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

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 The fact that that obsolete name has been replaced by Hadean, Archean, and Proterozoic reflects a great 20th century advance in dating and understanding Earth History.[2]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.