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Mass extinctions

A short history of Life on Earth

The Earth had already been revolving around the Sun for nearly four billion years when Life entered a major new stage. For more than two billion years, the only life forms had been isolated cells floating in the worldwide ocean. But now these cells began to associate with one another, becoming the first multicellular organisms. This was some 700 million years ago.[1]

It would take only another 100 Ma for certain organisms to develop a skeleton: hard parts that could be preserved in rock long after the organisms died. What we know of the past forms of Life on Earth is largely based on these fossils: they have given us a far more accurate picture of the past 600 Ma than we have of the billions of years that went before.

Another 100 Ma, and the seas are now populated with fish. Yet another 100, and their descendants can lay sturdy eggs; now equipped with lungs, they grow bolder, abandon the water, and conquer the continents, as yet uninhabited. Then, 260 Ma ago comes the "invention" of warm blood, and the first proto-mammals begin to prosper. Here, at the end of the Paleozoic Era (Fig. 1.1), the abundant and varied fauna and flora bear every mark of success, both in the ocean depths and on the emergent land. Yet almost all at once, 250 Ma ago, a catastrophe causes 90% of all species to vanish forever.[2] For an entire species to disappear, every individual it comprises must die without descendants. When 90% of all species

1 A million years will be our 'unit of reckoning' for geological time, and we will abbreviate it as Ma.

2 Biologists have developed a hierarchical classification of living organisms based on the concept of an 'evolutionary tree.' This taxonomy recognizes seven levels, from the kingdom (of which there are five: Plants, Animals, Fungi, Protista, and Monera) to the phylum (of which there are between 20 and 30), then the class, order, family and genus, and ending with the last, indivisible unit, the species. By definition, this last groups together those individuals capable of reproducing among themselves.

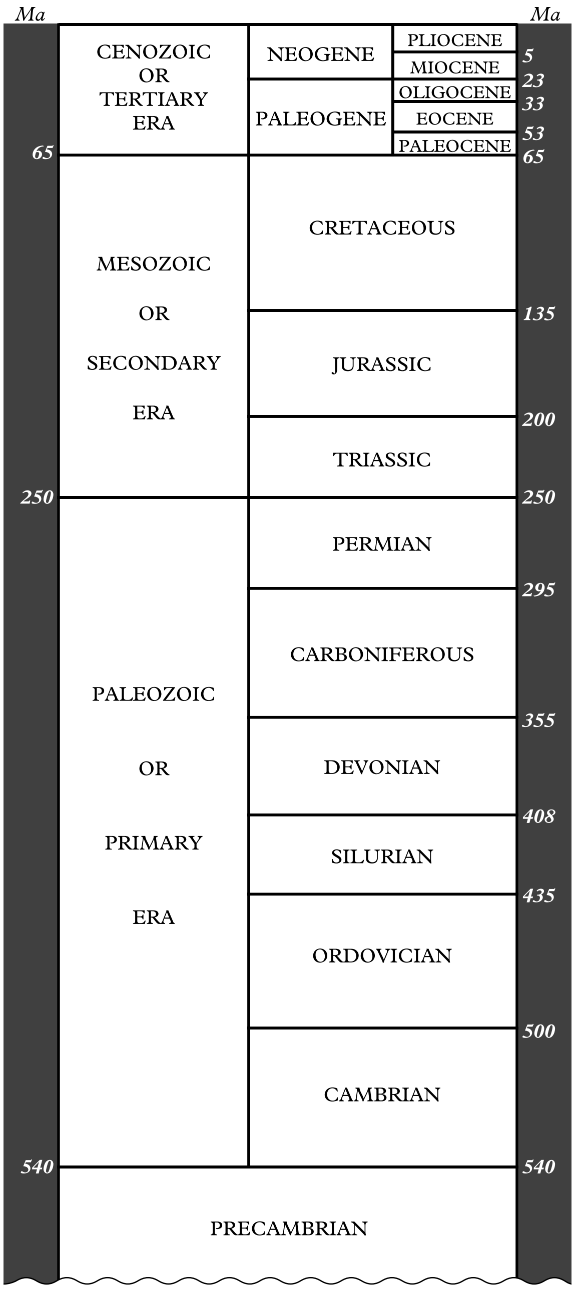

Figure 1.1
The geological time scale, with the main divisions since the Cambrian Period. Ages are given in millions of years (Ma).

die out, the populations of the remaining 10% will certainly be hard hit as well: in fact, perhaps 99% of all animals living at the end of the Paleozoic perished. This is the most extensive of all mass extinctions known today.

But not all died, and the survivors set out to reconquer the space so unexpectedly swept clear for them. This start of the Mesozoic Era is dominated by pig-sized plant-eaters called *Lystrosaurus*. They have large amphibians for company, along with other reptiles who will soon give rise to the first true mammals and the first dinosaurs. A new catastrophe, less violent than the first, arrives to decimate the last proto-mammals, the great amphibians, and (in the oceans) almost all species of ammonoids.[3]

Small, hiding in the trees and living on insects, our mammal ancestors were anything but conspicuous. You might almost say they encouraged the world to forget they were there. For this, in fact, was the real beginning of the age of dinosaurs. Recent paleontologic research has given us a whole new perspective on these beasts. Some may have been warm-blooded. The great long-necked, plant-eating sauropods, like the celebrated *Diplodocus*, gradually gave way to animals sporting horns and duckbills, grazing no longer on the treetops but on grass and bushes. Their predators were those great carnivores, colorful and agile, who for decades have delighted children and made film producers' fortunes. A few minutes of *Jurassic Park* and *The Lost World* (the movies) give a very fine view of them.

Then, 65 Ma ago, a huge catastrophe once again ravaged this world, which had seemed so perfectly adapted and balanced. This was the end of the dinosaurs and many mammals, but also of a great many other terrestrial and marine species, including the well-known ammonites and a considerable number of smaller and less familiar organisms that constituted the marine plankton. In all, two-thirds of the species then living (and possibly 80% of all individuals) were wiped out. This is the second great mass extinction.

Yet again the momentum resumes, and in less than 15 Ma we find the ancestors of most animals that still live on our Earth today.

3 The ammonites would later descend from their survivors.

As the climate turns colder, modern fauna comes into place some 30 Ma ago. The age of dinosaurs has yielded to the age of mammals, delivered at last from their chief rivals. And the Mesozoic is succeeded by the Cenozoic Era.

Extinctions and geological eras

Paleozoic, Mesozoic, Cenozoic:[4] for you, as for me, the names of the geological eras may summon up the boredom of old-fashioned junior-high science classes. Yet for all that, they still reflect the great rhythms of the evolution of species, and of great catastrophes that have shaken our globe down through its history.

It was in 1860 that John Phillips decided to define the three great geological eras on the basis of the two major biological disruptions we have just mentioned. These disruptions were discovered by George Cuvier (1769–1832), telling us something not only about this scientist's gifts but also (since they were recognized so early) of the exceptional magnitude of these catastrophes, when not only the actors in evolution but the very rules of the game itself abruptly seem to change. Species, like the living beings of which they consist, have a history: they are born, they develop, and then one day they are no more. No doubt it's hard for human beings to imagine the end of the species they belong to, or to conceive that over 99.9 % of the species that ever lived on Earth are already extinct. American paleontologist David Raup wryly observed that a planet where only one species in a thousand survives is hardly safe.

From the nature and distribution of the fossil remains he took from the rocky strata of the Paris Basin, Cuvier discovered that each stratum is characterized by an assemblage of its own typical fauna. But above all, he realized that a great many of these species no longer exist – they are extinct. Cuvier credited the Divinity for their sudden appearance and blamed their disappearance on some more earthly cause (a "terrible event," he wrote), such as a catastrophic

4 Geologists often prefer Greek etymology to Latin. But some, among them the French, also speak of the Primary, Secondary, and Tertiary Eras. The three Greek terms mean the ages of Ancient, Intermediate, and Recent Life. We'll use the two sets of terms interchangeably, particularly 'Cenozoic' and 'Tertiary.'

flood. It was thus that he identified the Biblical Flood as the last event preceding the modern age and the appearance of humans. According to him, none of the "agents" that Nature employs today "would have sufficed to produce its ancient works." When in 1801 his colleague Geoffroy Saint-Hilaire (1772–1844) brought back from Egypt the mummified bodies of animals identical to species still extant, Cuvier was convinced that between any two catastrophes the species remained the same and underwent no modifications.[5]

The rise of catastrophism

This catastrophism, adopted by many geologists, was in evident harmony with the predominant theology of the day and perhaps drew additional, if unconscious, support from the political turmoil amid which the "age of enlightenment" drew to a close. For instance, in 1829 Elie de Beaumont established the existence of a major episode of geological uplift in the Pyrenees, between the end of the Mesozoic and the beginning of the Cenozoic, and saw the rise of the mountains as the chief cause for the mass extinction of species between the two eras. Many naturalists back then believed that geological time had been punctuated by catastrophes, and that each event may have had a different cause.

Yet ever since the middle of the eighteenth century, another school, taking its independent and very different inspiration from Buffon (1708–88) in Paris and Hutton (1726–97) in Edinburgh, had resisted the appeal of catastrophes and attributed the magnitude of the observed phenomena to the immensity of geological time. Before Cuvier was even born, Buffon had rejected the notion of original catastrophes and estimated the Earth's age at the then-imposing figure of 75,000 years,[6] whereas the Biblical calendar set the Creation only 6000 years in the past. Twenty-five years older than Cuvier, and unaware of Hutton's works, the militant freethinker Lamarck (1744–1829) also reached the conclusion that the dynamics of

5 However, toward the end of his life, he would become persuaded that species are partly molded by their environment and may transmit some of the characteristics thus acquired to their descendants.

6 He would even propose – though without publishing it – the figure of 3 Ma, almost unimaginable in those days. See for example E. Buffetaut, *Des fossiles et des hommes*, Paris, Laffont, 1991.

geological processes are slow but inexorable. Without ever using the term evolution, he conceived the slow changing of species; unfortunately, his vision would degenerate into caricature in the hands of some of his successors. In particular, he realized that the 3000 years that separate us from Geoffroy Saint-Hilaire's Egyptian mummies are negligible in comparison with geological time. But Lamarck did not accept the idea that species might become extinct. According to him, they are gradually transformed by direct descent, or even (for those species that have apparently disappeared today) still survive in unexplored regions of the globe. His German contemporary Blumenbach (1752–1840) took a significant step in proposing that the two concepts of vanished species and distinct epochs in Nature should be combined.[7] He envisaged a long succession of periods, characterized by distinct faunas eliminated one after the other by climatically induced global catastrophes.

Where Lamarck intuited an extreme plasticity of species, Cuvier saw only absolute fixity. Able and powerful, the latter would ensure that his ideas were accepted, at least during his lifetime. It would be up to Charles Darwin to show that Cuvier's remarkable observations, which influenced him significantly, were to some extent compatible with the very theories Cuvier fought, and that Lamarck and Geoffroy Saint-Hilaire were not entirely on the wrong track. Which nevertheless did not prevent him, in his *The Voyage of the Beagle*, from taking a good many potshots at Lamarck, whom some view as the other founder of the theory of evolution.

Uniformitarianism replies

Cuvier's catastrophism was vigorously defended by Buckland in England and Agassiz (better known for his work on glaciation) in the USA. But Charles Lyell (1797–1875) took up the torch from Buffon and Hutton and carried it much further. In his *Principles of Geology*, the first edition of which appeared in 1830, he refuted the entire idea of catastrophes and postulated that all observed geological phenomena must be explicable by processes still in existence. He assumed that these processes had not varied, in either their

7 In E. Buffetaut, see note 6.

nature (a theory called uniformitarianism) or their intensity (and this theory acquired the name "substantive" uniformitarianism). Thus only the incredible length of geological time explains the magnitude of the observed phenomena: the erosion of valleys, the uplift of mountain chains, the deposition of vast sedimentary basins, movement along faults owing to cumulative seismic activity – and the mass extinction of species. As Lyell himself said, no vestige remains of the time of the beginning, and there is no prospect for an end. This world, in its state of equilibrium, held no place for evolution. A friend of Darwin, who was profoundly influenced by his work, Lyell nevertheless had the greatest difficulty rejecting the idea that species were static. Until 1860, he instead imagined a cyclic history for the Earth and the life forms inhabiting it. Darwin himself thought nothing more astonishing than these repeated extinctions, which he, in fact, explained by long periods that left no geological deposits. He discreetly discarded everything in observations that might support catastrophism and chalked up such findings to imperfections in the geological record instead.

The early nineteenth century witnessed the opposition – sometimes violent – of the catastrophist school and the uniformitarian school. Yet this theoretical quarrel did not prevent geology from growing. Quite the contrary. Lyell's views would ultimately triumph and make it possible to found a great many branches of modern scientific geology. In fact they remain deeply ingrained in the minds of most geologists, even as recent history has made us familiar with the concepts of evolution and dynamism and, unfortunately, given vigorous new life to the notion of catastrophe. Nuclear war, overpopulation, famine, desertification, the greenhouse effect, the hole in the ozone layer – so many threats, real or assumed, that frighten us and that our newspapers outdo one another in reporting – all are birds of ill omen for the agitated end of a millennium. Are humans at risk of disappearing, the victims of their own folly or of a Nature gone haywire? If, as Lyell thought, the present must be our key to understanding the past, this same past in fact harbors the keys, sometimes carefully concealed, to a better understanding of our present, and possibly to a way of safeguarding the future.

The geological time scale

To discover these keys, however, we need some kind of orientation mark. We have to measure time. Little by little, since the nineteenth century and Lyell, a history of geological time has been built up and is still being improved today. Paleontologists and stratigraphers have learned to recognize the regional or global significance of changes in fauna and flora, assess the size of these changes, and determine the continuity of their rhythm. This has allowed them to set up, and continue to refine, a time scale (Fig. 1.1), with its eras, periods, epochs, stages, and substages. The second half of the twentieth century contributed a method to measure these times absolutely; geochemists and geochronologists now know how to determine time from the radioactive decay of a number of chemical elements. More recently, in the lava of sea floors and later in exposed continental sediments, geophysicists discovered long sequences of sudden reversals in the magnetic polarity of rocks. Numerous, irregularly spaced, and very brief, these reversals made it possible, once they were identified, to establish an extraordinarily close-meshed web of correlations, and thus an effective means of determining dates (see Chapters 2 and 7).

Today we have an absolute geological time scale, particularly for the fossil-bearing ages (or in other words, approximately the last 600 Ma). In the brief description of the history of Life on Earth that we started with, we tossed about figures of hundreds of millions of years. But now we need to get more familiar with that very long unit of reckoning, a million years. Often the duration of geological time is illustrated by comparison to a single year.[8] But it seems just as illuminating to recall that our planet was formed about 4500 Ma ago; that the dinosaurs disappeared 65 Ma ago; that our ancestor (or cousin?) Lucy lived 3 Ma ago. It is also worth remembering that the last period of maximum glaciation was 20,000 years ago (0.02 Ma) and that the conflicting scenarios we are going to examine to describe what the Earth went through at the end of the Mesozoic took several Ma, according to some experts – and only a few seconds, accord-

8 In this case, the Mesozoic covers only two weeks of the last month of the year, from December 11 to 26, when the Cenozoic begins. The human race appears at 2 p.m. on December 31; the pyramids are built at 30 seconds to midnight.

ing to others! Between this second and the age of the Earth, the reader must blithely contemplate 17 orders of magnitude.[9]

"Normal" extinctions or mass extinctions?

Paleontologists know that apart from a few very rare "living fossils" (such as the fish called the coelacanth or that lovely tree the ginkgo), most species have a span of existence that is on the whole quite short in terms of the yardstick we have adopted: after a more or less extended period of stability, they ultimately die out. This lifespan ranges from a few hundred thousand years to several million years; the average, depending on the group, lies between 2 and 10 Ma. Within a given set of species, the probability of extinction is essentially constant over long periods (and, therefore, does not depend on how ancient the species may be) and is much greater during shorter "revolutions."[10] Extinctions during "calm" (or "normal") periods are thought to result from the normal evolution of species within a community in perpetual interaction, while revolutions are caused by a change in living conditions within the environment. The evolution of some groups of mammals during the Cenozoic, for example, is punctuated by changes in ocean currents and in climate, the causes of which must be sought partly in the famous Milankovic cycles[11] and partly in the changes in the ocean basins caused by incessant continental drift.[12]

But as we have already seen, the history of biological evolution is not limited to the humdrum course of "normal" extinctions. More rarely, there are mass extinctions in which a great many species from

9 Or 'ten to the seventeenth power,' i.e., a 1 followed by seventeen zeros, or a hundred million billion!

10 See Jean-Jacques Jaeger, *Les Mondes fossiles*, Paris, Odile Jacob, 1996.

11 The gravitational effect of the giant planets Jupiter and Saturn has a quasi-periodic influence on the angle (or 'obliquity') of the axis of rotation of the Earth and on the eccentricity (the elliptical shape) of its orbit. The Moon and Sun, for their part, exert forces that induce a precession of the Earth's axis of rotation. The periods corresponding to these three evolutions are, respectively, about 40,000 years (obliquity), 400,000 and 100,000 years (eccentricity), and 25,000 years (precession). The amount of sunshine, which varies as a function of latitude and season, is thus modulated over the same long periods. These Milankovic cycles are thought to be responsible for the changes in glaciation over the past million years (the last glacial period culminated 18,000 years ago) and also for the variations in climate recorded in far more ancient sediments.

12 See Claude Allègre, *The Behavior of the Earth*, Cambridge, MA, Harvard University Press, 1988.

most groups disappear almost simultaneously, so close together in time that chance alone cannot adequately explain it. The two most striking events of this kind mark the transition from the Paleozoic to the Mesozoic, and from the Mesozoic to the Cenozoic. To determine the age, duration, and extent of these events, David Raup and John Sepkoski have compiled the dates of appearance and disappearance of several thousand families[13] and several tens of thousands of genera of invertebrate marine organisms. The curve for the variation in number of families (Fig. 1.2, bottom) gives a quantitative view of this evolution in diversity, which we described qualitatively above. It shows a very rapid acceleration at the start of the Paleozoic, not only because of a very real diversification of species, but also because from this point on these species would be producing hard body parts. Over the next 200 Ma, diversity seems to remain constant, except for two crises, one around 440 Ma ago (the so-called Ordovician-Silurian boundary) and the other around 370 Ma ago (during the Upper Devonian Epoch). But the most dramatic event is the great catastrophe at the end of the Paleozoic (250 Ma), at the boundary between the Permian and the Triassic-whence the term Permo-Triassic crisis that we will use from now on is derived. Life, or more precisely diversity, then rapidly resumes its momentum, suffers a new crisis at the Triassic-Jurassic boundary (210 Ma), exceeds the richness it achieved during the Paleozoic and then suffers its second major crisis – which, as we have seen, marks the end of the Mesozoic: the famous Cretaceous-Tertiary boundary.[14]

13 See Note 2.

14 The term 'Tertiary' was coined in 1759 by an Italian geologist named Arduino, who used this name to describe relatively poorly consolidated and only slightly deformed rocks, while the underlying 'Secondary' rocks were simply more deformed and harder, and the 'Primary' basement exposed in some nearby mountains was even more severely affected. In 1833, Lyell subdivided the Tertiary, calling its earliest level the Eocene Epoch. After a number of different incarnations, the term Paleocene was introduced, which at first referred to the lower part of the Eocene and later became an epoch in its own right. As for the Cretaceous, the last period of the Secondary, it was introduced by Halloy in 1822 and takes its name from the chalk which often forms the strata of this age in northwestern Europe. In fact, we know today that the boundary between the Cretaceous and the Tertiary Periods, which as we will see is not easy to define nor often all that easy to observe precisely, is quite simply absent in the two regions where these periods were defined. Whether the corresponding strata were never laid down or were worn away later by erosion, this moment of geological time is not recorded there. The Cretaceous-Tertiary boundary is often known 'familiarly' as KT; the K refers to the first letter of Cretaceous in German ('Kreide'), so as not to confuse it with either Carboniferous or Cambrian (designated, respectively, as C and Є).