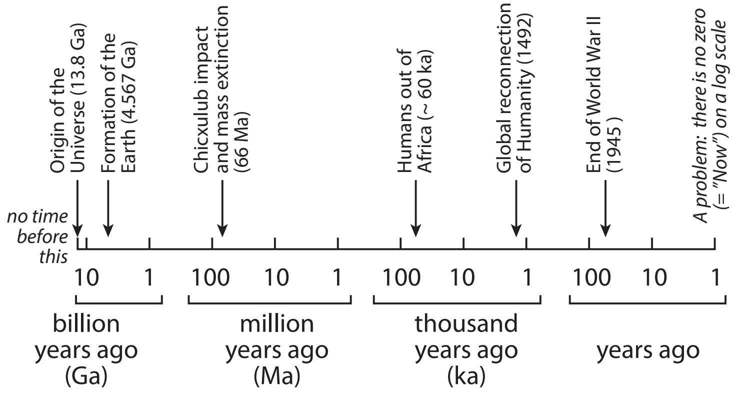
All history on a linear scale



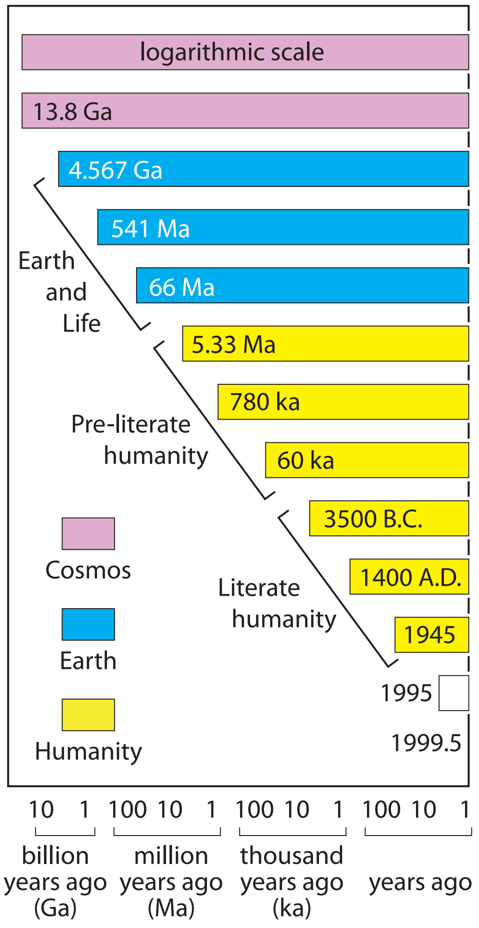
On a linear scale, human history, whether written history or genus Homo, *is reduced to invisibility, and most of the space is taken up by pre-Earth Cosmic history, for which little information is availble.*

All history on a logarithmic scale



A logarithmic scale is badly distorted (it looks like all Cosmic history before Earth formed was briefer than from Columbus to World War II), and there can be no zero on the horizontal scale.

ChronoZoom Graphical Index *(logarithmic)*



Panels

0 All Big Bang- and Big History (Log plot)
1 Cosmos (13.8 Ga to now)
2 Earth and Life (4.567 Ga to now)
3 Phanerozoic – Abundant fossils (541 Ma to now)
4 Cenozoic – Age of mammals (66 Ma to now)
5 Plio-Pleisto – Rise of humanity (5.33 Ma to now)
6 Brunhes normal and Ice age (780 ka to now)
7 Out of Africa (60 ka to now)
8 Civilization and writing (3500 B.C. to now)
9 Global reconnection (1400 A.D. to now)
10 Post World War II (1945 to now)
11 Sunset of the Millenium (1995 to now)
12 Millennium's end (1999.5 to now)

A.D. = C.E.
B.C. = B.C.E.

Neither a linear scale nor a logarithmic scale is satisfactory for portraying all of history. The solution adopted in ChronoZoom is to use 12 linear time lines, each covering about 10% of the previous one, as shown in this index. A problem is that details are available only for recent times.

Panel 0: Big-Bang and Cosmos, on a logarithmic time scale (13.8 Ga to now)

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This panel shows the very early history of the Universe. But to do this, it is necessary to depart from the basic ChronoZoom approach, which is to show panels with linear time scales. The problem is that the unfolding of the Big Bang has been calculated all the way back to the Planck time, 10^{-43} seconds after "the Beginning" **(A)**. To show the Big Bang with linear ChronoZoom drawings would require 46 panels **(B)**, and 60 panels to get to the first stars **(C)**. So the only practical way to portray early-Universe history is on a logarithmic time scale. But since it is only about 2 more factors of ten in time from the first stars to the present day, this drawing can show the entire history of the Universe, from the "Beginning" to now. This problem and its solution point out a fundamental paradox in Big History: On a linear time scale, the Big Bang (the first 3 minutes) is a trivial fraction of Cosmic history, but on a log scale, the Big Bang, with 45 orders of magnitude, is *most* of Cosmic history!

Until the 1960s, the Big Bang theory for the origin of the Universe was controversial, and in competition with the Steady-State theory. Both were explanations for the expansion of the array of galaxies in the Universe, discovered in 1929 by Edwin Hubble and Milton Humason.[1] In the Big Bang theory, the Universe began with a "singularity," an infinitesimally tiny point, at a particular instant in the past, in which all space and energy were created, with space expanding ever since. In contrast, the Steady-State theory saw an expanding Universe, perhaps of infinite age, that has always looked about the same, with new stars being continually created to fill the space generated by expansion. Today the latter theory is a historical curiosity, with the Big Bang almost universally accepted among astronomers and cosmologists. This acceptance is based on three overwhelming pieces of evidence:

(1) The Universe is expanding, with galaxies or galaxy clusters moving apart **(D)**, with the rate of separation greater for more distant objects. This of course fits both the Big Bang and Steady-State theories, which were each designed to explain it. However the other two lines of evidence unambiguously support the Big Bang theory.

(2) The Cosmos is pervaded by the cosmic microwave background (CMB) radiation **(E)**, an intense flash of light that was released when electrons combined with atomic nuclei to form the first atoms, rendering the Cosmos transparent for the first time, just as the Big Bang theory predicts. The CMB, now stretched into radio waves by cosmic expansion, was discovered in 1964, and has since been mapped in increasingly exquisite detail by the COBE, WMAP, and Planck satellites.

(3) Theory predicts that shortly after the end of the Big Bang, matter would be mostly hydrogen, with about 10% helium, and traces of lithium (the three lightest elements), formed by nucleosynthesis **(F)** before expansion carried the protons too far apart to fuse together. That is indeed the observed composition of the Cosmos (ignoring elements created later within stars — *see* "Metallicity" in Panel 1).

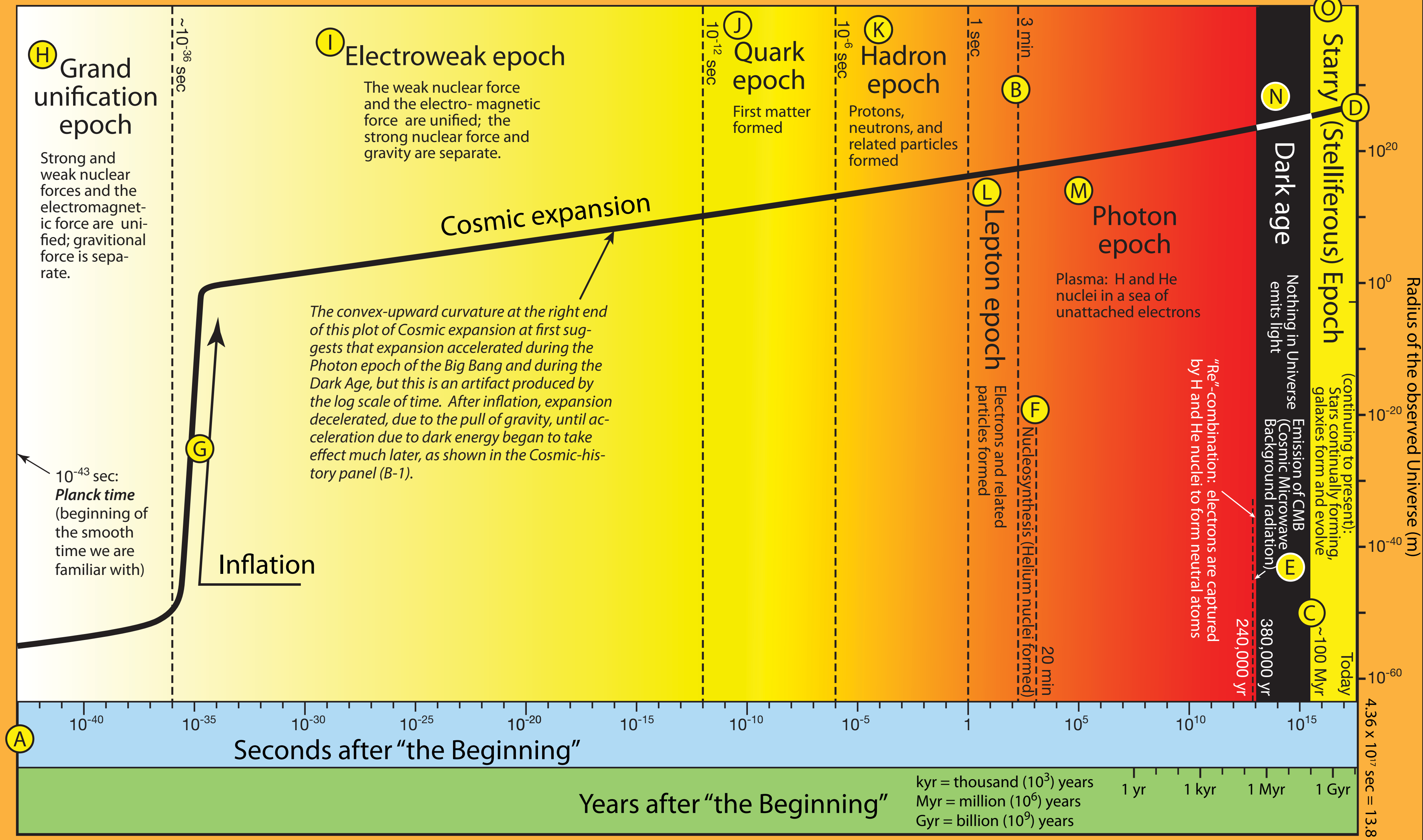
In contrast to the Steady-State version, the now-accepted Big Bang theory shows that the Universe is a historical object, with a definite beginning now dated at about 13.8 billion years.[2] The universe has had a particular history, which astronomers and cosmologists are now working out. The character of the universe was set up during the 3-minute history of the Big Bang, portrayed in this panel, and the working out of the consequences over 13.8 billion years of history is shown in Panel 1.

The expansion of the Cosmos has not been regular. Not only is the rate of expansion now accelerating **(D)**, but the Cosmos is thought to have undergone an episode of extremely rapid expansion early in the Big Bang, called cosmic inflation **(G)**.[3] The inflationary episode was extremely brief, from about 10^{-36} to 10^{-33} seconds after the beginning, but would have expanded the dimensions of the Cosmos by maybe 50 orders of magnitude.[4] Proposed in 1981 by Alan Guth,[5] the cause of inflation remains controversial, but it explains a number of unexpected features of the Cosmos, notably the question why an initially homogeneous Big Bang could produce a Universe with matter clumped into galaxies and clusters of galaxies; inflation would have magnified initial quantum fluctuations into the clumping we see today.

As the initially tiny Universe cooled, it went from conditions too hot for any matter to exist, into cooler (relatively speaking!) conditions in which different kinds of matter successively appeared. Cosmologists divide the sequence of conditions into six "epochs" — an amusing word, since the first three lasted only tiny fractions of a second! During the first two epochs energy existed, but no matter, and the four forces (gravity, electromagnetism, and the strong and weak nuclear forces) were in part combined. The initial Grand unification epoch **(H)** saw only gravity distinct from the other three combined forces, and in the subsequent Electroweak epoch **(I)**, the strong nuclear force also separated and became distinct. Inflation occurred during this epoch.

The era of matter[6] began with the Quark epoch **(J)**, with quarks being the particles that combine in threes to make protons, neutrons, and the related heavy particles. By a microsecond after the singularity that initiated the Big Bang, the Universe had cooled to the point where free quarks could combine, starting the Hadron epoch **(K)**. Electrons and related particles appeared at one second post-singularity, the start of the Lepton epoch **(L)**. The beginning of the Photon epoch **(M)** at 3 minutes is commonly taken as the end of the Big Bang proper.[7] This was also the time when some protons (hydrogen nuclei) combined to form the 10% helium which provides evidence supporting the Big Bang theory. During the Photon epoch, electrons could not yet attach to atomic nuclei (H and He), so the Universe was full of plasma — charged particles that scatter photons. When the Universe cooled to the point where electrons and nuclei could combine ("*Re*-combination" is confusing jargon), the scattering of light stopped, the Universe became transparent, and the CMB was released — the other observation that supports the Big Bang theory. The subsequent Dark Age **(N)** and Stelliferous (Starry) Epochs **(O)** are considered in the Cosmos panel (Panel 1).

PANEL 0: BIG BANG AND COSMOS, on a logarithmic time scale



Grand unification epoch

Strong and weak nuclear forces and the electromagnetic force are unified; gravitational force is separate.

10^{-43} sec: ***Planck time*** (beginning of the smooth time we are familiar with)

Electroweak epoch

The weak nuclear force and the electro- magnetic force are unified; the strong nuclear force and gravity are separate.

The convex-upward curvature at the right end of this plot of Cosmic expansion at first suggests that expansion accelerated during the Photon epoch of the Big Bang and during the Dark Age, but this is an artifact produced by the log scale of time. After inflation, expansion decelerated, due to the pull of gravity, until acceleration due to dark energy began to take effect much later, as shown in the Cosmic-history panel (B-1).

Quark epoch

First matter formed

Hadron epoch

Protons, neutrons, and related particles formed

Lepton epoch

Electrons and related particles formed

Nucleosynthesis (Helium nuclei formed)

Photon epoch

Plasma: H and He nuclei in a sea of unattached electrons

"Re"-combination: electrons are captured by H and He nuclei to form neutral atoms

Dark age

Nothing in Universe emits light

Emission of CMB (Cosmic Microwave Background radiation)

Starry (Stelliferous) Epoch

(continuing to present): Stars continually forming, galaxies form and evolve

kyr = thousand (10^3) years
Myr = million (10^6) years
Gyr = billion (10^9) years

A fundamental paradox:

- On a linear time scale, the Big Bang, to the end of the Lepton epoch (3 minutes), is a trivial fraction of Cosmic history.
- On a log time scale like this, the Big Bang, with 45 orders of magnitude, is *most* of Cosmic history!

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Panel 1: Cosmos (13.8 Ga to now)

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This panel portrays the entire history of the Universe, spread out on a linear plot. Astronomers and cosmologists have come to an interest in the history of their subject more recently than other historians and historical scientists,[1] and the relevant literature reflects this preliminary character. Unlike other Big Historians, astronomers can actually *see* the past, by looking at galaxies so far away that the light they see has taken billion of years to get to us. Of course very distant galaxies look tiny, and cannot be imaged in detail. The traditions of astronomy are not geared to historical understanding: In the first place, ages of distant objects are not usually given in years, but as red shift — how much the light waves have stretched, due to cosmic expansion — this is understandable, because red shift can be measured directly, but age must be calculated based on imperfectly known parameters **(A)**. Second, distances are commonly given in parsecs, which may be converted to light years, which are of more interest to Big Historians (1 pc = 3.26 l.y.).

Perhaps the most fundamental, essential feature of all of Big History is that the Universe, colossal to a degree that utterly defies comprehension, has been expanding since the beginning of time, with the space between galaxies or between galaxy clusters gradually stretching. Tracing that expansion backward brings us to the Big Bang — the sudden appearance of everything, 13.8 billion years ago — which is treated in logarithmic Panel 0 **(B)**. Cosmic expansion has not been steady — it surged during the period of inflation, early in the unfolding of the Big Bang.[2] More recently, rather than slowing because of gravitational attraction, as cosmologists had expected, expansion is *accelerating*, due to the mysterious phenomenon of dark energy. The evidence for accelerating expansion and dark energy is plotted here **(C)**.[3]

Immediately after the Big Bang, the normal matter in the Universe (excluding dark matter) was essentially all hydrogen and helium. The heavier elements (which astronomers call “metals”) were generated in stars by nuclear fusion and spread throughout the galaxies by supernovas — by the explosions of stars that have used up most of the hydrogen fuel that powers them as it fuses to form helium. As a result, the metallicity of the universe — the content of elements heavier than helium — has gradually increased through time **(D)**.[4] (The graphs used here are not recent, but are unusual examples of Cosmic-history plots from the astronomical literature.)

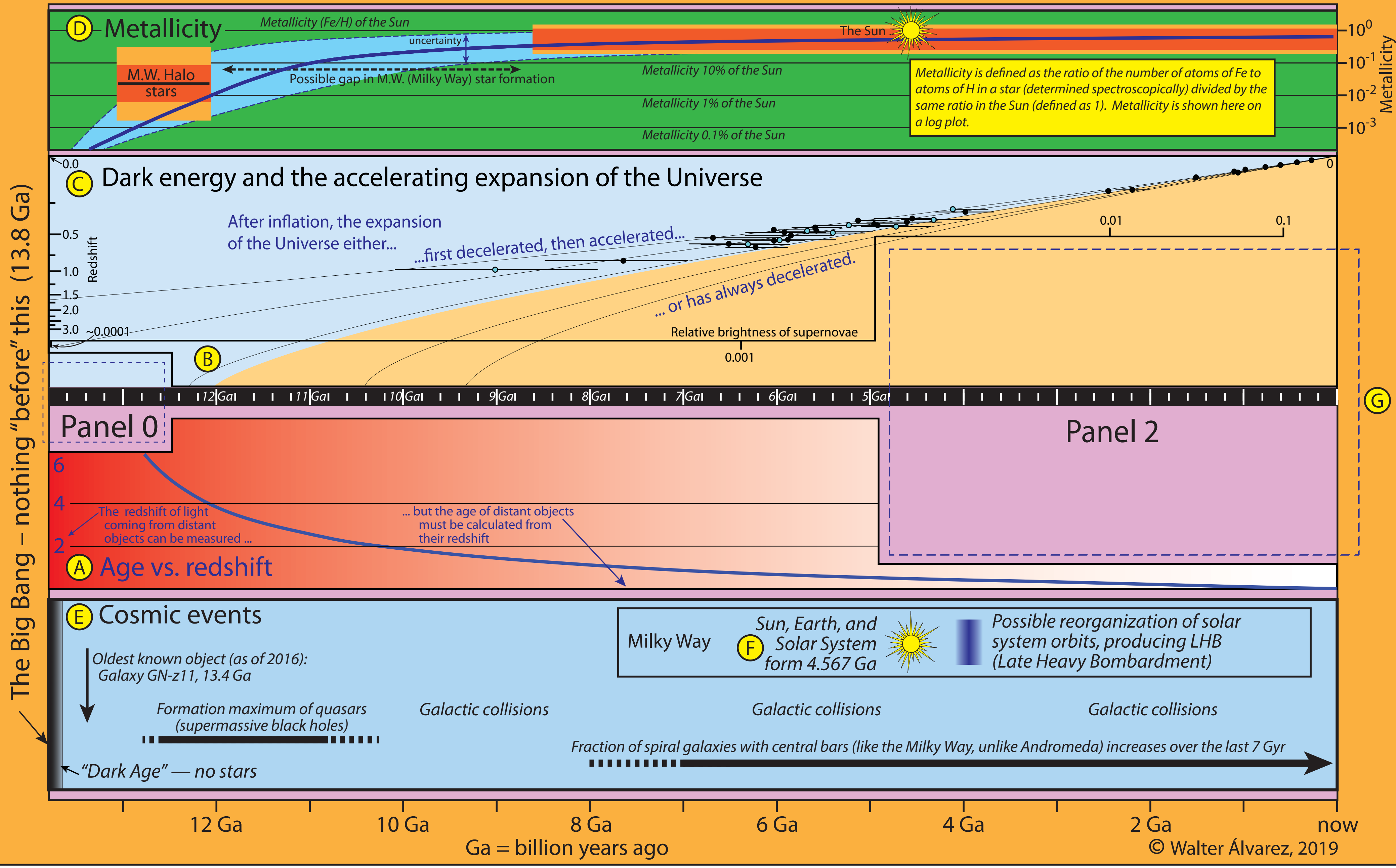
The metallicity of a star, detected by its spectroscopic absorption lines, is given by the ratio of the number of iron atoms to hydrogen atoms, divided by the same ratio in the Sun, whose Fe/H ratio is defined as 1; metallicity is shown here on a log plot. The history of metallicity is not easy to determine, and is probably different in different parts of different galaxies; these problems are reflected in the wide range of uncertainty in this plot. Hints of the historical evolution that probably underlies each galaxy are seen in the fact that stars in the darker halo of the Milky Way are older (of lower metallicity) than those, like the Sun, that lie in the thin bright disk.[5] There are also hints that there may have been a gap in time between formation of these two stellar populations.[6]

Astronomers have two ways of learning about the past — they can look at very distant galaxies, seeing them as they were when the light was emitted, billions of years ago, or they can look for very old stars in the Milky Way and nearby galaxies. The first method yields discoveries about Cosmic events **(E)** back to nearly the beginning of the Stelliferous (Starry) epoch. At the distances for which objects are far enough away to be seen as they were early in Cosmic history, individual stars cannot be resolved, and galaxies are the objects of study. Vast numbers of early galaxies are seen in the Hubble Deep Field (HDF), Hubble Ultra-Deep Field (HUDF), and Hubble Extreme Deep Field (XDF) images,[7] and can be treated statistically. As of 2016, the oldest known galaxy (i.e., with the greatest red shift) is GN-z11, dating from 13.4 Ga, or just 400 Myr after the Big Bang.

In these deep images, there are galaxies of a whole range of ages (as suggested by their size and brightness, and measured by their red shift), so it is possible to recognize a general pattern of galactic evolution. Events that may occur in the history of a galaxy include the formation of a central black hole, or of the kind of supermassive black holes that power the enormously energetic quasars, whose rate of formation peaked about 11-13 Ga;[8] collisions between galaxies, in which gravitational disruption as one galaxy passes through another turns the spirals into a structureless elliptical galaxy;[9] and the progressive conversion of spiral galaxies like our neighbor Andromeda, into barred spirals like the Milky Way.[10] We can expect a great enriching of this picture of Cosmic history over the next few decades.

Returning to historical events about which we know a great deal, the origin of the Sun, the Earth, and the Solar System occurred about 1/3 of the way back through Cosmic history **(F)**. (In fact the easily-remembered age of the Earth, 4.567 Ga is *exactly* 1/3 of 13.7 Ga, which was the best age value for the Cosmos until the recent adjustment to 13.8 Ga. (Too bad!) By the time Earth formed, there had been enough time for “metals” to become abundant through stellar nucleosynthesis, and enough supernovas to spread them around, so that our planet could contain all the chemical elements that make it interesting and suitable for life. Much older stars could not have rocky planets like Earth. The next panel shows the history of the Earth, **(G)** about which a very great deal more is known.

PANEL 1: COSMOS (13.8 Ga to now)



Metallicity is defined as the ratio of the number of atoms of Fe to atoms of H in a star (determined spectroscopically) divided by the same ratio in the Sun (defined as 1). Metallicity is shown here on a log plot.

After inflation, the expansion of the Universe either...

...first decelerated, then accelerated...

... or has always decelerated.

The redshift of light coming from distant objects can be measured ...

... but the age of distant objects must be calculated from their redshift

Oldest known object (as of 2016): Galaxy GN-z11, 13.4 Ga

Formation maximum of quasars (supermassive black holes)

Galactic collisions

Galactic collisions

Galactic collisions

Sun, Earth, and Solar System form 4.567 Ga

Possible reorganization of solar system orbits, producing LHB (Late Heavy Bombardment)

Fraction of spiral galaxies with central bars (like the Milky Way, unlike Andromeda) increases over the last 7 Gyr

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Panel 2: Earth and Life (4,567 Ma to now)

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The broadest, most schematic view of the 4.5-billion-year history of the Earth **(A)** would recognize an initial billion years in which Earth was physically and chemically very active because of heat from impacts and radioactivity; then a long, quiet middle age; and finally a time of great biological complexity during the most recent billion years. The Eons of the geological time scale[1] **(B)** roughly correspond to these intervals. Prior to the 20th century, when radiometric dating gave us abundant ages in years, rocks could only be placed in chronological sequence on the basis of fossils, and all rocks older than the Cambrian—the first period of the Phanerozoic (which has abundant fossils; the name means "visible life")—could only be called "Precambrian." The fact that that obsolete name has been replaced by Hadean, Archean, and Proterozoic reflects a great 20th century advance in dating and understanding Earth History.[2]

Perhaps the central question of Earth history is this: "The birth of Earth was violent and hot. How did such an angry young planet grow and differentiate into the seemingly well-adjusted, mature planet we know today?"[3] A remarkable feature of the growth and differentiation of the Earth **(C)** is how rapidly it was assembled, by innumerable small, impacting objects that we call planetesimals. But one of those objects was huge, about the size of Mars, and its collision knocked off a substantial fraction of Earth, some of which pulled together to form the Moon.[4] The Moon has been gradually receding ever since, because of tidal friction, and it acts as a stabilizer for Earth's rotation, preventing wild fluctuations in seasonality and making this a very hospitable place for life.

The big-four elements delivered to Earth by impacting planetesimals were magnesium, silicon, iron, and oxygen (Mg, Si, Fe, O). The large excess of iron accumulated, along with considerable nickel, to make the Earth's liquid-metal core. This happened rapidly when Earth was still molten, because of the high density of iron. Beginning at an uncertain time[5] the core has been gradually freezing, forming a slowly-growing, solid-iron core. Mg, Si, O, and left-over Fe went into forming the silicate minerals of the mantle, for example olivine (Mg_2SiO_4).

The mantle loses heat by slowly convecting, driving plate-tectonic motions of the crust. Plates, better thought of as caps on the spherical Earth, do not deform internally very much, but move around relative to other plates along three kinds of plate boundaries, where major deformation is concentrated. At spreading boundaries, new oceanic crust is formed, as plates move apart; at consuming margins, old oceanic crust is subducted, sinking down into the mantle; at transform boundaries like California's San Andreas fault, two plates slide past each other.

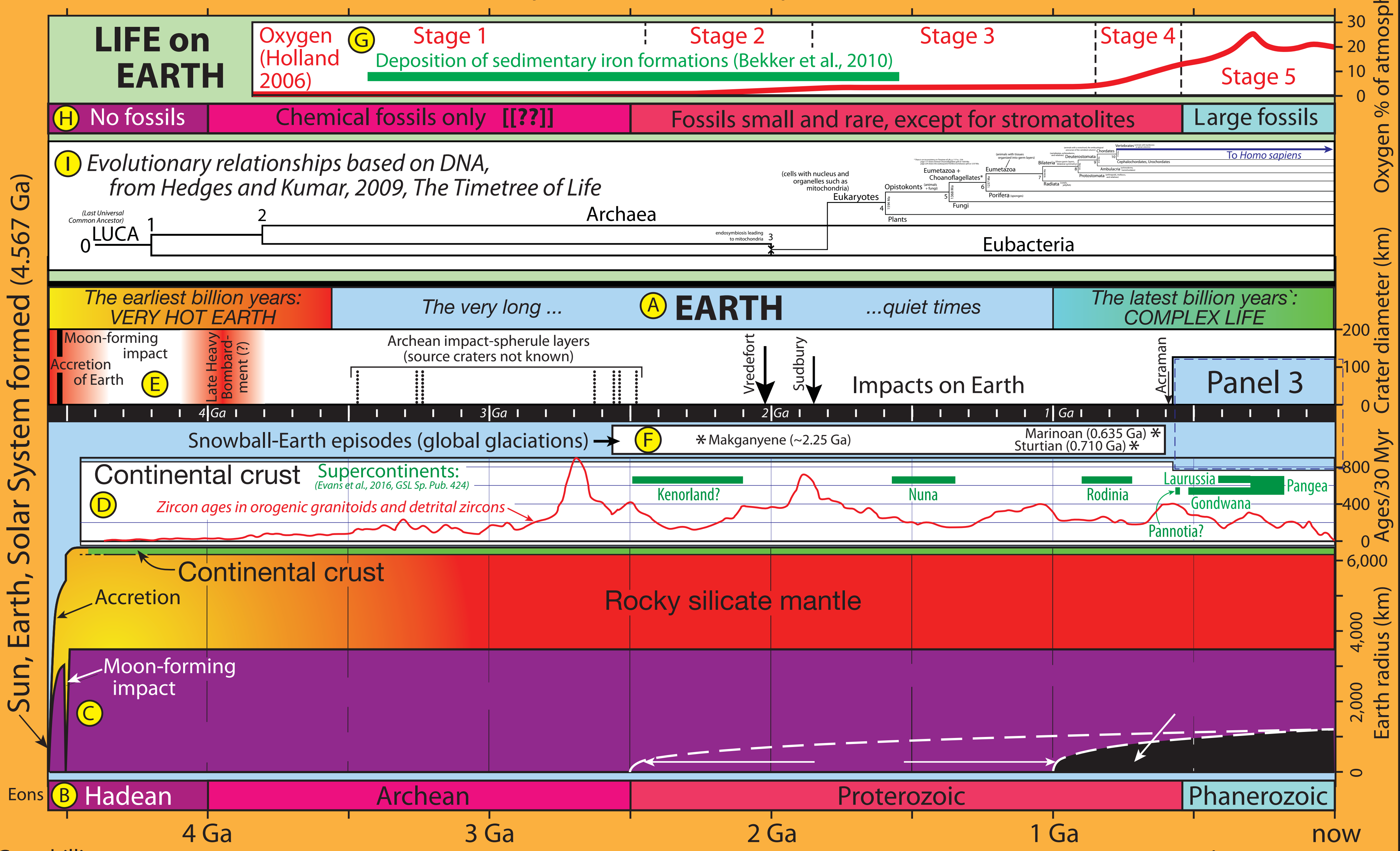
There is currently no agreement when plate tectonics began.[6] Continental crust, about 35 km thick, floats on the top of the mantle, with the continents changing configuration as they ride around on tectonic plates, separated by the growing and shrinking oceans that are floored by oceanic crust. At times, most of the continental crust has been assembled into a supercontinent;[7] at other times there have been several smaller continental fragments, as there are today **(D)**. Radiometric ages on the uranium-bearing mineral zircon, originating in the granitic rocks of the continents,[8] suggest that there have been pulses in the growth of continental crust.[9]

Impacts, frequent in the first hundred million years, tapered off for most of the Hadean, then apparently resumed during the Late Heavy Bombardment at about the Hadean-Archean boundary **(E)**. The LHB may have resulted from a major reorganization of the Solar System, with the four giant planets trading places and deflecting many smaller objects into orbits crossing that of the Earth—an astonishing but possible event.[10] The LHB probably accounts for the huge, lava-filled craters on the moon that can be seen with the naked eye. Our planet is so tectonically active that only a couple hundred impact craters have been found, none more than half the age of the Earth, in contrast with the nearly uncountable, very ancient craters on the much smaller and therefore geologically-dead Moon.[11] Another astonishing feature of our planet's past is that there have been a few times when Earth was nearly or entirely covered by ice—from pole to equator and from mountain top to sea surface **(F)**.[12] It is at first hard to see how such global ice could ever have melted, when it would reflect away most of the sunlight, but probably CO_2 from volcanoes would have accumulated in the atmosphere, producing greenhouse warming that eventually ended these Snowball-Earth episodes.

Our knowledge of the history of life on Earth is based on proxies like the oxygen content of the atmosphere, on fossils, and on studies of DNA in living organisms. Oxygen[13] **(G)** was effectively absent in the early atmosphere, as it still is on other planets of our Solar System. Oxygen began to be given off as a byproduct when photosynthesis appeared in single-celled organisms, but did not rise above trace levels until after huge amounts of ferrous iron were oxidized to ferric iron and deposited as sedimentary iron formations.[14]

Fossils **(H)** are absent in Hadean rocks. They are tiny, rare, and difficult to find in the Archean and Proterozoic, except for stromatolites—layered structures formed where sediment stuck to algal mats—and for impressions of the soft-bodied Ediacaran animals in the late Proterozoic.[15] The appearance of abundant fossils, marking the start of the Phanerozoic, may reflect an arms race, in which animals needed hard shells as a defense against predators. A recent development is the ability to determine the genetic relationships between living organisms from their DNA **(I)**.[16] The family tree determined in this way is better than a tree inferred from fossils, but the dates of the branching nodes are very uncertain, and better learned from radiometric dating of rocks that contain fossils.

PANEL 2: EARTH and LIFE (4.567 Ga to now)



Ga = billion years ago

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Panel 3: Phanerozoic (541 Ma to now)

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This panel begins 541 million years ago, currently the best age for the beginning of the Phanerozoic (visible life) Eon, the Paleozoic Era, and the Cambrian Period. At that point in Earth history there was a sudden appearance of abundant fossils. Once thought to mark the sudden origin of life, it is now realized that life is very much older, and this was instead the rapid appearance of hard parts, like shells, that can be preserved as fossils. Shells may have arisen as protection against increasingly effective predation. The 2012 Geological Time Scale **(A)** divides the Phanerozoic into the Paleozoic (old life), Mesozoic (middle life), and Cenozoic (recent life) Eras, which in turn are divided into 11 periods.[1]

For life history, we follow the branches of the tree of life **(B)** that lead to humans, remembering that every other modern organism has a similarly complicated evolutionary history. In this anthropocentric view, the tree of life based on DNA from living organisms first focuses on fish and then land animals. Humans and our close relatives are confined to near invisibility at the recent end of the Phanerozoic. This DNA-based time-tree of life, from Hedges and Kumar,[2] is used because it is the most detailed and comprehensive study available, but it is important to remember that the dates of the nodes where lineages split are based on the dubious assumption that genetic change accumulates at a constant rate. A further problem is that DNA cannot be recovered from extinct lineages (except for extremely recent lines like the Neanderthals). The DNA-based evolutionary relationships shown, however, are apparently more reliable than those inferred from fossils.

In the 1990s Jack Sepkoski compiled stratigraphic ranges from the literature for hundreds of families and thousands of genera **(C)** of fossil marine animals.[3] His plots provided the first quantitative portrayal of fossil biodiversity through the Phanerozoic and showed five sudden drops in biodiversity which he identified as mass extinctions (the drops are much more dramatic in the original plots, with an expanded vertical axis). These extinction events occurred at the Ordovician-Silurian, Frasnian-Fammenian (FF, late Devonian), Permian-Triassic, Triassic-Jurassic and Cretaceous-Paleogene (KPg, formerly called Cretaceous-Tertiary = KT) boundaries. Since then, the PT event, the greatest of the mass extinctions, has been recognized as a double extinction, with the PT extinction preceded, just 7.6 Myr earlier, by the Capitanian-Wuchiapingian extinction (CW). The correspondence between four mass extinctions and period boundaries is not a coincidence, for the early geologists placed the period boundaries at sudden changes in the fossil fauna. (The placement of mass extinctions on Sepkoski's diagram may not exactly match the period boundaries, because of slight adjustments of the boundary ages in the meantime.) Sepkoski's plot also shows the remarkable increase in genera now called the Great Ordovician Biodiversification Event.[4]

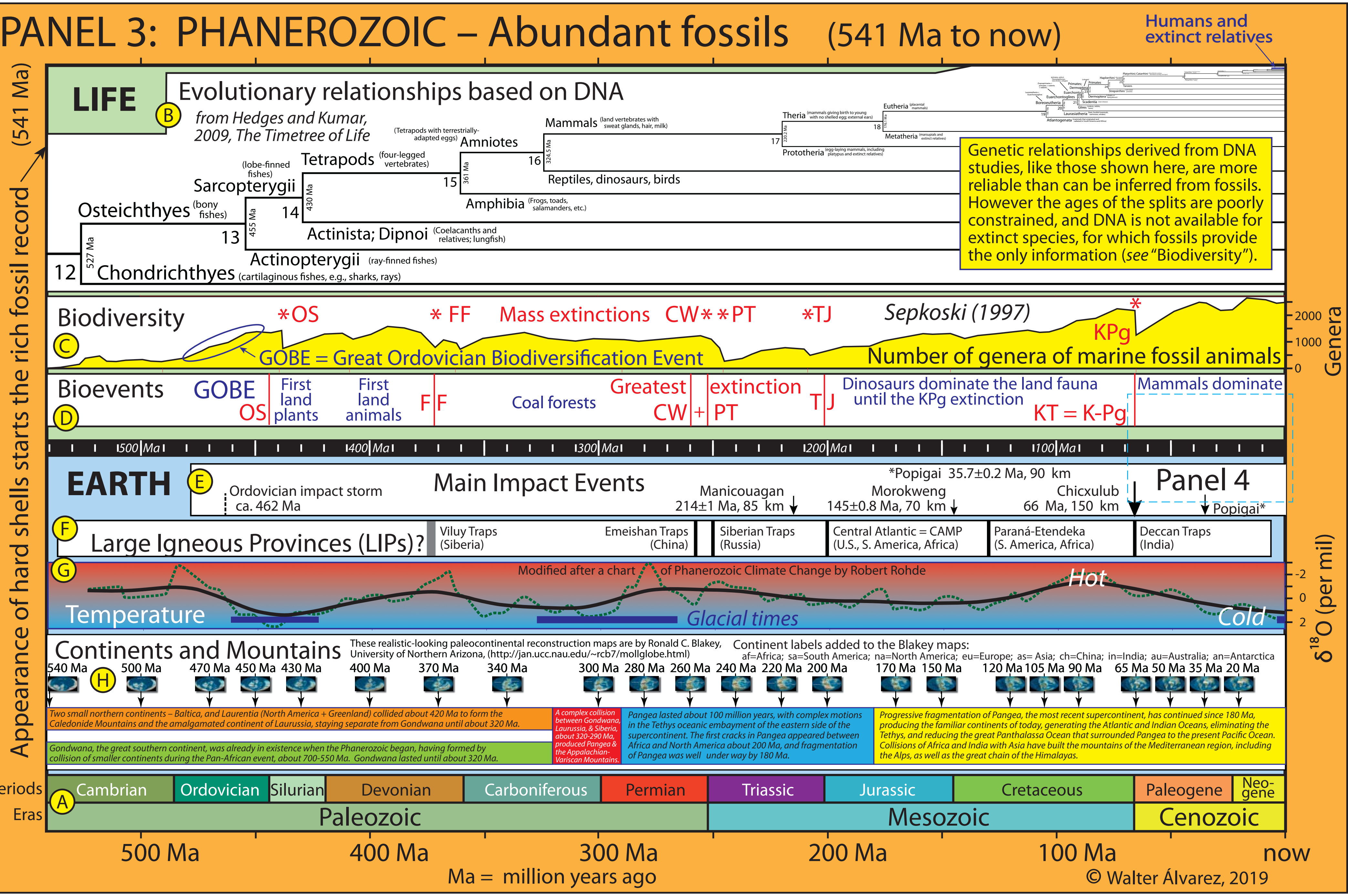
In addition to the six mass extinctions and the Great Ordovician Biodiversification Event, critical Big-History bio-events **(D)** include the population of the land surface. This probably began with single-celled organisms well before the Phanerozoic, although no fossil record has been found. The oldest fossils of land plants occur in the Silurian. There is now a detailed fossil record of the evolution, during the late Devonian, from lobe-finned fishes to tetrapods – land animals with legs.[5] By the Carboniferous Period there were great swampy forests which have turned into coal — hence the name of the period. The Triassic was largely a time of recovery from the double whammy of the CW and PT extinctions. The Jurassic and Cretaceous were the time of dinosaurs, ending with the KPg mass extinction, succeeded by the Cenozoic blossoming of mammals.

The cause of the great extinctions remains a challenging problem. The most recent extinction (KT) coincided precisely with the extraterrestrial impact that produced the huge Chicxulub crater, on Mexico's Yucatán Peninsula[6] **(E)**, but there is no evidence for large-body impact at the times of any of the other five extinctions. However, the four most recent extinctions, and possibly the FF as well, occurred during times when massive outpourings of basaltic lava were taking place — the LIPs, or Large Igneous Provinces **(F)**.[7] The effects of the Chicxulub impact were certainly capable of producing a mass extinction, but there is no obvious global killing mechanism that would result from a LIP. Perhaps there is some combination that would explain why the KPg extinction coincided with both an impact and a LIP.[8]

The ratio of the oxygen isotopes, ^{16}O and ^{18}O, in marine fossils reflects the temperature of the ocean water, giving a rough record of temperature through the Phanerozoic **(G)**. Although not calibrated in degrees, this shows an irregular fluctuation between hot and cold climates, the latter in approximate agreement with times of known glacial episodes.[9]

The various events of the Phanerozoic took place on an evolving global stage that saw the assembly of ancient continents (including the long-lasting southern supercontinent of Gondwana) to form the global supercontinent of Pangea, the persistence of Pangea for about 100 Myr, and its progressive breakup, beginning in the Jurassic and still continuing **(H)**. Examining Ronald Blakey's map reconstructions, beginning with the earliest (540 Ma), we first see unfamiliar continents — Laurentia, Siberia, Baltica, and massive Gondwana — in a pattern that did not change much until 300 Ma, when the northern continents collided with Gondwana to produce the enormous Appalachian mountain chain, which originally continued into modern Europe as the Variscan Mountains. The resulting supercontinent, Pangea, endured until about 200 Ma, surrounded by the even-larger global ocean of Panthalassa, although there were complicated motions of continental fragments within the wedge-shaped Tethyan Ocean that indented Pangea on the east. Pangea began to break up at about 200 Ma, and in later maps the continents of today are recognizable, with their jostlings and collisions producing the Mediterranean Sea and mountain chains of the Himalayas, the Zagros, and the Alps.

PANEL 3: PHANEROZOIC – Abundant fossils (541 Ma to now)



from Hedges and Kumar, 2009, The Timetree of Life

Genetic relationships derived from DNA studies, like those shown here, are more reliable than can be inferred from fossils. However the ages of the splits are poorly constrained, and DNA is not available for extinct species, for which fossils provide the only information (*see* "Biodiversity").

These realistic-looking paleocontinental reconstruction maps are by Ronald C. Blakey, University of Northern Arizona, (http://jan.ucc.nau.edu/~rcb7/mollglobe.html)

Continent labels added to the Blakey maps:
af=Africa; sa=South America; na=North America; eu=Europe; as= Asia; ch=China; in=India; au=Australia; an=Antarctica

Two small northern continents – Baltica, and Laurentia (North America + Greenland) collided about 420 Ma to form the Caledonide Mountains and the amalgamated continent of Laurussia, staying separate from Gondwana until about 320 Ma.

Gondwana, the great southern continent, was already in existence when the Phanerozoic began, having formed by collision of smaller continents during the Pan-African event, about 700-550 Ma. Gondwana lasted until about 320 Ma.

A complex collision between Gondwana, Laurussia, & Siberia, about 320-290 Ma, produced Pangea & the Appalachian-Variscan Mountains.

Pangea lasted about 100 million years, with complex motions in the Tethys oceanic embayment of the eastern side of the supercontinent. The first cracks in Pangea appeared between Africa and North America about 200 Ma, and fragmentation of Pangea was well under way by 180 Ma.

Progressive fragmentation of Pangea, the most recent supercontinent, has continued since 180 Ma, producing the familiar continents of today, generating the Atlantic and Indian Oceans, eliminating the Tethys, and reducing the great Panthalassa Ocean that surrounded Pangea to the present Pacific Ocean. Collisions of Africa and India with Asia have built the mountains of the Mediterranean region, including the Alps, as well as the great chain of the Himalayas.

Ma = million years ago

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Panel 4: Cenozoic (66 Ma to now)

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Beginning with the Chicxulub impact and mass extinction 66 million years ago, this panel shows the entire Cenozoic Era, during which mammals dominated the land fauna. The Geologic Time Scale 2012 **(A)** shows the division of the Cenozoic into periods, epochs, and stages, based on fossils and now dated radiometrically.[1] These subdivisions continue back through the entire Phanerozoic, although the stages and even the epochs are too brief to show on the preceding panels. The divisions in the GTS-2012 at first look like the divisions historians apply to Human history — Renaissance, Enlightenment, etc., but are in fact very different. The humanistic divisions are subjective, and can be used in different ways by different authors; there is no general agreement about the exact meaning of these terms. By contrast, each formal subdivision of the Geologic Time Scale has been fixed by the international geologic community after long, rigorous discussion, and its base is defined by a physical marker in the best available sedimentary rocks of that age.

The polarity of the Earth's magnetic field **(B)**, either normal – pointing near the north rotation pole as at present, or reversed – pointing near the south pole, has provided an additional way to calibrate the geologic time scale, and is also formally specified in the GTS. The sequence of polarity chrons is well known through the Cenozoic, and with lesser resolution back through the Phanerozoic, interrupted by at least one long normal and one long reversed chron, normal in the Cretaceous and reversed in the Carboniferous-Permian.[2]

Probably the most important Big-History trends of the Cenozoic were the rise of primates, leading to humanity, and the gradual cooling **(C)** from the very warm Eocene to the current glacial age. The ratio of the two oxygen isotopes, ^{18}O and ^{16}O, in marine fossils reflects the ocean temperature, because the ratio of ^{18}O to ^{16}O incorporated in shells varies with water temperature, and because ^{16}O is preferentially evaporated from the ocean surface and stored in glaciers, enriching the ocean in ^{18}O. There are many data sets of oxygen isotopes in marine fossils of different ages, from different kinds of fossils and different geographic and depth settings. One such set, compiled by E.L. Grossman and used here,[3] clearly shows the Cenozoic temperature decline.

Cenozoic geological events **(D)** were dominated by ongoing dispersal of the fragments of the Pangea supercontinent, which began in the Jurassic (see the zoomable maps in Panel 3). Because continents cannot disperse indefinitely on a spherical planet, collisions must take place. Collision between Africa-Arabia and Eurasia closed off the western Tethys, generating the Alps and the Zagros Mountains of Iran, and the jostling of microplates and small continental fragments, like Corsica and Sardinia, in the collision zone has produced the complex small seas and mountain belts of the Mediterranean. The greatest collision was between the rapidly northward-moving Indian continent and the south margin of Asia. This collision, dated in different places and by different methods as 60-50 Ma,[4] has generated the enormous elevated zone of the Himalayas and Tibet, which continue to deform today, because collision slowed but did not stop the India-Asia convergence.[5]

As explained in the drawing, the temperature decline during the Cenozoic may have resulted from geologic events, like uplift of plateaus and changes in ocean circulation, but these have proven very hard to date.

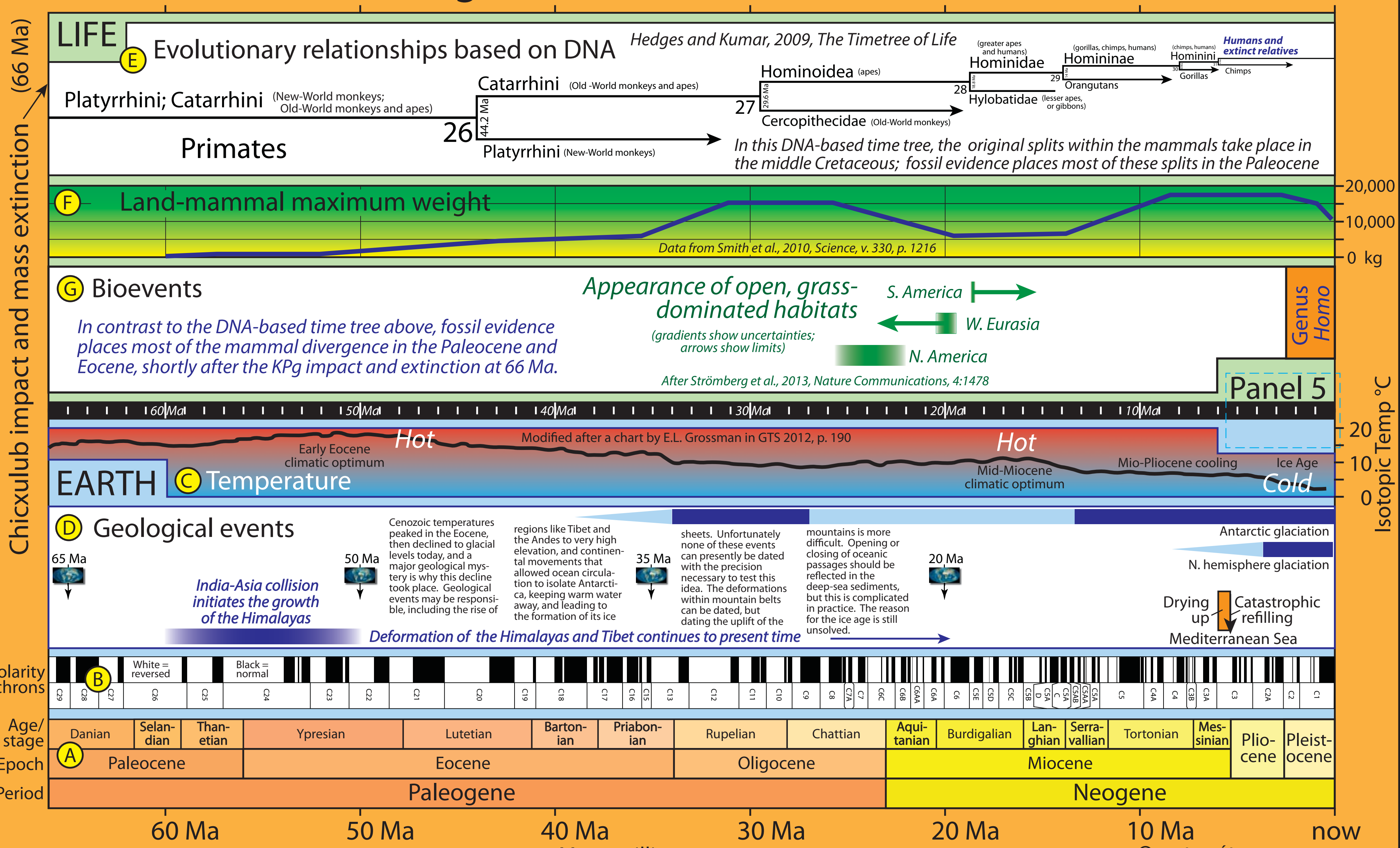
During the late Miocene Messinian stage, tectonic uplift closed the Gibraltar inlet and resulted in evaporation of the Mediterranean Sea down to a deep desert, as discussed in Panel 5.[6] When the Atlantic Ocean broke through the Gibraltar barrier, the deep Mediterranean desert suddenly refilled, at 5.33 Ma; this event is taken as marking the start of the Pliocene and the next panel.

Following, in our Big-History way, the branches of the tree of life leading to humanity **(E)**, we see the history of primates leading to *Homo sapiens*. In this DNA-based reconstruction, the branching from the ancestral mammals to the many modern orders, including primates, took place in the middle of the Cretaceous (Panel 3), earlier than the time covered by this panel, which thus begins well along in the evolutionary sequence of the primates. However, DNA-based trees are more reliable for the pattern of relationships than for the dates of the branching nodes, which rely on the questionable assumption that the rate of mutations is constant.

Based on reliably-dated fossils, there is a striking Cenozoic increase of the maximum size of mammals **(F)**, rising from around 50 kg in the Paleocene to 15,000 or more kg in the second half of the Cenozoic. This is generally attributed to the K-Pg mass extinction at 66 Ma having removed the dinosaurs, thus freeing the mammals to occupy the large-animal niches.

In contrast to the DNA-based evolutionary tree, the evidence from well-dated fossil mammals places the main divergence, and the origin of mammalian orders like the primates, in the Paleocene and Eocene **(G)**. The details are controversial, because the earliest Cenozoic mammals were tiny and their fossils, especially teeth, must be collected on fine-mesh screens, and because suitable fossil-bearing sediments are largely limited to eastern Montana. It is striking that the evolutionary burst of the early Cenozoic mammals immediately followed the extinction of dinosaurs at 66 Ma. Another extremely significant biological event occurred in the late Oligocene and early Miocene, with the spread of grasslands, which now cover about 40% of the land surface.[7] Grass has been important in feeding large numbers of herbivorous browsing animals. The appearance of Genus *Homo* took place about 2.5 Ma and is shown in detail in Panel 5.

PANEL 4: CENOZOIC – Age of Mammals (66 Ma to now)



In this DNA-based time tree, the original splits within the mammals take place in the middle Cretaceous; fossil evidence places most of these splits in the Paleocene

In contrast to the DNA-based time tree above, fossil evidence places most of the mammal divergence in the Paleocene and Eocene, shortly after the KPg impact and extinction at 66 Ma.

India-Asia collision initiates the growth of the Himalayas

Cenozoic temperatures peaked in the Eocene, then declined to glacial levels today, and a major geological mystery is why this decline took place. Geological events may be responsible, including the rise of

regions like Tibet and the Andes to very high elevation, and continental movements that allowed ocean circulation to isolate Antarctica, keeping warm water away, and leading to the formation of its ice

sheets. Unfortunately none of these events can presently be dated with the precision necessary to test this idea. The deformations within mountain belts can be dated, but dating the uplift of the

mountains is more difficult. Opening or closing of oceanic passages should be reflected in the deep-sea sediments, but this is complicated in practice. The reason for the ice age is still unsolved.

Deformation of the Himalayas and Tibet continues to present time

Ma = million years ago

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Panel 5: Pliocene-Pleistocene (5.33 Ma to now)

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During the Messinian (the last stage of the Miocene) the connection between the Atlantic and the Mediterranean was closed off by tectonic uplift. As would be the case if the same thing happened today, the rivers flowing into the Mediterranean could not replace the water lost by evaporation, and with its Atlantic connection blocked, the Mediterranean Sea slowly evaporated, becoming a desert a mile or more below sea level! Rivers entering the Mediterranean basin, like the Nile, eroded deep canyons, cutting down to the desert floor. At 5.33 Ma Atlantic water spilled over into the deep basin, catastrophically eroded a new entrance at Gibraltar, and suddenly refilled the Mediterranean Sea. This refilling event is used by geologists to mark the beginning of the Pliocene Epoch.

Since the time scale **(A)** is regularly updated and improved, its divisions can change. For example, in GTS 2004, the Pliocene-Pleistocene boundary was placed at the end of the Gelasian stage; after much deliberation, in GTS 2012 it has been moved to the beginning of the Gelasian. The numerical calibration of time-scale divisions can also change on the basis of new and improved radiometric dating. As opposed to the subjective periodizations of history used by historians of written history (e.g., "Renaissance," "Industrial Revolution"), time-scale construction in geology is rigorous, quantitative, and based on standard procedures accepted by geologists everywhere, and is constantly being improved.[1]

The gradual cooling of Earth's climate since the Late Cretaceous (Panel 3), and since the early Eocene temperature maximum (Panel 4), has led finally to glaciation in the Pleistocene. This is shown clearly in the oxygen isotope ($^{18}O/^{16}O$) record from the tiny shells of benthic (bottom-dwelling) single-celled foraminifera[2] **(B)**. Three regimes have been recognized in the Pliocene-Pleistocene record of temperature and ice volume: (1) In the Pliocene there was nearly constant temperature with a slightly noisy signal. (2) In the Gelasian and most of the Calabrian the average temperature declined slightly, with symmetrical fluctuations having a 41-kyr (41,000) period; this is the period of the obliquity (axial tilt) of the Earth's rotation axis. (3) For about the last 1 Myr, the fluctuations have greater magnitude and a 100-kyr period, which is the period of Earth's orbital eccentricity. These fluctuations over the last 1 Myr are asymmetrical, with slow increase in ice volume followed by a sudden warming and melting. The asymmetry probably reflects the fact that covering Canada with ice is a slow process because all the snow has to be brought in as evaporated sea water, and ice accumulation is constantly reduced by flow of the glaciers to lower, warmer areas where it melts; by contrast, there are no restrictions on how fast glaciers can melt if the climate warms.

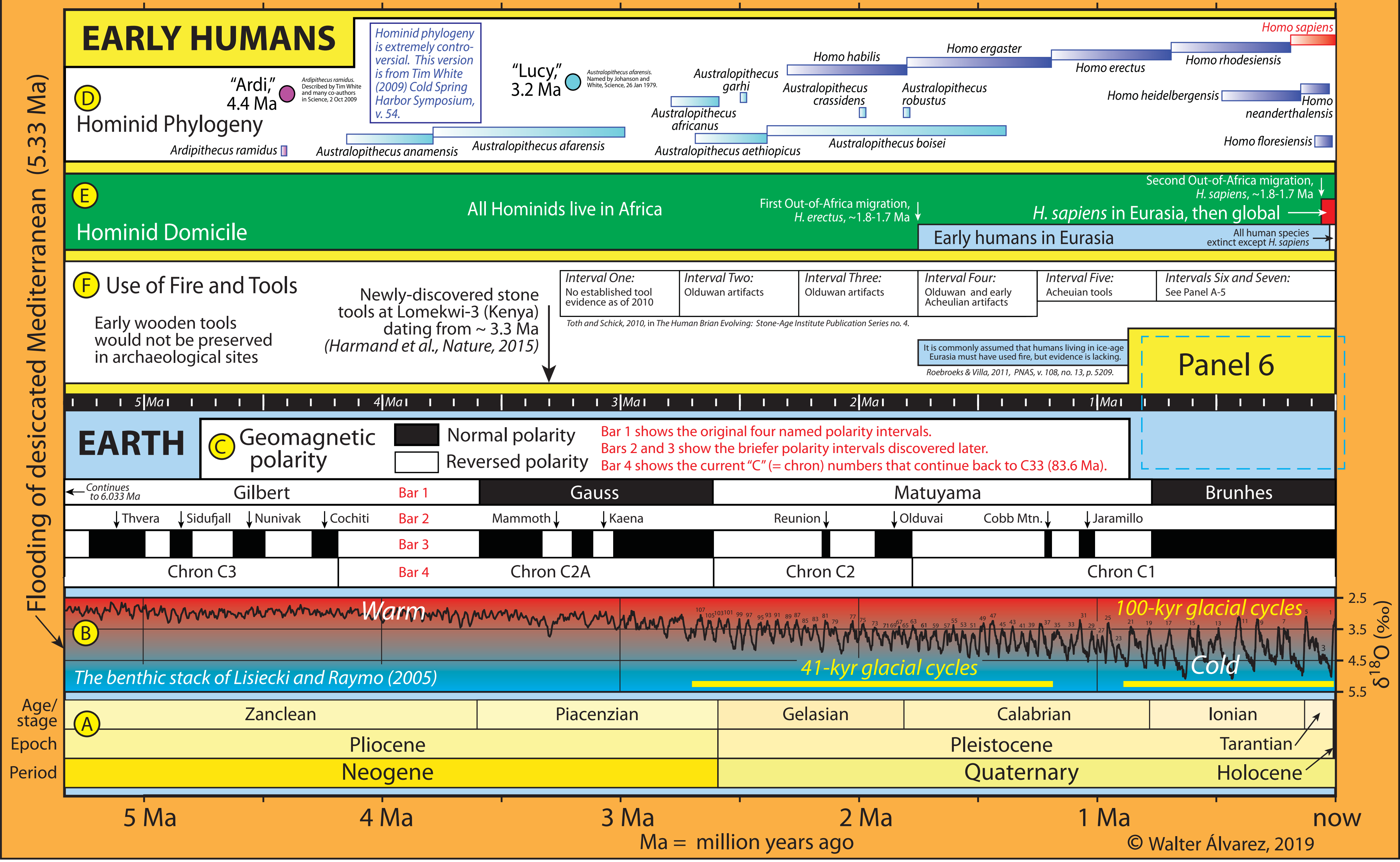
The original way of dating rocks was by paleontology. Fossils allow you to put rocks into chronological sequence, and to say that a particular fossil and the rocks that contain it are of Pliocene age, for example. In the 20th century, geologists learned how to date some (but not all) minerals, and the rocks that contain them, in years before the present, based on radioactive decay. Beginning in the 1960s, a third method was discovered, based on the fact that the Earth's magnetic field preferentially aligns close to the Earth's rotation axis, occasionally reversing from pointing roughly north, as it does today (N = normal polarity) to pointing roughly south (R = reversed polarity). The resulting geomagnetic polarity time scale is now an important tool for Earth historians.[3] Much early work on the geomagnetic polarity time scale was done on the Pliocene-Pleistocene, where originally four polarity zones were recognized **(C)** — Brunhes (N), Matuyama (R), Gauss (N) and Gilbert (R). Subsequent work showed that there were shorter intervals of the opposite polarity in each of these zones except for the Bruhnes, and eventually a new scheme was developed that numbers polarity chrons from C1 (Brunhes and part of the Matuyama) back to C33, in the Late Cretaceous, before which there was the Cretaceous Long Normal Chron.[4] Although the named intervals do not go back farther than the Gilbert, those four names are still used in the study of early humans by paleoanthropologists.

Paleoanthropology **(D)** is particularly difficult because of the rarity of these "hominid" fossils and the impossibility of extracting DNA from any but the most recently extinct lineage, the Neanderthals.[5] There is little agreement on the genetic relationships; the one shown here[6] is by no means universally accepted. Two famous fossils are critical for understanding human origins. Lucy (*Australopithecus afarensis*, 3.2 Ma) showed that walking upright came before our large brain.[7] Ardi (*Ardipithecus ramidus*, 4.4 Ma) has a strange big toe showing that climbing trees came before walking.[8]

An important result of careful and detailed paleoanthropologic research is the recognition that human ancestors lived exclusively in Africa until less than 2 million years ago. The fossil record is now interpreted as showing two separate "Out-of-Africa" migrations. **(E)** The first migration, beginning about 1.8-1.7 Ma, led to the widespread occupation of Eurasia by *Homo erectus* and its descendants. A second migration, beginning about 60 thousand years ago, has spread *Homo sapiens* all over the globe. These migrations should not be thought of as intentional exploration and colonization, but as the very gradual and unintentional spread of people over thousands of generations.[9]

Among the features that make us human **(F)** are language, tools and the use of fire.[10] Sadly, language before writing has left no trace, and languages evolve so rapidly that hypothetical ancestral languages reconstructed on the basis of comparisons between modern descendent languages are useless back beyond a few thousand years. Stone tools[11] are the basis for archaeologists' time-scale units, like Paleolithic and Mousterian. Intentional fire use may be the most uniquely human activity, but the evidence[12] is very scant and uncertain until the last few hundred thousand years (Panel 6).

PANEL 5: PLIOCENE-PLEISTOCENE – Rise of Humanity (5.33 Ma to now)



EARLY HUMANS

Hominid phylogeny is extremely controversial. This version is from Tim White (2009) Cold Spring Harbor Symposium, v. 54.

Ⓓ Hominid Phylogeny

"Ardi," 4.4 Ma — *Ardipithecus ramidus.* Described by Tim White and many co-authors in Science, 2 Oct 2009

"Lucy," 3.2 Ma — *Australopithecus afarensis.* Named by Johanson and White, Science, 26 Jan 1979.

Ardipithecus ramidus
Australopithecus anamensis
Australopithecus afarensis
Australopithecus africanus
Australopithecus garhi
Australopithecus aethiopicus
Australopithecus crassidens
Australopithecus robustus
Australopithecus boisei
Homo habilis
Homo ergaster
Homo erectus
Homo rhodesiensis
Homo sapiens
Homo heidelbergensis
Homo neanderthalensis
Homo floresiensis

Ⓔ Hominid Domicile

All Hominids live in Africa

First Out-of-Africa migration, *H. erectus*, ~1.8-1.7 Ma

Second Out-of-Africa migration, *H. sapiens*, ~1.8-1.7 Ma

H. sapiens in Eurasia, then global

Early humans in Eurasia

All human species extinct except *H. sapiens*

Ⓕ Use of Fire and Tools

Early wooden tools would not be preserved in archaeological sites

Newly-discovered stone tools at Lomekwi-3 (Kenya) dating from ~ 3.3 Ma *(Harmand et al., Nature, 2015)*

Interval One:	*Interval Two:*	*Interval Three:*	*Interval Four:*	*Interval Five:*	*Intervals Six and Seven:*
No established tool evidence as of 2010	Olduwan artifacts	Olduwan artifacts	Olduwan and early Acheulian artifacts	Acheuian tools	See Panel A-5

Toth and Schick, 2010, in *The Human Brian Evolving: Stone-Age Institute Publication Series no. 4.*

It is commonly assumed that humans living in ice-age Eurasia must have used fire, but evidence is lacking.

Roebroeks & Villa, 2011, PNAS, v. 108, no. 13, p. 5209.

Panel 6

5 Ma 4 Ma 3 Ma 2 Ma 1 Ma

EARTH

Ⓒ Geomagnetic polarity

■ Normal polarity
□ Reversed polarity

Bar 1 shows the original four named polarity intervals.
Bars 2 and 3 show the briefer polarity intervals discovered later.
Bar 4 shows the current "C" (= chron) numbers that continue back to C33 (83.6 Ma).

Bar 1: ← Continues to 6.033 Ma; Gilbert; Gauss; Matuyama; Brunhes

Bar 2: Thvera; Sidufjall; Nunivak; Cochiti; Mammoth; Kaena; Reunion; Olduvai; Cobb Mtn.; Jaramillo

Bar 3

Bar 4: Chron C3; Chron C2A; Chron C2; Chron C1

Ⓑ 100-kyr glacial cycles

41-kyr glacial cycles

The benthic stack of Lisiecki and Raymo (2005)

Ⓐ

Age/ stage	Zanclean	Piacenzian	Gelasian	Calabrian	Ionian	Tarantian
Epoch	Pliocene		Pleistocene			
Period	Neogene		Quaternary			Holocene

Ma = million years ago

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Panel 6: Brunhes Normal and Ice Age (780 ka to now)

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Earth's geomagnetic polarity has been "normal," i.e., pointing close to the north rotation pole, for the last 780,000 years (since 780 ka); this is the Brunhes normal polarity chron **(A)** which, rather unusually, has not been interrupted by any short reversed intervals.

The Geological Time Scale 2012 **(B)** expands the very youngest part of Earth history, so that the Tarantian, corresponding to the most recent glacial advance, and the Holocene, the post-glacial times in which agriculture and civilization have developed, are now visible. The name "Quaternary" has an ancient pedigree in geological nomenclature, dating back to the beginning of the recognition that rocks record Earth history. Giovanni Arduino (1714-1795) divided the rocks in Italy into a sequence — Primary, Secondary, Tertiary, and Quaternary. The first two names went out of use long ago, but Tertiary remained in use until it was replaced by Paleogene and Neogene, and it is still used informally. Only Quaternary remains a formal Period, and in GTS 2012 the Quaternary has been expanded, to begin at 2.6 Ma, rather than at 1.8 Ma, as in GTS 2004 (Panel 5).

The Brunhes normal polarity chron includes most of the time of the major Quaternary glaciations, each lasting about 100 kyr, for which the oxygen-isotope temperature curve based on benthic forams[1] **(C)** shows a saw-tooth pattern, with slowly expanding northern-hemisphere ice sheets followed by rapid deglaciation. This saw-tooth pattern makes sense, for ice sheets can expand only as fast as evaporation and winds can bring in new snow, with the ice meanwhile flowing to lower elevations and melting; by contrast, there are no restrictions on how fast a glacier can melt when the temperature rises. The peaks and valleys in the temperature curve are numbered with the Marine Isotope Stages (MIS: odd for warm, even for cold); these mark the ca. 100-kyr cycle, except for stages 3 and 4, which were numbered early on.

The geological events of this time interval are dominated by the abrupt endings of glacial advances, which are identified as Terminations and numbered with Roman numerals **(D)**. Picking the exact age of a termination is subjective, because it took some time for each ice sheet to disappear; one well-known set of age picks is shown here,[2] but other picks have been suggested.[3] One non-glacial event that may be of great importance is the super-eruption of the Toba Volcano in Sumatra — an event so enormous that it has been suggested to have caused a major bottleneck in the history of humanity.[4] Dating of the Toba eruption has not been easy, but seems to be converging on a date of 73.9 ka.[5] Also shown is the date of the Barringer impact crater in Arizona, not a geologically significant event, but a beautifully preserved and easily visited young crater, and a reminder that impact events continue to the present.

In the time interval of this panel, the only hominid species are *Homo sapiens* and earlier members of genus *Homo* **(E)**. The lines of ancestry among these species are controversial, and the pattern shown here is the simpler of two alternatives portrayed in a figure by Rightmire (2007);[6] the more complicated version shows the additional species *H. antecessor* and *H. rhodesiensis*. This diagram shows how the closely-related Neanderthals were contemporaneous with *Homo sapiens*, but does not show the critical information on where each species was living at a given time; that information is given in the next time line of this panel.

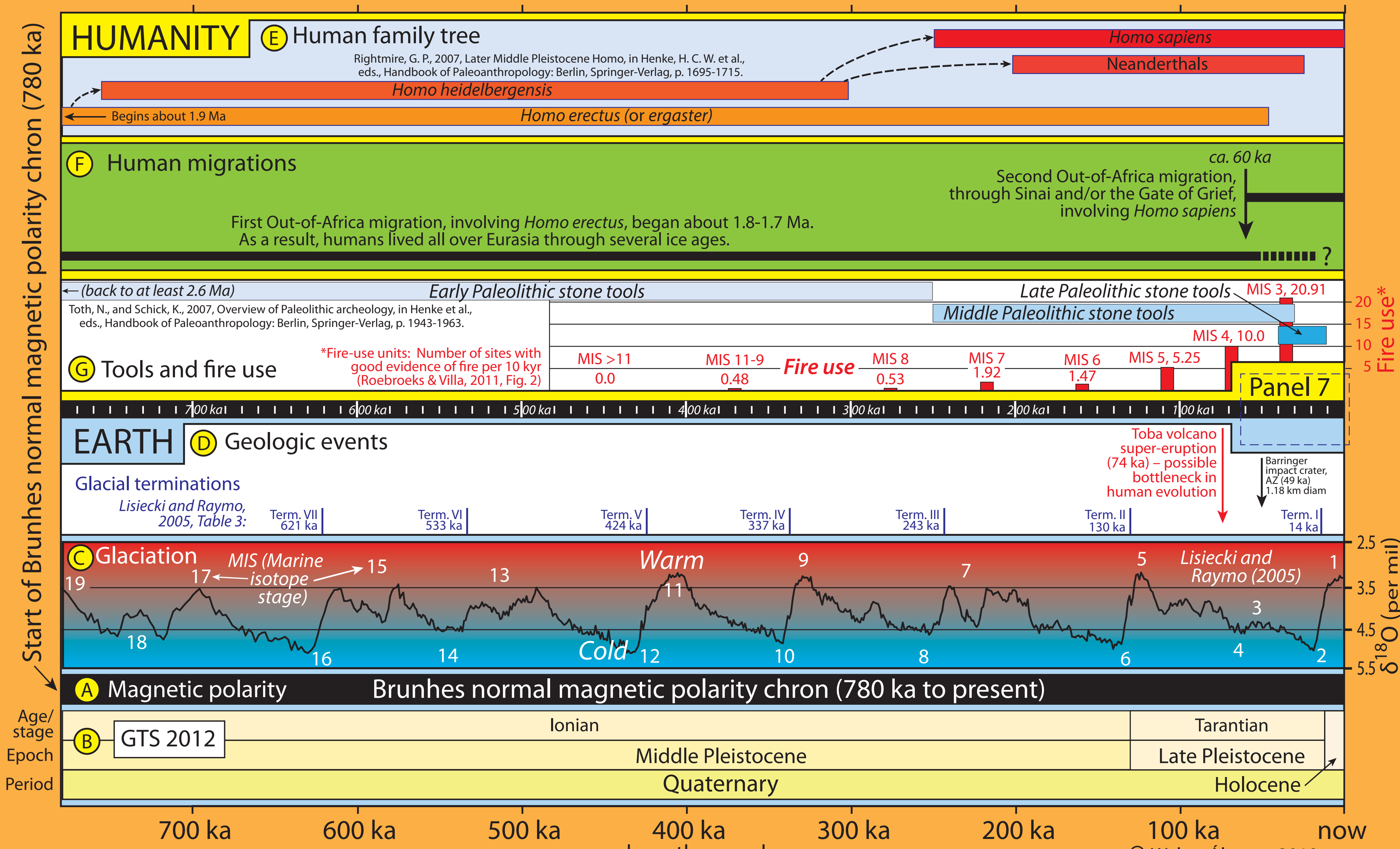
The story of human migrations out of Africa **(F)**, as currently understood, is quite remarkable. The first humans left Africa for Eurasia as early as about 1.8 Ma, based on the findings of fossils of probable *H. erectus* at Dmanisi in the Georgian Caucasus, dating from 1.77 Ma.[7] Thus *H. erectus* must have lived in Eurasia through the entire sequence of 100-kyr glacial cycles corresponding to the Brunhes normal polarity chron. There is as yet no evidence for other Out-of-Africa migrations until the departure of *H. sapiens* about 60 ka, during the most recent glacial age.

There are two possible routes for humans to have escaped the African homeland — neither of them easy.[8] One route is across the narrows at the southeast end of the Red Sea, which the Arabs call Bab-al-Mandab (the Gate of Grief), made narrower still by sea-level draw-down during the last Glacial. The other route is across the Sahara. This would not be practical at the present time, but during times of more rain (pluvials) the Sahara was well watered and would have attracted nomads from the areas to the south. When the Sahara dried out between pluvials, the Saharan nomads would have been driven out both southward and northward, with the latter people then able to cross the Sinai into Eurasia. This is the Saharan Pump hypothesis.[9]

Of the characteristics that distinguish humans from other animals **(G)**, language and tool use are to some extent ambiguous, for whales may have some form of language, and chimpanzees and some birds make use of simple, found tools. Fire may be the most unambiguous, for all humans make intentional use of fire, and no other species does. Language, before writing, leaves little or no trace, and its history before a few thousand years ago remains completely obscure. The earliest human tools, perhaps made of wood, would rarely survive in archaeological excavations, but stone tools, immune to destruction, have long been the basis for assigning early human sites to a sequence of intervals — early, middle, and late Paleolithic, and then the Mesolithic, and Neolithic, and then the Bronze and Iron Ages.

The history of fire use has been less discussed, but is very interesting if rather difficult to assess, because charcoal found in excavations may or may not have been formed by intentional fire use. It has long been assumed that *Homo erectus*, living in glacial-age Eurasia, would have had to use fire in controlled ways in order to survive. However, a recent review has carefully evaluated the evidence, as shown in here in the red histogram, and found no indications that fire was used habitually by human in Europe prior to MIS 11, a little before 400 ka.[10] This surprising result suggests that *H. erectus* humans were able to live in glacial Europe without controlled fire use!

PANEL 6: BRUNHES NORMAL and ICE AGE (780 ka to now)



HUMANITY

(E) Human family tree

Rightmire, G. P., 2007, Later Middle Pleistocene Homo, in Henke, H. C. W. et al., eds., Handbook of Paleoanthropology: Berlin, Springer-Verlag, p. 1695-1715.

Homo sapiens

Neanderthals

Homo heidelbergensis

← Begins about 1.9 Ma *Homo erectus (or ergaster)*

(F) Human migrations

ca. 60 ka

Second Out-of-Africa migration, through Sinai and/or the Gate of Grief, involving *Homo sapiens*

First Out-of-Africa migration, involving *Homo erectus*, began about 1.8-1.7 Ma. As a result, humans lived all over Eurasia through several ice ages.

?

(G) Tools and fire use

← *(back to at least 2.6 Ma)* *Early Paleolithic stone tools*

Toth, N., and Schick, K., 2007, Overview of Paleolithic archeology, in Henke et al., eds., Handbook of Paleoanthropology: Berlin, Springer-Verlag, p. 1943-1963.

Late Paleolithic stone tools

Middle Paleolithic stone tools

*Fire-use units: Number of sites with good evidence of fire per 10 kyr (Roebroeks & Villa, 2011, Fig. 2)

Fire use

EARTH

(D) Geologic events

Glacial terminations

Lisiecki and Raymo, 2005, Table 3:

Toba volcano super-eruption (74 ka) – possible bottleneck in human evolution

Barringer impact crater, AZ (49 ka) 1.18 km diam

(C) Glaciation

MIS (Marine isotope stage)

Lisiecki and Raymo (2005)

(A) Magnetic polarity Brunhes normal magnetic polarity chron (780 ka to present)

(B) GTS 2012

Age/ stage	Ionian	Tarantian
Epoch	Middle Pleistocene	Late Pleistocene
Period	Quaternary	Holocene

ka = thousand years ago

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Panel 7: *Homo sapiens* out of Africa (ca. 60 ka to now)

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The Holocene, or post-glacial, is the last formal stage in the Geologic Time Scale **(A)**. The term "anthropocene," meaning the time during which human beings have seriously affected climate and other aspects of the Earth, was proposed by non-geologists, and geologists are now debating whether it should be formalized and adopted, and if so, when it should begin and what marker would identify it in the stratigraphic record.[1]

For the temperature (and ice volume) of the last 60,000 years, the best record comes from the Greenland ice core, GISP-2 **(B)**.[2] Water evaporating from the sea is enriched in the more-easily-evaporated light isotope, ^{16}O; when this is stored in ice sheets, the sea is correspondingly enriched in ^{18}O. As a result, oxygen from H_2O in GISP-2 ice gets lighter in warm intervals, while oxygen from $CaCO_3$ in benthic forams (Panels 4 to 6) gets heavier. The GISP-2 record dramatically shows the end of the Pleistocene Ice Age about 11 ka, the Bølling-Allerød warm and Younger Dryas cold intervals that preceded the deglaciation, and the remarkably constant temperature of the Holocene. The still poorly-understood Dansgaard-Oeschger warm events within the last glacial probably reflect local North Atlantic-Greenland-Canada conditions; they are not visible in the benthic-foram record (Panel 6), which responds to global conditions.

During the glacial times of the Tarantian Stage, six levels rich in ice-rafted debris are recognized in North Atlantic sediment cores **(C)**. These Heinrich events represent times when large numbers of icebergs calved off the northern-hemisphere ice sheets and floated southward, dropping their entrained rocks as they gradually melted.[3] The unexplained Heinrich sedimentary events do not seem to correlate with the equally mysterious Dansgaard-Oeschger thermal events.

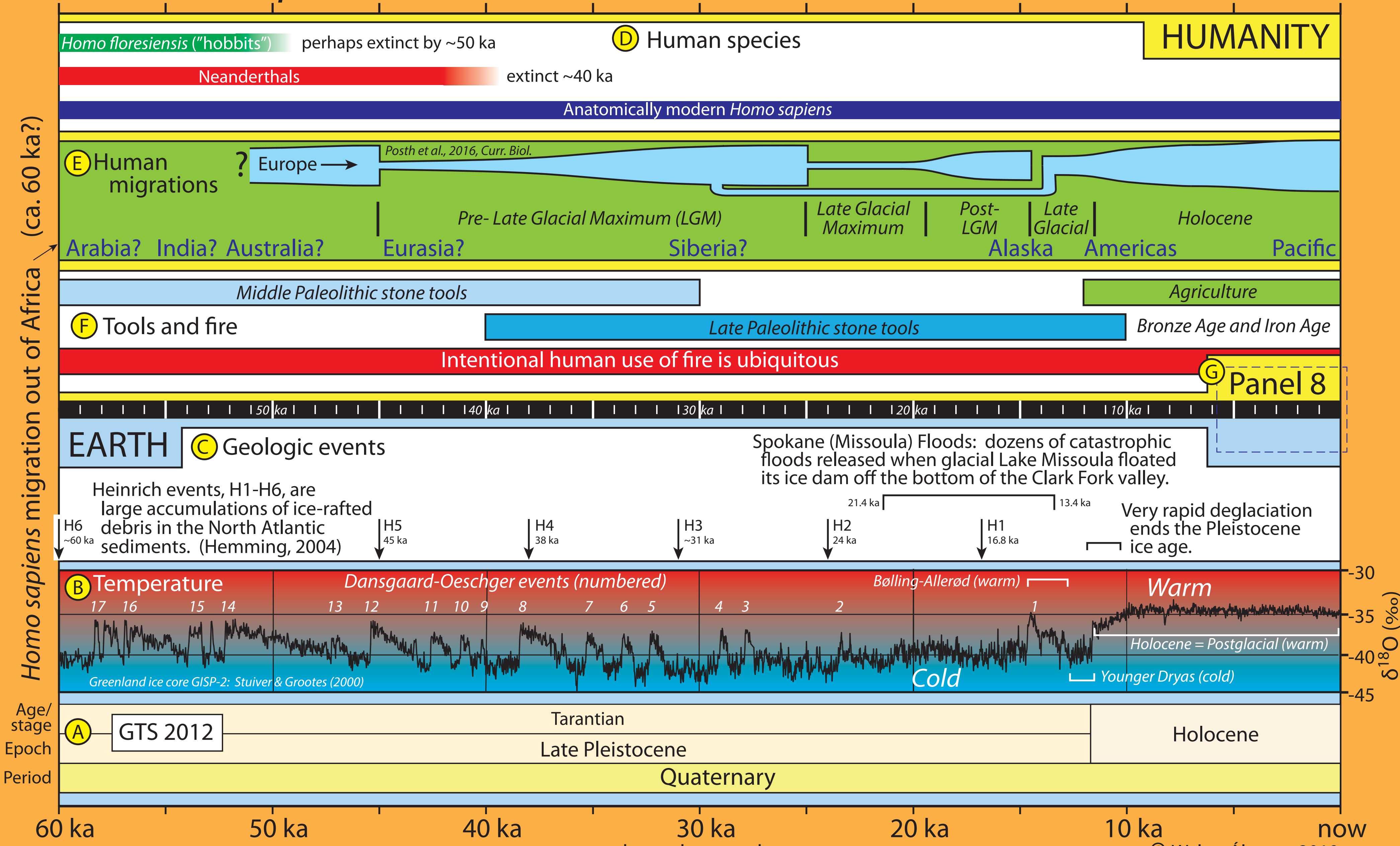
During the maximum glacial advance, around 20 ka, the ice sheet of the Canadian Rockies blocked the valley of the Clark Fork River in northern Idaho, impounding the huge Glacial Lake Missoula. When the lake water rose high enough, it floated the ice dam off its rocky floor; the ice dam disintegrated into icebergs which were swept down the Columbia River in a colossal flood.[4] This scenario happened dozens of times between 21.4 and 13.4 ka;[5] its recognition by J Harlen Bretz in 1923 opened the first crack in the uniformitarian gradualist mindset which had dominated geological thinking since Charles Lyell in the 1830s.[6] Similar though less studied superfloods have been recognized in Asia as well as on Mars.[7] The slow build-up of the Northern-Hemisphere ice sheets was followed by their very rapid melting, complicated by the warm and cold couplet of the Bølling-Allerød and the Younger Dryas.

Until recently it seemed that among humans, only Neanderthals and modern *Homo sapiens* lived during this time interval, with Neanderthals dying off about 40 ka **(D)**. With the last Neanderthals living so recently, it has been possible to sequence their genome.[8] And then, in 2003, came the discovery on the Indonesian island of Flores of fossils of a new species of humans, standing about 1 m high, who have been named *Homo floresiensis*, and are sometimes informally called "hobbits."[9] The discoverers pointed out that in stature and brain size these fossils resemble the pre-human Australopithecines, but with anatomical features that place them in genus *Homo*. They appear to be an example of the dwarfing that has occurred among other mammals, notably elephants, isolated on islands in the Mediterranean.[10] Dating *H. floresiensis* has been controversial; the latest work dates the fossils and enclosing sediment at 100-60 ka, and associated stone tools to 190-50 ka,[11] and it is unknown whether these small humans lived long enough to encounter modern *H. sapiens* spreading from Africa toward Australia.

The "multiregional" hypothesis — that *Homo erectus* evolved into *Homo sapiens* independently in different parts of Eurasia — is now less supported than the "Out-of-Africa" hypothesis — that *H. sapiens* evolved in Africa and then spread over Eurasia, replacing the earlier people who had lived outside Africa since about 1.8-1.7 Ma. Much effort is currently going into tracing how modern humans spread over every continent except Antarctica **(E)**. It is widely assumed that *H. sapiens*, migrating out of Africa over many generations, would have followed the south coast of Arabia and Asia. This means that archaeological sites will not be very helpful in tracing the migrations, because coastlines during glacial times would have been lower than now and have been drowned by the post-glacial sea-level rise. Tracing the migrations is now done largely by studies of DNA in current indigenous populations — mitochondrial DNA tracing the female line and Y-chromosome DNA the male.[12] Directly dating DNA events involves major assumptions about mutation rates, and available maps of the human migration show very different ages for the departure from Africa and arrival in successive places. The place names across the bottom of the green diagram give a general idea but their ages are not at all well constrained. The blue "spindle diagram" at the top (a double-sided histogram common in the paleontological literature) is one example of the kind of detail that DNA studies should eventually provide.[13] It shows a single population occupying Europe, with a couple of bottlenecks during the last glacial interval, followed by extinction of the main genetic line during the Late Glacial (the Younger Dryas cold interval), and a subsequent replacement by an offshoot of the main line.

By 60 ka, humans were probably using fire everywhere[14] (although evidence for fire use by *H. floresiensis* is still controversial). The use of Middle Paleolithic stone tools overlapped with the Late Paleolithic stone industry from about 40 to 30 ka, with the latter gradually dying out about 10 ka, as the use of copper and then bronze gradually spread, eventually succeeded by iron **(F)**.[15] The Agricultural (or Neolithic) Revolution seems to have begun in the Near East about 12 ka (10,000 BC). Metal tools, agriculture, and writing will be dominant in the 5.5 ka Panel 8 **(G)**.

PANEL 7: *H. sapiens* OUT OF AFRICA (60 ka to now)



HUMANITY

Ⓓ Human species

Homo floresiensis ("hobbits") perhaps extinct by ~50 ka

Neanderthals extinct ~40 ka

Anatomically modern *Homo sapiens*

Ⓔ Human migrations

? Europe ⟶

Posth et al., 2016, Curr. Biol.

Pre- Late Glacial Maximum (LGM) | *Late Glacial Maximum* | *Post-LGM* | *Late Glacial* | *Holocene*

Arabia? India? Australia? Eurasia? Siberia? Alaska Americas Pacific

Homo sapiens migration out of Africa (ca. 60 ka?)

Ⓕ Tools and fire

Middle Paleolithic stone tools

Late Paleolithic stone tools

Agriculture

Bronze Age and Iron Age

Intentional human use of fire is ubiquitous

Ⓖ Panel 8

50 ka 40 ka 30 ka 20 ka 10 ka

EARTH

Ⓒ Geologic events

Heinrich events, H1-H6, are large accumulations of ice-rafted debris in the North Atlantic sediments. (Hemming, 2004)

H6 ~60 ka

H5 45 ka

H4 38 ka

H3 ~31 ka

H2 24 ka

H1 16.8 ka

Spokane (Missoula) Floods: dozens of catastrophic floods released when glacial Lake Missoula floated its ice dam off the bottom of the Clark Fork valley.

21.4 ka – 13.4 ka

Very rapid deglaciation ends the Pleistocene ice age.

Ⓑ Temperature

Dansgaard-Oeschger events (numbered)

17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Bølling-Allerød (warm)

Warm

Cold

Holocene = Postglacial (warm)

Younger Dryas (cold)

Greenland ice core GISP-2: Stuiver & Grootes (2000)

-30 -35 -40 -45

$\delta^{18}O$ (‰)

Age/stage: Tarantian

Epoch: Late Pleistocene | Holocene

Period: Quaternary

Ⓐ GTS 2012

60 ka 50 ka 40 ka 30 ka 20 ka 10 ka now

ka = thousand years ago

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Panel B-8: Civilization and writing (3500 BC to now)

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Beginning with this panel, time intervals on the human scale make a difference in the geologists' system of "years before the present." It is necessary now to define "the present," and to specify dates in both the geologic and the humanistic systems. For the purposes of ChronoZoom, it is useful to define the present as midnight at the end of the year 1999, at the moment when the calendar changed over to 2000. If still more detailed panels were prepared, it could be specified that this is the end of the second millennium, Eastern Standard Time (in New York). Choosing "the present" in this way avoids the necessity of constantly changing the reference frame for human history, and it honors the humanist historians' recognition that "current events" (in the ChronoZoom case, defined as everything beginning January 1, 2000) are the province of journalists, lacking the chronological perspective that allows historians to make sense of the bewildering complexity of human events.

In humanistic history it is traditional to establish a reference date at some time in the past, with date numbers increasing toward the past prior to the reference date, and increasing toward the present and the future after it. ChronoZoom uses BC and AD **(A)**, which are numerically equivalent to BCE (Before the Common Era) and CE (Common Era). There are other systems with different reference dates, and with complexities such as the use of lunar rather than solar calendars, and with improvements in the calendar introduced at times in the past (such as the change from the Julian to the Gregorian Calendar, adopted by Catholic countries in 1582, and at subsequent times, up to 1923, in Protestant and Eastern Orthodox European countries). Calendrical conversions are a complex mathematical subject which a future, more sophisticated ChronoZoom might need to consider.[1]

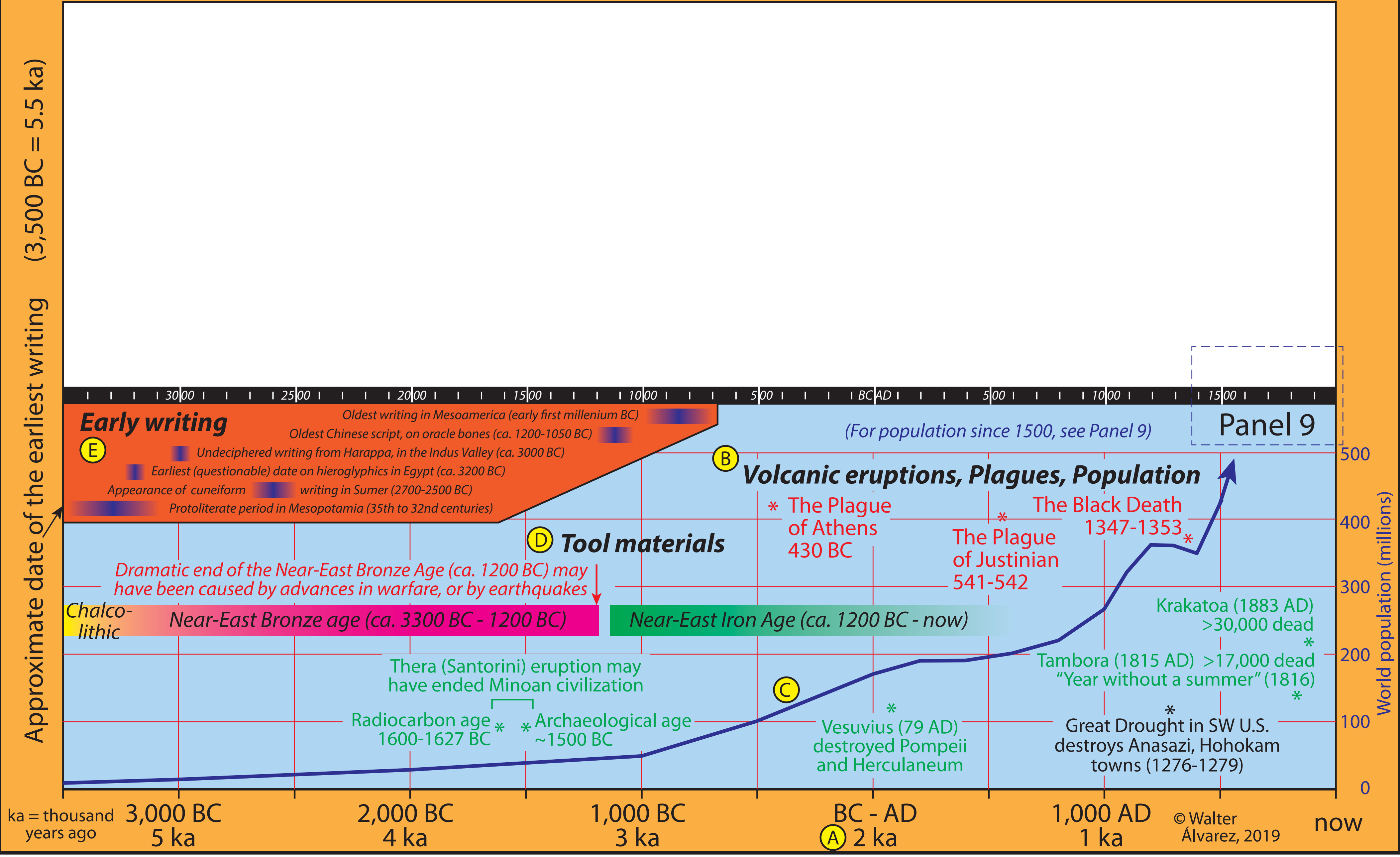
During the 5,500 years of this panel there have been a number of major natural disasters, including explosive volcanic eruptions, pestilences, and drought **(B)**, of which only the Black Death of the middle 14th century was sufficient to produce even a brief downturn in the growth of global population of humankind **(C)**. In fact, from the beginning of this panel to the beginning of the next one, at 1400 AD, the rate of population growth increased, reaching a global total of about 400 million.[2]

Human history prior to the invention of writing (Panel 7) is largely recovered from archaeological excavations. Tools and other artifacts provide much of the available information about how pre-literate people lived. The earliest tools may have been made mainly of wood, which rarely survives in archaeological sites. The main information comes from non-perishable tools, particularly those made from stone or metal. In many parts of the world, it has been useful to divide material cultures, from older to younger, into Stone Age, Bronze Age, and Iron Age **(D)**, and those may be subdivided repeatedly (e.g., Cyprus Late Bronze Age II-C). In some places a Chalcolithic Age (stone plus the soft metal, copper) can be recognized between the Stone Age and the Bronze Age. The Near Eastern region surrounding the Eastern Mediterranean was a center from which these technologies diffused,[3] so this panel shows the ages in this region; each technology arrived later in peripheral regions. In contrast to the usual gradual changes in technology, the end of the Near Eastern Bronze Age, about 1200 BC, was evidently catastrophic, and remains puzzling; it has been attributed both to advances in warfare, rendering chariots useless,[4] and to clusters of major earthquakes.[5]

The beginning of writing **(E)** marks a huge change in how history is understood. Before the invention of writing, the history of human affairs may have been told and remembered for a few generations, perhaps, and then it either entered the realm of legend or, more commonly, was simply lost. After people learned to write, historical records become available in human language, some of it intentionally documenting history, but much of it useful for historians although not written for that purpose — like merchants' inventories, and tax records. Written records are so abundant and rich that even now some historians argue that only written documents constitute real history — a view strongly rejected by historical scientists and Big Historians.

Because of the complexity and detail of global human history, it is not possible to present a useful summary of literate history on a ChronoZoom panel. So we have chosen to leave half of this panel empty, suggesting that users might wish to print out the panel and sketch in the history that interests them on this and the following panels.

PANEL 8: LAST 5,500 YEARS – civilization and writing (3,500 BC to now)



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Panel 9: Global reconnection (1400 to 2000 AD)

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This panel begins 600 years ago, at 1400 AD, **(A)** chosen because this includes the beginning of the Voyages of Discovery, which gradually reconnected people from all over the globe who had been isolated since the Out-of-Africa migration of *Homo sapiens* about 60,000 years ago. In a more regional view, it is also the approximate date of the transition from the Middle Ages to the Renaissance, which has long been a major periodization boundary in Western history.

During the time interval of this panel, a number of serious natural disasters have been visited upon humanity. The Shaanxi event of 1556 **(B)** was the deadliest known earthquake, with huge numbers of people killed when their homes, excavated into loess, the soft, wind-borne glacial deposits, collapsed. The Lisbon Earthquake of 1755 not only largely destroyed Lisbon and most of the historical records of the Portuguese explorations, which may have been the beginning of modern science,[1] but shook the Enlightenment viewpoint in which the world was seen as a benign environment, designed by the deity for human life. Volcanic eruptions **(C)** in Perú and Iceland causes widespread crop failures, and two exceptionally violent volcanic explosions occurred in Indonesia during the 19th century, at Tambora and Krakatoa. Several recurrences **(D)** of the 14th century bubonic plague, or black death, occurred in Europe in the 17th and early 18th centuries, and the great influenza pandemic of 1918-1919 caused an enormous number of fatalities — even the lowest estimate exceeds the loss of life in World War I, and higher estimates are much larger than that **(E)**. Meanwhile, the human population **(F)** continued to grow, at an accelerating pace, especially as the Industrial Revolution unfolded, reaching 1 billion in the early 19th century, and just over 6 billion by the year 2000.[2]

The global dispersal of *Homo sapiens* that began with the second Out-of-Africa migration about 60,000 years ago (Panels 6, 7) left all the continents except Antarctica, as well as many islands, occupied by human beings. Most of those people no longer knew how or when their ancestors got there, and were unaware of people who lived beyond their own networks of travel and communication. These tens of thousands of years of isolation came to an end, beginning in the 15th and 16th centuries **(G)**, when the Voyages of Exploration brought about the global reconnection which has led, in our times to the phenomenon of globalization.

Long-distance seafaring began with the seven voyages of the Chinese admiral Zheng He in the early 15th century. These giant expeditions with hundreds of large ships and tens of thousands of men seem to have been more about establishing Chinese dominance and extracting tribute from kingdoms around the known Indian Ocean than about exploring the unknown, and after Zheng died and a new Emperor took the throne, the Chinese abandoned long-distance seafaring.

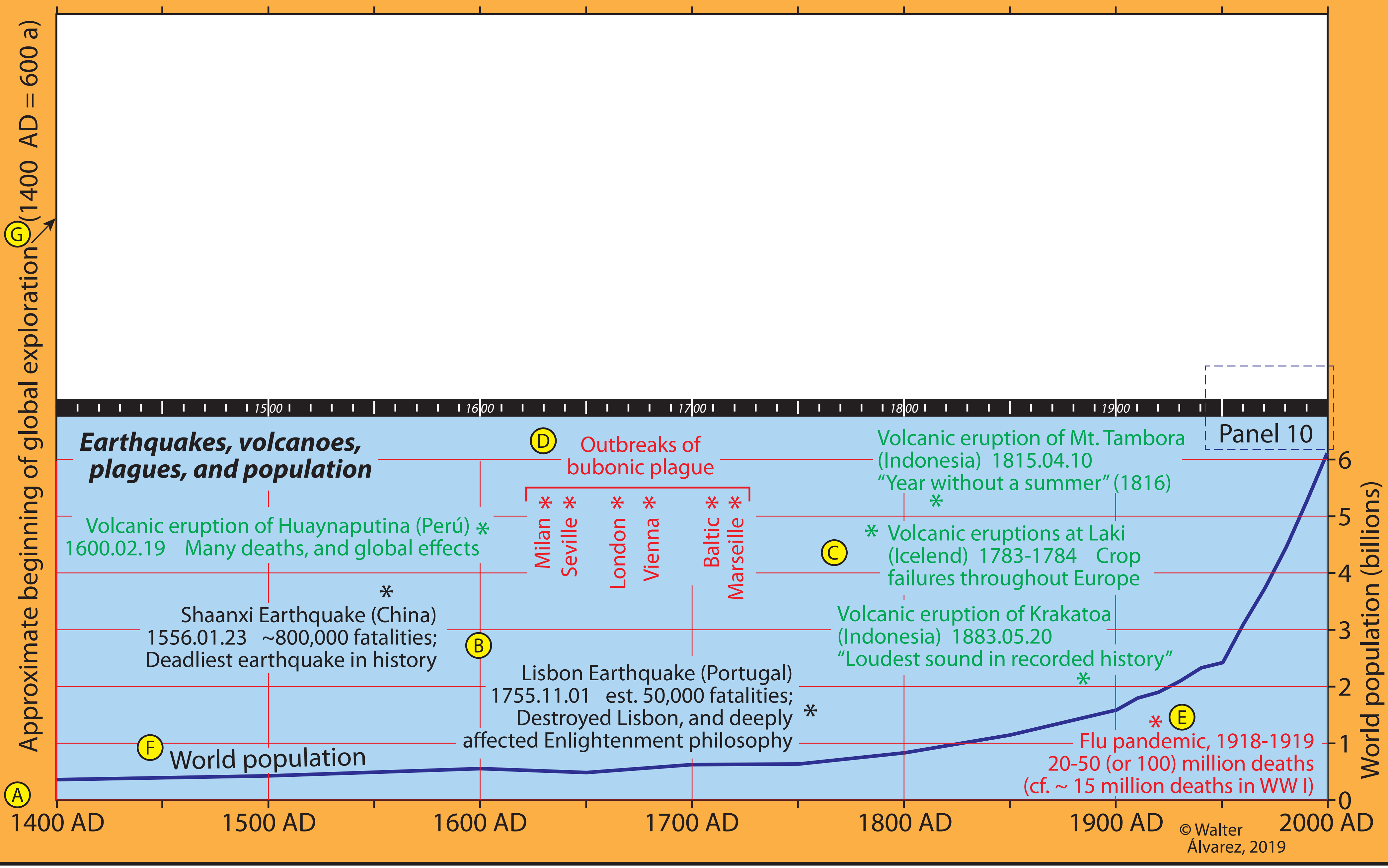
Instead tiny Portugal, on the shores of the Atlantic Ocean and unaffected by the wars that distracted the major Atlantic-facing countries of England, France, and Spain, began the Age of Exploration. Driven by Prince Henry the Navigator, tiny Portuguese caravels gradually explored the west coast of Africa, mapping winds, currents, and magnetic declinations, and discovering a sea route to India by the end of the 15th Century.

With the conquest of Granada completed in 1492, the Spanish discovered and colonized what turned out to be the two new continents of the Americas. For good or ill, humanity around the globe had been re-connected.

It is worth noting a disadvantage of the ChronoZoom design, in which each linear panel enlarges the most recent ~10% of the preceding panel. Although this honors the anthropocentric Big-History approach by zooming in on ever more recent episodes in the history that has led to present-day humanity, it does mean that historical details from farther back in time must be neglected. Nothing in Big History prior to 1400 AD can be shown at the scale of Panel 9, or at larger scale. This of course is a problem at every scale: Panel 3, for example, which shows the history of the entire Phanerozoic, cannot show the history of the Ordovician or the Cretaceous at the level of detail with which panel 4 portrays the Cenozoic.

As in Panel 8, we have shown, in the lower half of this panel, the global population and some natural events that affected human history. Again we have left the upper half of this panel blank for the user to fill in with a personal selection of events and trends from the vast cornucopia of knowledge available to historians of literate humanity.

PANEL 9: LAST 600 YEARS – Global reconnection (1400 to 2000 AD)



Earthquakes, volcanoes, plagues, and population

Outbreaks of bubonic plague

Milan *
Seville *
London *
Vienna *
Baltic *
Marseille *

Volcanic eruption of Huaynaputina (Perú) *
1600.02.19 Many deaths, and global effects

*
Shaanxi Earthquake (China)
1556.01.23 ~800,000 fatalities;
Deadliest earthquake in history

Lisbon Earthquake (Portugal)
1755.11.01 est. 50,000 fatalities;
Destroyed Lisbon, and deeply *
affected Enlightenment philosophy

Volcanic eruption of Mt. Tambora
(Indonesia) 1815.04.10
“Year without a summer” (1816)
*

* Volcanic eruptions at Laki
(Icelend) 1783-1784 Crop
failures throughout Europe

Volcanic eruption of Krakatoa
(Indonesia) 1883.05.20
“Loudest sound in recorded history”
*

*
Flu pandemic, 1918-1919
20-50 (or 100) million deaths
(cf. ~ 15 million deaths in WW I)

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Panel 10: Cold War/Long Peace (1945 to 2000 AD)

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In this panel, for the first time, individual years are resolved on the time axis, so the tick marks are labeled as January 1 of the relevant year **(A)**. Compare this with Panel 2, showing all of Earth history, where each tick mark represents 100 million years! The start of this panel is January 1, 1945, a few months before the end of World War II, when the global human situation changed from all-out warfare to the uneasy, armed peace that lasted until and beyond the year 2000.

Even in this short time interval, there were a number of major natural disasters. The greatest earthquakes **(B)** recorded in North America (Alaska, 1964, $M_w = 9.2$) and globally (Chile, 1960, $M_w = 9.5$) took place during the 1960s, along with the Mexico City earthquake of 1985, which was particularly destructive because of instability of the soft sediment of former Lake Texcoco, on which much of the city is built. All three of these events, and in fact, most of the earthquakes with $M_w \geq 8$ since 1900 have occurred on subduction zones either surrounding the Pacific Ocean or around Indonesia.[1]

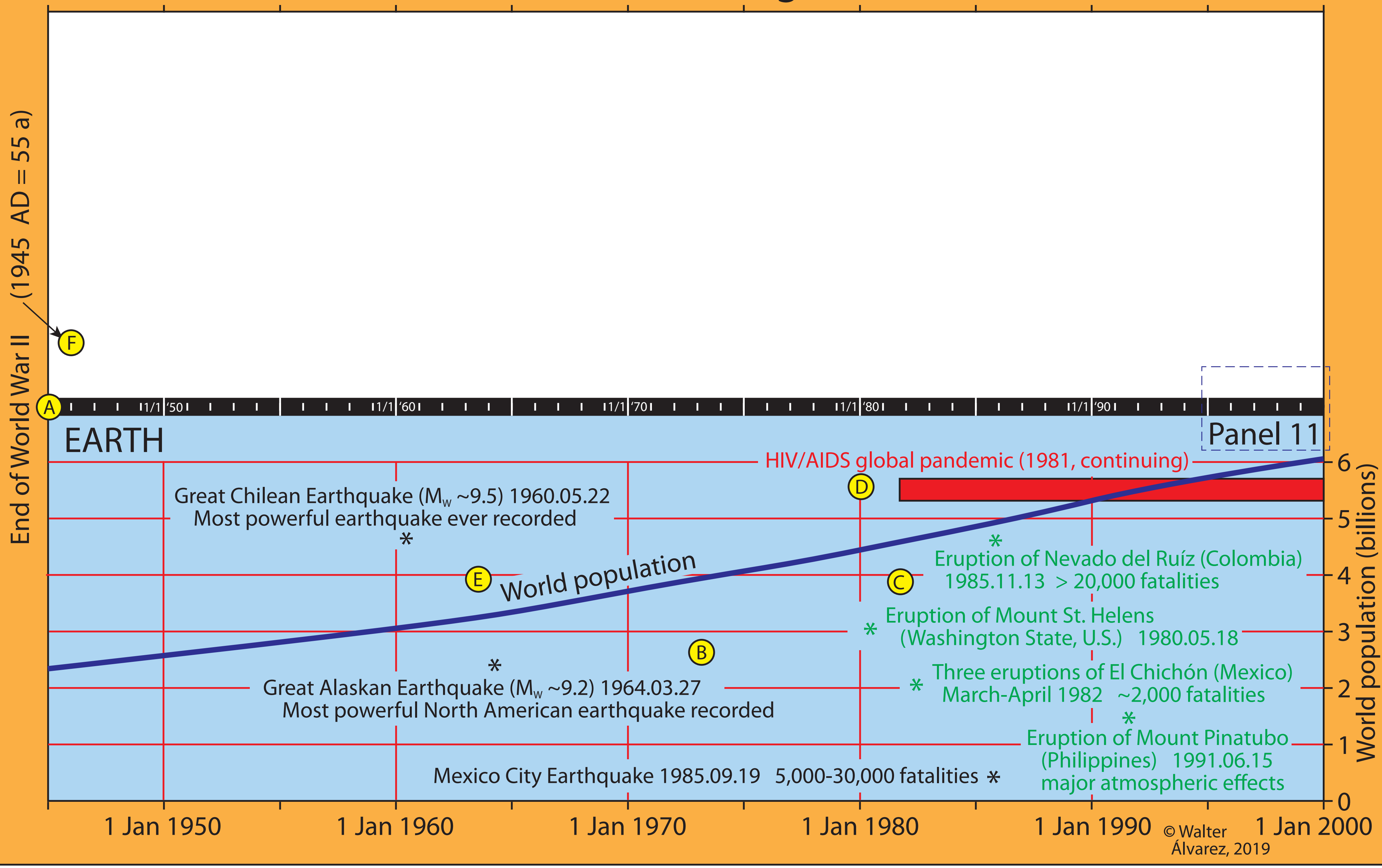
The decade of the 1980s saw three devastating volcanic events **(C)**, with another in 1991. The worst of these was the eruption of the stratovolcano, Nevado del Ruíz, in the Colombian Andes, on November 13, 1985. Although only 5° north of the equator, this mountain is 5,300 m (17,500 ft) high, and was covered with snow at the time of the eruption. During the event, large amounts of hot volcanic ash fell onto the snow, melting it and generating lahars, or volcanic mudflows, which swept down valleys on the east side of the volcano. One lahar overwhelmed the town of Armero, killing 2/3 of its nearly 30,000 inhabitants.[2] This event, known as the Tragedy of Armero, was greatly worsened by the paralysis of the Colombian government, then facing the height of an armed insurgency, and by the fact that the Mexico City earthquake had taken place just two months earlier, so that much of the global emergency response capability was already deployed in Mexico. Major volcanic events with fewer fatalities took place at El Chichón in Mexico, Mount Pinatubo in the Philippines, and Mount Saint Helens in the Cascades of Washington State — the latter being first eruption in the lower United States since Mount Lassen in 1915.

Beginning in 1981 and continuing to the present day, the global HIV/AIDS pandemic **(D)** has killed more than 30 million people, and is only slowly being brought under control.[3]

The growth of the human population **(E)**, reaching 6 billion just before the year 2000, looks less steep than it does on Panel 9, but this is because of the expansion of the time scale by a factor of ~10. Human beings are now so numerous and health care so advanced that the population curve shown here does not reflect even great natural disasters. However, this situation is not necessarily permanent. Much greater disasters are certainly possible. Impact of a 10-km asteroid or comet 66 million years ago caused a mass extinction throughout the plant and animal worlds. Full-scale nuclear war nearly took place at least twice during the time of this panel, and many such weapons remain, with new nuclear powers emerging. Collapse of the economic system or of agricultural production and distribution are not impossible. The current economic system depends on continual growth, but unrestrained growth is clearly not sustainable indefinitely on a finite Earth. It is hard to avoid the conclusion that we must voluntarily transition to a non-growing population and a sustainable economy, or Nature will do it for us.

A major human milestone was passed, for good or ill, on July 16, 1945, with the explosion of the first ever atomic (fission) bomb at Alamogordo, New Mexico **(F)**. Within a month, two such weapons destroyed Hiroshima and Nagasaki, the Japanese surrendered, and World War II was over. Within a decade the Soviet Union tested its own atomic bomb, the U.S. tested a much more powerful hydrogen (fusion) bomb, the Soviet Union matched it, and the world entered a new era, living constantly under the threat of nuclear annihilation.

PANEL 10: LAST 55 YEARS – Cold War/Long Peace (1945 to 2000 AD)



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Panel 11: Sunset of the Millennium (1995 to 2000 AD)

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Panel 10 was the last one for which there is major historical content to portray graphically and describe. Two more panels, 11 and 12, have been added in order to continue to the last day of 1999, so that ChronoZoom can display a continuous, linear historical sequence from one day to the entire duration of the Cosmos — a zoom factor of 5 x 10^{12} (5 trillion). Blank space again is left for users, and a few natural events have been selected to populate the two panels, but rather than describing them in detail, the available text space is used to consider broader issues of Big History — Dating and periodizing history (Panel 11), and the Character of history (Panel 12).

Dating and periodizing history

Human beings are not born with the ability to date events in the past, or even to remember and pass on their memories of bygone events for more than a few generations. Before writing and written documents became available, the more distant past would become part of legend. Under those conditions, serious history was not possible.

Writing does not guarantee dated history, however. First a calendar is needed, and the recognizable changes of the four seasons make *years* the obvious calendrical basis. Modern calendars count years in continuous sequence, but students of early civilizations must deal with dates like "in the fourteenth year of the reign of King So-and-So." Much effort has gone into translating phrases like this into years BC, but questions remain — for example, there are several decades difference between the "high" and "low" Egyptian Bronze Age chronologies. The Mayan calendar was still more complicated and challenging to decipher.[1] Even for times and places with well-established chronologies, many documents are not dated. However, once the modern times of Panel 9 are reached, there are few problems with dating the written historical record. This has led generations of scholars to consider that the only "history" is written history. Historical scientists and Big Historians consider this view outmoded, and it is gradually passing away.

During the 20th century, historical *scientists* learned to date many kinds of events that occurred before the invention of writing. Geology was the first, starting with fossils in the 19th century, which allowed rocks to be placed in chronological sequence, followed by several systems of radiometric dating in years during the 20th century. Two things make radiometric dating possible. First, radioactive atoms in a mineral grain decay at a statistically constant rate given by the half-life, so that the ratio of daughter atoms to parent atoms gives the age of the mineral grain (although this is more complicated in practice!). Second, radioactive decay takes place in the tiny nucleus of the atom, shielded by the much larger surrounding electron cloud, so the decay rate is protected from the temperature and pressure conditions that make rates of *chemical* change vary with time. Hundreds of thousands of radiometric dates now constrain the chronology of Earth history. In the later 20th century, additional ways of dating rocks were developed, including fingerprinting with geomagnetic polarity reversals, various kinds of stable isotope stratigraphy, cyclostratigraphy and, for other solar-system bodies, crater-count statistics.[2]

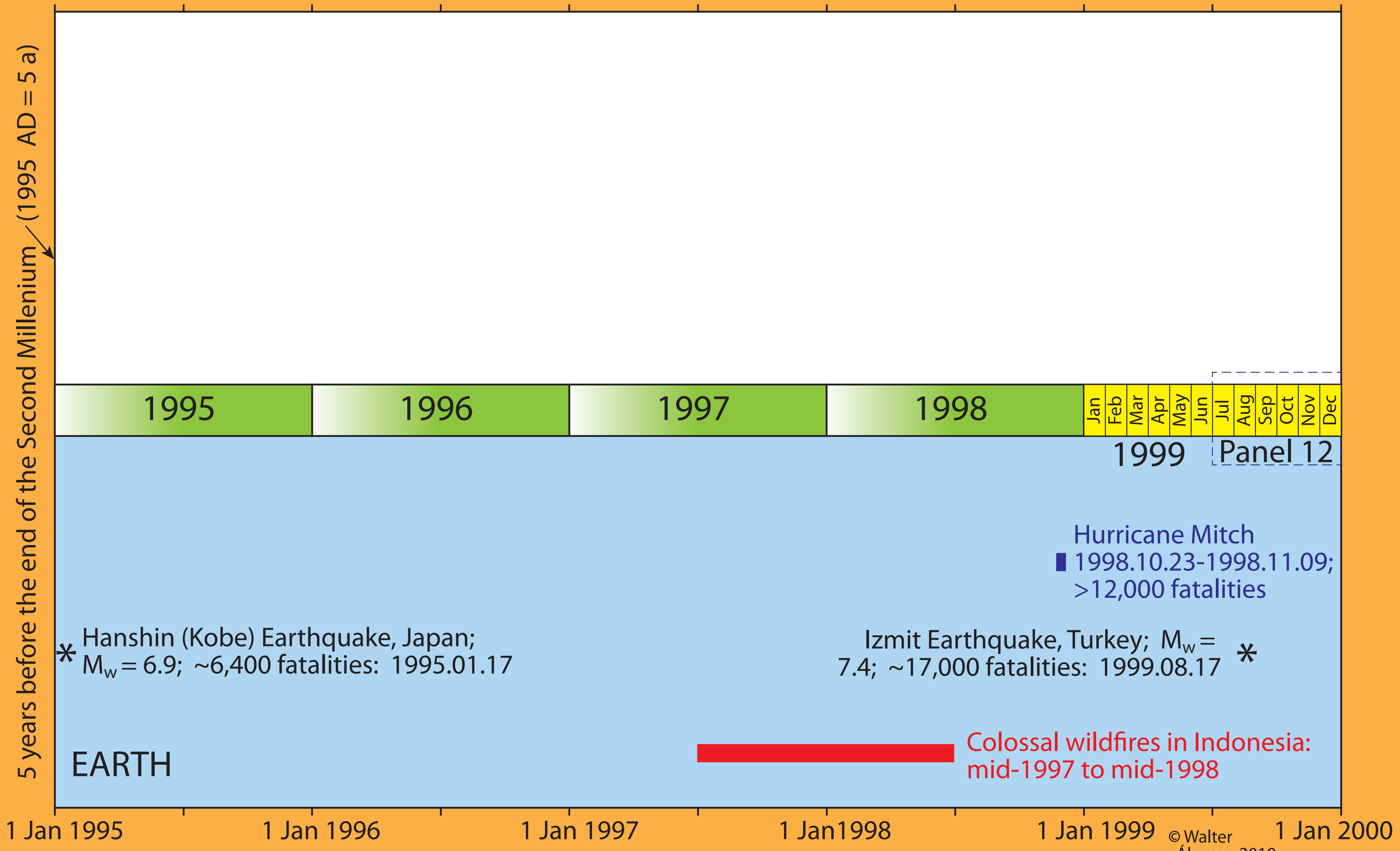
Archaeologists date their findings in ways similarly to those used in geology, although with radiocarbon dating being of great importance, because ^{14}C, produced by cosmic-ray bombardment of nitrogen in the atmosphere, has a half life of only ~5,730 years, so it is suitable for obtaining dates back to about 40,000 years. In archaeology, artifacts, especially pottery shards and coins, play the same role as fossils do in geology.

Paleontologists cannot get dates in years directly from fossils, except for very young ones where radiocarbon dating can be used. Dating of fossils is done indirectly, often by dating volcanic mineral grains in associated volcanic ash beds. The grains in an ash bed will have had their age set to zero when hot magma cooled during the eruption, and if the grains then fell in an ash bed, their radiometric age also dates the bed. Much work is currently being done on establishing evolutionary trees based on the DNA of living organisms, and attempts have been made to date nodes in these family trees using the assumption that rates of mutation are constant through time.[3] This assumption seem unlikely to be correct, since it involves chemical changes in DNA, unlike the protected nuclear changes that make radiometric dating so successful.

Astronomers have come most recently to dating history. With cosmic expansion understood, redshift allows the dating of light emitted from distant galaxies. Globular clusters, huge gravitationally-bound collections of stars in the Milky Way can be been dated by the mass of the stars that turn off the main sequence, for larger, brighter stars burn out more quickly.[4] It has long been impossible to date individual stars, but this may be solved by a new technique called gyrochronology, for it has been shown, perhaps surprisingly, that the rotation rate of a star is a function of its age.[5] The ages of events during the Big Bang are calculated theoretically.

Dividing history into periods is essential for understanding it. Historians and archaeologists use informal periodizations (e.g., Roman Empire, Late Bronze Age). Only in geology and paleontology are there formal periodizations (e.g., Cretaceous), established by standard procedures and accepted internationally, leading to the constantly improving geologic time scale.[6]

PANEL 11: SUNSET OF THE MILLENNIUM – (1995 AD to now)



Hurricane Mitch
1998.10.23-1998.11.09;
>12,000 fatalities

* Hanshin (Kobe) Earthquake, Japan;
$M_w = 6.9$; ~6,400 fatalities: 1995.01.17

Izmit Earthquake, Turkey; $M_w =$
7.4; ~17,000 fatalities: 1999.08.17 *

Colossal wildfires in Indonesia:
mid-1997 to mid-1998

© Walter Álvarez, 2019

Panel 12: Millennium's End (1995.5 to end of the Second Millennium)

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In a sense, history is everything that has happened from the Big Bang up to "now," that being the name for the mysterious and fleeting instant between past and future.[1] It has been convenient however, in ChronoZoom, to cut off the time line at midnight between December 31, 1999 and January 1, 2000 — at the exact end of the Second Millennium. This has two advantages: it avoids the problem that "now" is constantly advancing, which would require continual updating of the time line, and it avoids the last few years, which historians think of as current events, not yet offering the advantage of hindsight and perspective. As is the case for Panel 11, this panel was added to bring the resolution down to one day, and a few events are shown for this half year, but not described. Instead this space is used to give some consideration to the character of history.[2]

The Character of History

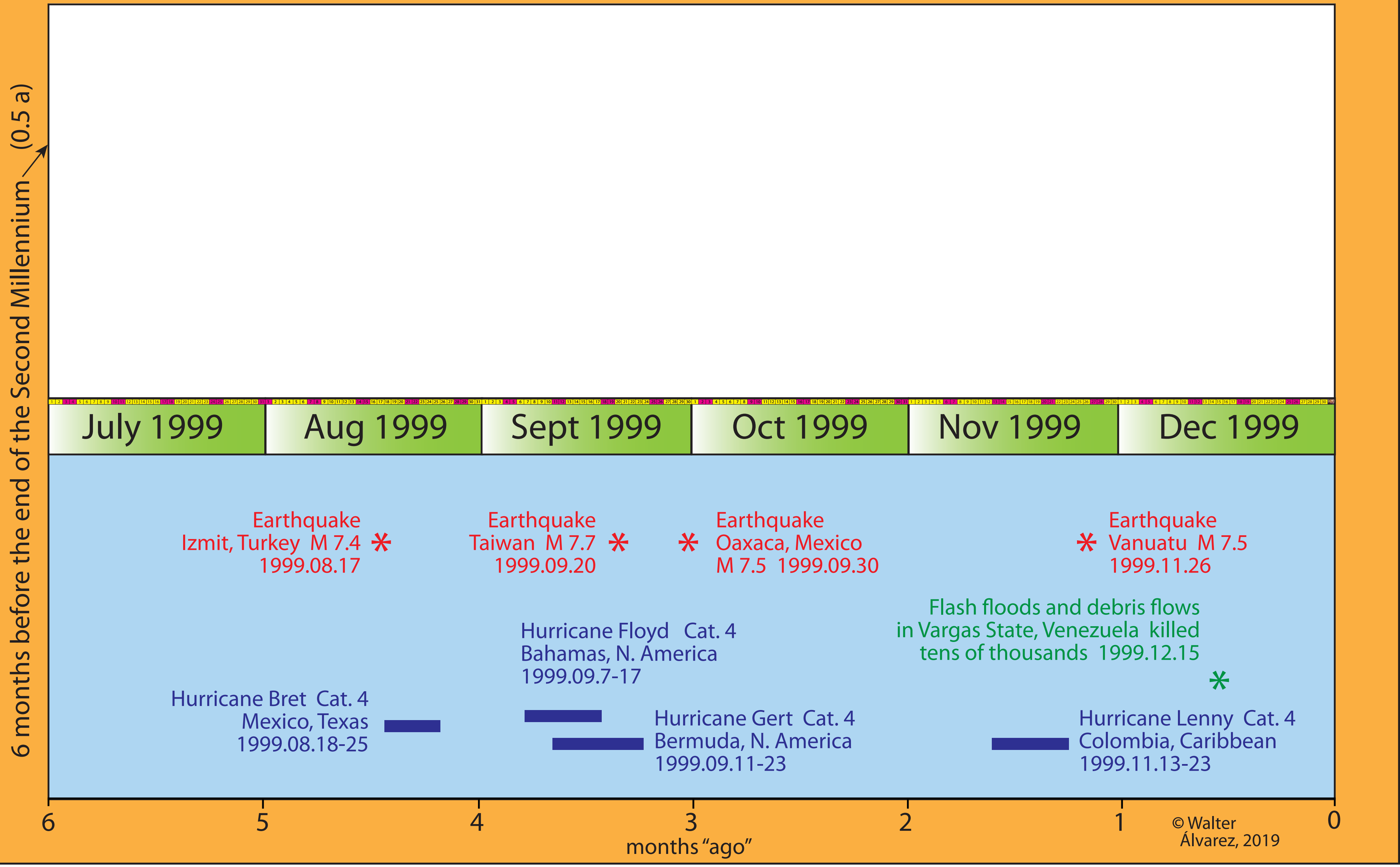
After Isaac Newton and the physicists who followed him showed that the behavior of the world is governed by unbreakable mathematical laws, an obvious corollary was that history also unfolds according to natural laws, and historians sought to uncover those laws. The effort was notably unsuccessful,[3] and the reasons for that lack of success are beginning to be clear. The laws of physics specify what *can* happen and what cannot (like rocks suddenly rising into the air, or ashes in a cold fireplace bursting into flame), and so physics may be thought of as a *process* science. But there are limits to the ability of physics to predict outcomes — in the case, for example, of sensitive dependence on initial conditions,[4] or when a human being thinks about desired outcomes and makes choices. Finding out what exactly *did* happen is the realm of the *historical* sciences like geology. The complexity of history portrayed by the ChronoZoom panels makes it hard to suppose that the natural situation could have been predicted millions of years in advance, or that its human aspects were inevitable even a few years ago. Rather than search for *laws* of history, it therefore makes more sense to ask what is the *character* of history.

A traditional way to think about the character of history is to ask whether it has unfolded as a very long series of cycles, as in Hindu philosophy, or with linear trends, as in the brief Christian trajectory from Creation to the Day of Judgment. This dichotomy was also prominent in the thinking of the early geologists.[5] It is easy to talk about arrows like "the decline of the West," or cycles like "the rise and fall of empires," but these easy descriptions are difficult to justify in the light of the abundant quantitative data that is more and more available in the historical sciences, especially geology. An excellent example comes from the temperature records in ChronoZoom. Panel 3 shows a long temperature history for the Phanerozoic which is clearly cyclical, but whether the period of the cyclicity is about 40 million years or about 100 million years depends on how the curve is fitted. Panel 4 shows a long cooling trend, but there are long cyclical fluctuations superimposed upon it. Panel 5 shows fluctuations which look random until about 3 Ma, then are high-frequency, symmetrical cycles until about 1 Ma, and finally, as enlarged in Panel 6, low-frequency, asymmetrical cycles continuing until the present time. Finally Panel 7 shows that the temperature for the last 10 kyr has been quite constant. When faced with quantitative historical data sets, neither time's arrow nor time's cycle seems like a useful description of the character of history.

A better approach may be to think in terms of continuities vs. contingencies. Continuities are time sequences like those just considered, with some degree of order and at least short-term predictability, whether more arrow-like or more cycle-like. Contingencies punctuate the continuities of history, and are relatively brief compared to the intervals of continuity that flank them. Natural examples include the assembly of Earth (Panel 2), the Great Ordovician Biodiversification Event and the KT impact and extinction (Panel 3), and the desiccation and refilling of the Mediterranean (Panel 4). It is not at all clear how to define contingency with rigor. Perhaps a contingency needs to be rare, unpredictable, and significant, but there are problems in quantifying each of these. Rarity is scale dependent — for example, only one impact of an Everest-size object is known from the entire Phanerozoic, but sand-size micrometeorites, making meteor streaks, happen many times each night. Unpredictability is ambiguous — orbital movements of potential impactors are predictable with exquisite precision over time scales of years or centuries, but unpredictable over Solar-system history because of sensitive dependence on initial conditions. Significance depends on context — the deaths of most individuals are significant only for their families, while the death of Julius Caesar profoundly affected history.

The unpredictability introduced in natural systems by considerations like sensitive dependence on initial conditions is dwarfed by the unpredictability of sexual reproduction in multicellular organisms and by the human brain. Each human being has two parents, 4 grandparents, etc., with ~1,000 family-tree boxes 10 generation back, ~10^6 boxes 20 generations back, ~10^9 boxes 30 generations back, etc. The sex of each ancestor was determined essentially randomly at conception, and if even one of those myriad ancestors had been of the opposite sex, that person could not be in that box of the family tree, and none of the descendants of that ancestor would exist. The ability of human beings to do thought experiments and make decisions introduces even more unpredictability to history, which might be thought of a system for ensuring unforeseeable outcomes.

PANEL 12: MILLENNIUM'S END – (1999.5 AD to end of the Second Millennium)



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Last 600 Years – Global Reconnection (Panel 9)

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Cold War/Long Peace (Panel 10)

1. For a useful graph showing the history of earthquake magnitude and fatalities from 1900 to 2015, prepared by Cmglee, see https://commons.wikimedia.org/wiki/File:USGS_magnitude_8_earthquakes_since_1900.svg (This graph cannot be expanded back in time, because instrumental seismology does not go back much before 1900.)
2. The remains of Armero can be seen on Google Earth at 4° 57.8' N, 74° 54.3' W.
3. AIDS Info Online (http://www.aidsinfoonline.org/devinfo/libraries/aspx/dataview.aspx) does not give figures for the 1980s, but shows about 34 million AIDS-related fatalities from 1990 to 2015.

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