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The Measurement of Geological Time

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1 Introduction

Most would agree that one of the principal attractions of science lies in the ways it stimulates the imagination into the realms of objects and events that are far beyond the bounds of direct human experience. Thus the chemist manipulates his atoms with complete familiarity even though he has never seen one, and never will. He is particularly confident in the transition to a world in which the scale of distances has been reduced by some eight orders of magnitude. The nuclear physicist goes even further and worries about the structure of objects some 10^{13} times smaller than the letters on this page. At the other extreme, astronomers reporting the observation of stars near the edge of the observable universe are talking of distances some 10^{27} times the width of this page. Objects move; and so we are interested in the duration of events and the intervals between them. The chemist reports that those molecules of nitrogen in the room that are vibrating do so with a period of $1.4316566 \times 10^{-14}$ seconds, which, on average at room temperature, is some 580 times faster than the time taken for one overall rotation. Physicists think about even shorter times, the shortest probably being the time it takes light to traverse a small atomic nucleus – some 10^{-23} seconds. Cosmologists speak with conviction of the age of the Universe, 15,000 million years or 10^{18} seconds, which sounds rather like a time-span outside which we need not be overly concerned. Yet experiments are in progress at this moment[1] to measure the average life-time of the proton, the nucleus of the hydrogen atom, predicted by theory to decay spontaneously after 3×10^{31} years or 10^{39} seconds. These dramatic extensions of our horizons depend heavily on the advances of technology of the past 30 years and I shall not dwell on them further, beyond one final comment. Progress at the frontier has become expensive, both in hardware and in manpower. The successful outcome of a crucial experiment in high-energy particle physics recently carried out at CERN, Geneva, is reported in two brief communications[2] over the names of 194 authors.

Instead, I should like to say a little about another field that has also seen progress, namely the measurement of time in some processes which, although intermediate in rate, are still too slow to be directly more than barely perceptible. Their cumulative effects are however evident to us all: they are the processes that shape the surface of the Earth as we see it. It has become clear in the past 50 years that the outer layers of the Earth behave as if they were rigid only on a relatively short time-scale. Over longer periods there occur, and have done since the

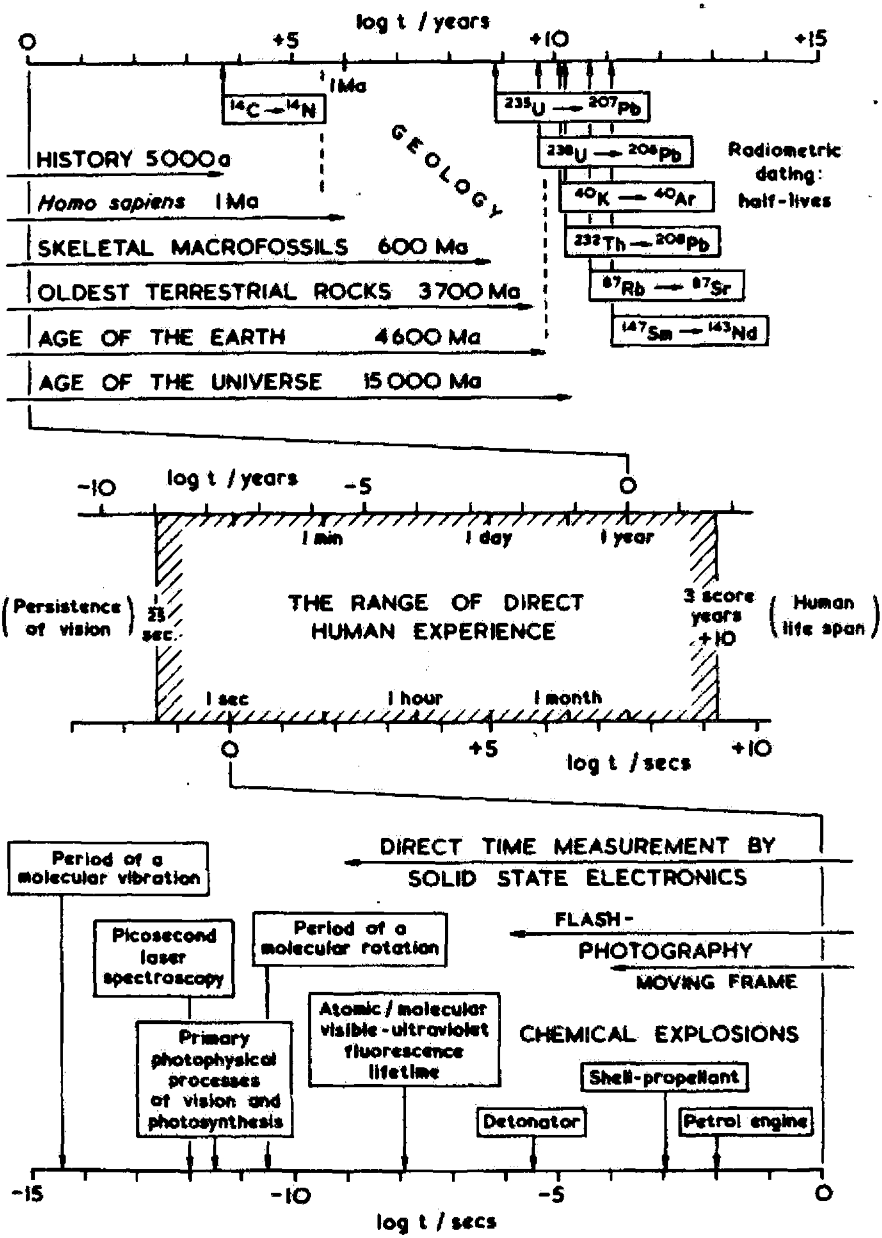

Fig. 1 *The scale of time and events*

beginning, movements involving the transport of not insignificant fractions of the whole mass of the Earth over enormous distances. Mountains rise and fall; continents and oceans come and go. Although the primary causes of these movements are still not very clear, we have some plausible theories and, in any case, some very good descriptions of what has actually occurred.

There are three basic phenomena. The first is mountain-building in its widest sense: tectonics, the deformation of the Earth's surface in response to stresses deeper down, resolved into its vertical and horizontal components. The second and third are consequent upon the first: erosion and sedimentation. Of these, erosion is necessarily a source of negative evidence. By far the richest source of information for a historical geology has been the study of sediments, namely stratigraphy. This is based on the Law of *Superposition*, going back to Steno, 1699, which states that in a normal succession of sediments, the higher strata are the younger. This transforms a static description in terms of height into a dynamic description in terms of time: *relative* time, for inspection of a sedimentary succession can by itself tell us nothing about the absolute time taken to deposit the succession. The historical information to be obtained from a study of the sediments by themselves – *lithostratigraphy* – tends to be severely limited, however, for it cannot extend beyond the boundaries of the area in which continuous outcrops can be observed or in which scattered outcrops can be correlated lithologically: distances rarely greater than 1000 km, and quite inadequate, for instance, in any attempt to compare the geology of Great Britain with that of North America.

By the greatest of good fortune, however, the record in the rocks of the physical evolution of the Earth's crust bears within it simultaneously the record of its biological evolution, in the form of fossils. The study of fossil successions is the subject of *biostratigraphy*. It had been known since early times that many fossils may have a very widespread geographic distribution, but we owe it to William Smith to have discovered (1799–1813) that not only do the same fossil species occur again and again at distant localities but so do whole successions of fossil species in identical order. The implication of such parallel, homotaxial sequences is that rocks containing the same fossils are of the same age. This can therefore be made the basis of a *chronostratigraphy*. Rocks can be correlated and thus classified by age, by means of the fossils they contain. For this purpose, some fossils are better than others, and the identification of good *guide-fossils* is a matter of trial and error. In favourable cases correlations can be carried over the whole of the globe. Fossil sequences are translated into time-sequences and used to construct relative time-scales. These time-scales form the basis of most of historical geology and, by the same token, of historical biology.

The exploitation of these principles progressed with great speed and sophistication after the publication of William Smith's first geological map of England and Wales (1815), and the Golden Age of geology, in the ensuing half-century or so, saw the emergence of the geological time-scale in its larger outlines much as we know and use it today (Fig. 2). The Eras and Periods reflect major changes in the fossil record that can be recognised all over the world. Nobody

Eon	Era	Period	
PHANEROZOIC (Chadwick, 1930)	CAINOZOIC	RECENT	Lyell, 1873
		PLEISTOCENE	Lyell, 1839
		PLIOCENE	Lyell, 1833
		MIOCENE	Lyell, 1833
		OLIGOCENE	Beyrich, 1854
		EOCENE	Lyell, 1833
		PALAEOCENE	Schimper, 1874
	MESOZOIC	CRETACEOUS	Omalius d'Holloy, 1822
		JURASSIC	Brongniart, 1829
		TRIASSIC	Alberti, 1834
	PALAEOZOIC	PERMIAN	Murchison, 1841
		CARBONIFEROUS	Conybeare, 1822
		DEVONIAN	Sedgwick/Murchison, 1839
		SILURIAN	Murchison, 1833
		ORDOVICIAN	Lapworth, 1879
		CAMBRIAN	Sedgwick, 1835
PROTEROZOIC (Emmons, 1888)	skeletal macrofossils appear		
	(Phillips, 1840)	PRECAMBRIAN / ARCHAEAN ???	Dana, 1872

Fig 2. *The biostratigraphical time-scale*

pretended that the Periods were of equal duration as Fig. 2 might imply, but as there were no consistent ways of determining what the relative durations in fact were, this way of drawing the figure was as good as any other. Nothing in the development of geological science depended on it. Neither did anything depend on a knowledge of the absolute ages of rocks, in years, although this naturally aroused much curiosity, if for no other reason than because of its possible conflict with the received doctrine from other sources. Attempts to satisfy this curiosity generated some ingenious arguments, and one of the first major clashes between geological common sense and the full authority of the exact sciences in the form of Lord Kelvin. Some of the early estimates of geological time we now know to have been of the correct order of magnitude but most of them retain little more than historical interest. In particular, Fig. 2 immediately raises two important questions, to which there were no answers: what fraction of the age of the Earth is represented by the Phanerozoic, fossil-bearing part of the succession? And what were the relative durations of the Phanerozoic and Proterozoic, going back to the oldest rocks we can now still find at the Earth's surface? Which, in fact, are the oldest rocks? These are among many questions that were answered following the discovery of natural radioactivity in uranium by Becquerel in 1896.

2 Absolute Age Determinations: Radiometry

Some early estimates of geological time are summarised in Table 1.[3] Leaving aside the first two, based more or less on divine revelation, most are derived from uniformitarian extrapolations into the past of processes seen to occur at measurable rates today. About all they have in common is to put the shots into the range of millions of years rather than thousands, which was adventurous at the time. The weakness of the geological methods was that they could grasp only

Table 1 *Early estimates of geological time*

1 Astrologers: the appearance of man			
	Babylonians, Chaldeans		½–2 Ma
	Zoroaster, Persia		12,000 a
2 Historical: Hebrew chronicles			
1650	Archbishop Ussher: the Creation		5654 a
3 Geological: rates of sedimentation			
480 BC	Herodotus: Nile delta		20,000 a
1839–60	J. Phillips: all stratified rocks		20–90 Ma
1895	J. Sollas	base of the Cambrian	17 Ma
1897	J. S. Goodchild	base of the Cambrian	700 Ma
4 Geological: rates of erosion			
1859	C. Darwin: Cretaceous, South Downs		300 Ma
1860	J. Phillips: Cretaceous, South Downs		3 Ma
5 Geological: sodium in the ocean			
1715	(Halley: suggested the method)		
1899	J. Joly: age of the oceans		80–330 Ma
6 Astronomical: age of the Sun			
1854	Helmholz: radiative energy from gravitational collapse		22 Ma
7 Geophysical: cooling of the Earth			
1862–95	Kelvin: solidification of surface from molten state		25–400 Ma

the most recent phases of what are largely cyclical processes, which was freely admitted. The source of the failure in the physical estimates was more serious. Each was derived from a reliable physical measurement – the rate of radiative energy-loss by the Sun, or the geothermal gradient at the surface of the Earth – by impeccable deduction. The error lay in the basic assumptions made, that radiative cooling from an initial hot, fluid state was the only process entering the heat-balance that determines the temperatures of these bodies. If geological uniformitarianism and physical theory were in conflict, so much the worse for uniformitarianism.[4] Today we might perhaps have been more cautious and at least considered the question: could there be a hidden variable, an additional process that we had not yet thought of?

The discovery of the radioactive transmutation of chemical elements in 1896 and its exploration largely at the hands of Rutherford and the Curies in the years that followed, revealed both the presence of such processes in abundance and the enormous energies they release – more than enough to create the heat-flow through the Earth's crust that determines the geothermal gradient. Kelvin's calculations, although perfectly correct, were thus irrelevant. Instead, the discovery of radioactivity provided us with a new method of estimating geological times. The early discoveries all centred on just two elements, uranium and thorium. These decay by rather complicated chains of relatively rapid steps to two stable end-products: radiogenic lead, and helium. The laws of decay are precisely known. Each step decays exponentially at a rate specified by a single rate-constant, or half-life, characteristic of the element and wholly unaffected by the environment in which it finds itself, *i.e.* mineral or rock, hot or cold. Provided, therefore, that neither the product of decay – the daughter-elements – nor the residual parent-element are lost by migration out of the mineral or rock after its formation, the ratio of daughter to parent element as now observed depends only on the time elapsed. Any mineral that entraps uranium or thorium during its crystallisation has built into it a geological clock set to start from the moment that it becomes chemically immobile. There are of course further requirements, such as the absence of subsequent contamination by lead from external sources.

Clearly, the constraints of chemical stability over the enormous spans of geological time are severe, and although uranium and thorium are widely diffused throughout the rocks, occurring particularly commonly in igneous rocks such as granites, the samples that come up to specification are few. In the earlier days, when analysis for uranium, thorium, and lead had to be by chemical "wet" methods, the only rocks that were at all suitable were those in which the elements had been heavily concentrated at the time of formation, *i.e.* their ores, such as pitchblende, uraninite, or thorite. The first ages to be determined were therefore all uranium–lead ages. The alternative, the measurement of uranium–helium ratios, followed soon after. The estimation of helium has certain advantages in that small amounts of mass translate into relatively large volumes of a gas which, because of its total chemical inertness, is the easiest of all substances to separate and purify. The vacuum-lines needed to separate the tiny

Table 2 *Radioactive elements used to date rocks*

Decay	*Half-life (Ma)**	*First used*	
$^{235}U \rightarrow {}^{207}Pb + 7\,{}^{4}He(\alpha)$	704	1938	
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He(\alpha)$	4,470	1938	1907–1937
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He(\alpha)$	13,700	1938	
$^{40}K \rightarrow {}^{40}Ar + e^{+}(\beta^{+})$	11,930	1948	
$^{40}K \rightarrow {}^{40}Ca + e^{-}(\beta^{-})$	1,400	-	
$^{87}Rb \rightarrow {}^{87}Sr + e^{-}(\beta^{-})$	48,800	1946	
$^{147}Sm \rightarrow {}^{143}Nd + {}^{4}He(\alpha)$	106,000	1975†	
$^{176}Lu \rightarrow {}^{176}Hf + e^{-}(\beta^{-})$	35,300	1980≠	
cf. Base of the Cambrian	570		
Oldest known rocks	3,700		
Age of the Earth	4,600		
Age of the Universe (Big Bang)	? 15,000		

*Ma = 1 million years

†For a review of this new method, see McCulloch and Wasserburg, (1978)[15]

≠ Patchet and Tatsumoto (1980)[21]

traces of helium expelled from minerals by heating or dissolution called fo prodigious feats of glass-blowing. What is perhaps surprising is that man minerals have crystalline cages capable of retaining helium for any length of tim at all, for the smallness of its atoms and its chemical inertness makes it also th most mobile of substances. However, quite a few minerals were found to giv uranium–lead and uranium–helium ages that were in satisfactory agreement. I many others, helium had clearly been lost.

The half-lives are given in Table 2. They are determined in the laboratory b counting in a Geiger counter the individual atoms of helium (α-particles) emitte per second from a known mass m of parent element. The total number of atom in the mass m is known through a well-determined fundamental constant Avogadro's constant L_A (the number of atoms in 12 grams of elemental carbon) Hence the proportion of atoms in m lost by disintegration per second is obtained from which the half-life, the time needed for half of them to decay, may b calculated simply. The first estimates of radiometric ages were obtained by B. B Boltwood (1905–07), professor of chemistry at Yale and a skilled analyst. Hi examination of 10 samples of uraninite and thorianite revealed Pb–U ratio ranging from 4% to 22%. Estimating the rate of decay of uranium to be crudely one part in 10,000 million each year ($1:10^{10}$, about 50% too small), and assuming all the lead to be radiogenic, he calculated the ages of the minerals to lie between 400 and 2,000 million years. The number and refinement of determinations rose rapidly in the ensuing years, including now samples whose age of formation could also be dated geologically, in terms of the relative time-scale of Fig. 2. These determinations made it possible for A. Holmes (1937)[6] to put forward one of the first consistent Phanerozoic time-scales calibrated in absolute terms, shown in Fig. 3.

A breakthrough in radiometric age-determinations came with the development of physical methods of chemical analysis. The most notable and versatile of these is the high-resolution mass-spectrometer developed by Niehr in 1938. This has two great advantages. It works by converting the atoms in a sample proportionally into electric currents, one for each type of atom. The relative abundances of atoms can therefore be measured over the whole of the enormous dynamic range of modern electrical measuring devices – the relative magnitudes of electric currents that can be compared directly, differing by perhaps up to nine orders of magnitude. And the measurements can be made on individual isotopes of the elements – atoms of same chemistry but differing in nuclear masses and radioactive decay-paths. It has been possible therefore to expand the list of radiometric clocks to include the three additional elements shown in Table 2, potassium, rubidium, and samarium. This extends the range of minerals and rock-types accessible to age-determinations enormously, for potassium-rich micas and feldspars are constituents of almost all igneous and metamorphic rocks, and rubidium is concentrated with potassium in about the only chemically immobile primary mineral formed in marine sediments, glauconite (responsible for the colour of greensands).

As an example, to give an idea of what is involved, consider a typical muscovite or biotite mica. Of all the atoms making up the crystal, 5% are potassium. Of these, only 0.01% belong to the radioactive isotope ^{40}K. This in turn decays by two parallel paths, of which only the slower, minor path to ^{40}Ar is useful, for the major, faster one proceeds to ^{40}Ca indistinguishable from the naturally-occurring one invariably present in great excess already. After 100 million years, say, for every atom of ^{40}K originally present there will have been produced 0.0057 atoms of ^{40}Ar. Therefore, all in all, it takes 300 million atoms of mica to produce one atom of ^{40}Ar after 100 million years. To obtain such an age with acceptable precision, say of $\pm 1\%$, therefore calls for a measurement of an overall atom: atom ratio to one part in 3×10^{10}. Fortunately, in this case the residual parent ^{40}K and the daughter ^{40}Ar can be separated chemically, easily and totally, and then estimated individually, for argon is almost as inert as helium. Nevertheless, the demands made on apparatus remain severe; yet K–Ar age-determinations have become routine.

Rubidium–strontium ages are more difficult. Rubidium is present in almost all potassium-bearing minerals in amounts comparable to that of ^{40}K, typically between 0.1% and 0.01% of the total potassium. The radioactive isotope, ^{87}Rb,

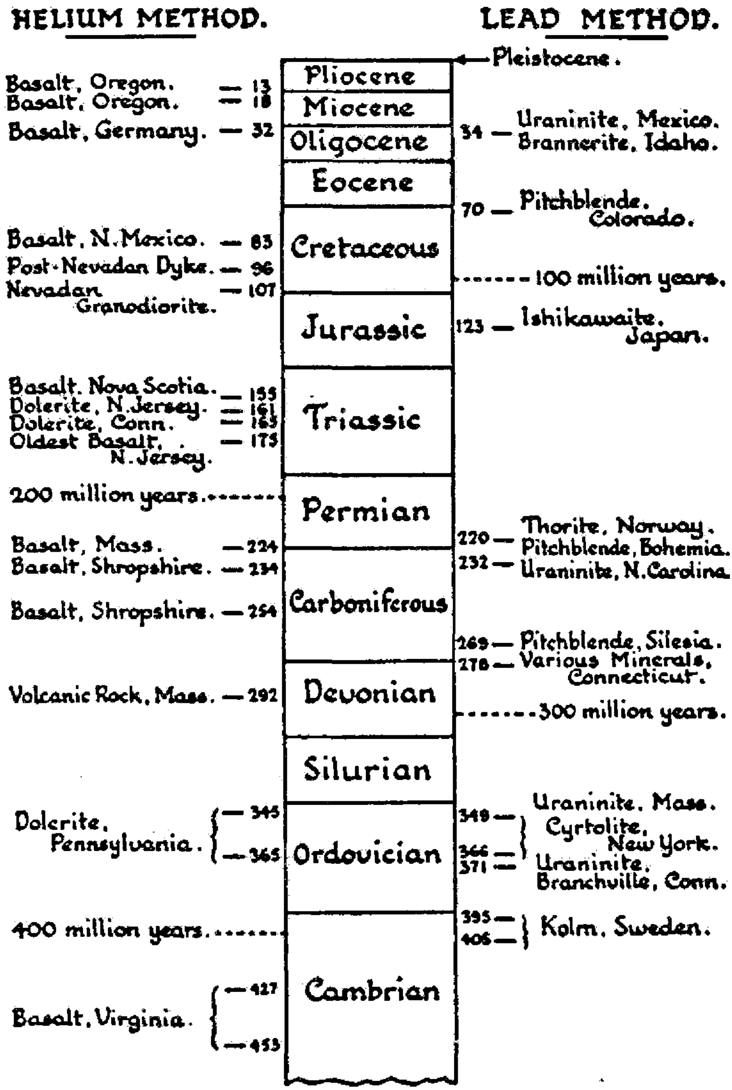

Fig. 3 *The radiometric time-scale in 1937, based on uranium, thorium and their products lead and helium. (A. Holmes)*[6]

makes up 28% of the total rubidium, but its decay-rate is four times slower than that of ^{40}K. There are in addition some six further elements with naturally radioactive isotopes, but they are so scarce in themselves, or so limited in geological distribution, that it seems unlikely that they will ever be used for radiometric dating.

What, then, are the status and prospects of radiometric age-determinations? How versatile is the method and how good are the ages obtained? And if rocks can now be dated absolutely by direct methods, why continue with the tedious business of collecting and identifying fossils? Are the days of biostratigraphical chronometry numbered?

Absolute accuracies are probably limited by our knowledge of the values of radioactive decay-constants, or half-lives, for to count the number of α- or β-particles emitted per gram of weakly radioactive element incorporated into a chemical crystal is not as simple as it sounds. To obtain a count significantly above background may call for samples of some volume, and then the particles emitted in the interior of the sample tend to be reabsorbed. Uncertainties in decay-constants as a whole are however not important, for provided the values adopted for all the isotopes used are consistent it really matters very little whether the base of the Cambrian, for example, is thought to be 500 million or 600 million years old. A consistent set for all the constants in Table 2 is however only of quite recent origin (described *e.g.* in Harland *et al.* 1982,[7] Appendix 1), and before 1978 many laboratories were using values differing by up to 5% even for the same isotope. Instrumental precision in determining atomic abundance-ratios in a given sample, typically around 1%, is probably also good enough not to be limiting.

What does matter in practice is one or more of three severe restrictions. Firstly, as outlined above, only very few minerals are suitable for radiometric dating on chemical grounds. Potassium–argon dates are obtainable only from those that have retained the argon. But there is no way of telling by simple inspection how much argon may have been lost. Independent checks may be obtained by testing for sampling-consistency – the scatter of ages obtained from different samples of the same or even different minerals drawn from as widely as possible over the rock-body to be dated – and by comparing the ages from one isotope with those of another, *e.g.* rubidium–strontium. Few samples survive these tests, and one can be pleased if their consistency lies within ±5%. For a Triassic rock 200 million years old this means an uncertainty of ±10 million years.

Secondly, few rocks contain any of the minerals suitable for dating, on geological grounds. Thus, while it is usually possible to find somewhere amongst all the beds in the world of a particular stratigraphical age, one that can be made to yield a radiometric age, the converse holds only rarely: the particular bit of rock, without fossils, whose age one needs to know now, at all costs to solve a particular geological problem, is almost always unsuitable for radiometric dating. The unravelling of the structure and tectonic history of the Alps, without doubt one of the great triumphs of geological science, was achieved without a single radiometric age determination. So the stratigraphical column as a whole has been well dated; but individual beds can in general not be dated. Thirdly, even when the isotopes in a radioactive mineral have been satisfactorily analysed, to what does the calculated age refer? In a plutonic rock, the date of emplacement, or final cooling? Or, most commonly, the last metamorphic episode in a long thermal history? In a sedimentary rock, the date of synsedimentary chemical formation or the date of redeposition of a much older material subsequently eroded and transported? Such problems are almost endless, and no reported absolute rock age can be accepted at its face-value without the most extensive investigation of all the circumstances.

The radiometric methods finds its greatest application to the solution of day-to-day problems in Precambrian geology, where indeed it is all we have, and to the dating of isolated igneous rock-bodies or rock-samples whose ages cannot be related to those of adjacent Phanerozoic strata through field-observations because the contacts are covered or have been lost by erosion. Thus, in the Precambrian, the major features of the history of those rocks still preserved at the surface of the Earth are becoming apparent (for a recent summary, see Harland *et al.*,[7] 1982). The age of the oldest rocks has been pushed back to around 3700 million years, the record oscillating between West Greenland, South Africa and Finland. Thus, the Phanerozoic constitutes only one-sixth of the history of the Earth visible in the rocks. The figure quoted for "the age of the Earth", of 4,600 million years, is obtained by comparing the isotopic composition of ordinary terrestial lead with that found in meteorites, or by assuming it to be the same as the radiometric age of meteorites or of the Moon dated directly. It is therefore probably more correctly referred to as the age of at least partial solidification of the ferro-siliceous members of the Sun's planetary system.

What is interesting is, that amongst the oldest rocks now visible on Earth, what are clearly water-laid sediments of same types as those being formed today are to be found: uniformitarianism had already been switched on after the Earth was only one-fifth as old as it is today, and covers 80% of the Earth's history. Structures claimed to be stromatolites of organic origin are present in South African rocks 3,000–3,500 million years old; the earliest indisputable fossils are preserved in the Gunflint Cherts of southern Ontario, around 2,000 million years old, and show evidence of already considerable cellular differentiation in what probably included photosynthetic eukaryotic biota. There appear even to have been Ice-Ages already 2,300–2,600 million years ago.

Among more recent geological results dependent almost entirely on direct radiometric dating, one of the most spectactular was the demonstration that the Hawaiian chain of Pacific islands and sea-mounts varied in age along its length.[8] This chain includes some 50 extinct volcanoes extending 3,500 km WNW of the present active centre of eruption on and around the island of Hawaii itself, and then continues with a change in a more northerly direction as the Emperor chain of seamounts, with 30 more volcanoes, for a further 2,500 km to the tip of the Aleutians. The volcanoes become progressively older the further they are from Hawaii, reaching back to 40–48 million years ago in the southern Emperors, just as would be expected from a model of a Pacific crustal plate moving WNW-wards over a hot-spot, or plume, fixed in the Earth's mantle underneath. The mean velocity of the plate relative to the hot-spot then works out at around 10 cm a year.

There are therefore many classes of geological problem in which direct radiometric dating is both essential and sufficient. But there can be no doubt whatever that for the reasons outlined above it will never replace the classical methods of biostratigraphical chronometry in the main body of Phanerozoic geology. There is, in fact, a further reason that is even more compelling. On the scale of the uncertainties inherent in the values of absolute ages obtained radiometrically, most local geological processes are fast. To reconstruct them one must therefore distinguish closely adjacent before-and-after: one is not primarily interested in absolute ages at all, but in short time-*intervals*, in *relative* ages. It is for just this that biostratigraphy is ideally suited, for the whole body of biostratigraphic chronology has been constructed by a painstaking piecing-together of ever smaller time-intervals. Biostratigraphy has an intrinsically high *secular resolving power*, whereas radiometric methods can estimate short time-intervals only as small differences between large quantities, an inherently unsatisfactory way of making measurements. How well biostratigaphy works will be discussed in the next section.

3 Relative Age Determinations: Biostratigraphy

The major divisions of Phanerozoic time shown in Fig. 2, the geological Periods, have been much subdivided into ever finer units by means of fossils. Almost any group of organisms whose changes with time can be observed in the rocks could in principle be pressed into use as chronometric guide-fossils, and many have; but in practice, at any one level, some groups are always much better than others for a wide variety of reasons. The ideal guide-fossil group evolved rapidly; occurs abundantly in rocks of all facies (lithologies, *e.g.* limestones, sandstones, shales; and conditions of deposition *e.g.* shallow-water, deep-water, marine, lagoonal, fluvial, lacustrine); requires no special techniques of preparation or of study (*e.g.* thin-sectioning and electron microscopy); and is easy to identify by visual inspection. No single group ever attained this ideal, and each Period of the geological column tends to be zoned stratigraphically by means of a group or groups characteristic of it that approached the ideal more or less closely. Thus the Cambrian, Ordovician, and Silurian are classified primarily by their trilobites and graptolites; the Devonian to Permian by goniatites and conodonts; and the whole of the Mesozoic by ammonites. The study of many geological problems is severely constrained by methods of sampling. Subsurface rocks are accessible almost exclusively through drilling, and the needs of the oil industry and the deep-sea drilling programmes of oceanic exploration have generated great efforts to produce biostratigraphic zonations of almost the whole of the Phanerozoic based on microfossils of all kinds.

To review this enormous field in a few paragraphs is quite impossible. Instead, I should like to take as an example just one group of fossils, in one Period of the geological column, to illustrate the principles and to show what can be done. How close to the ideal can one come? What level of time-resolution can be achieved? What sets the limits on how well one can do? And what sorts of interesting rate-constants of geological processes can one estimate on the time-scales thus available?

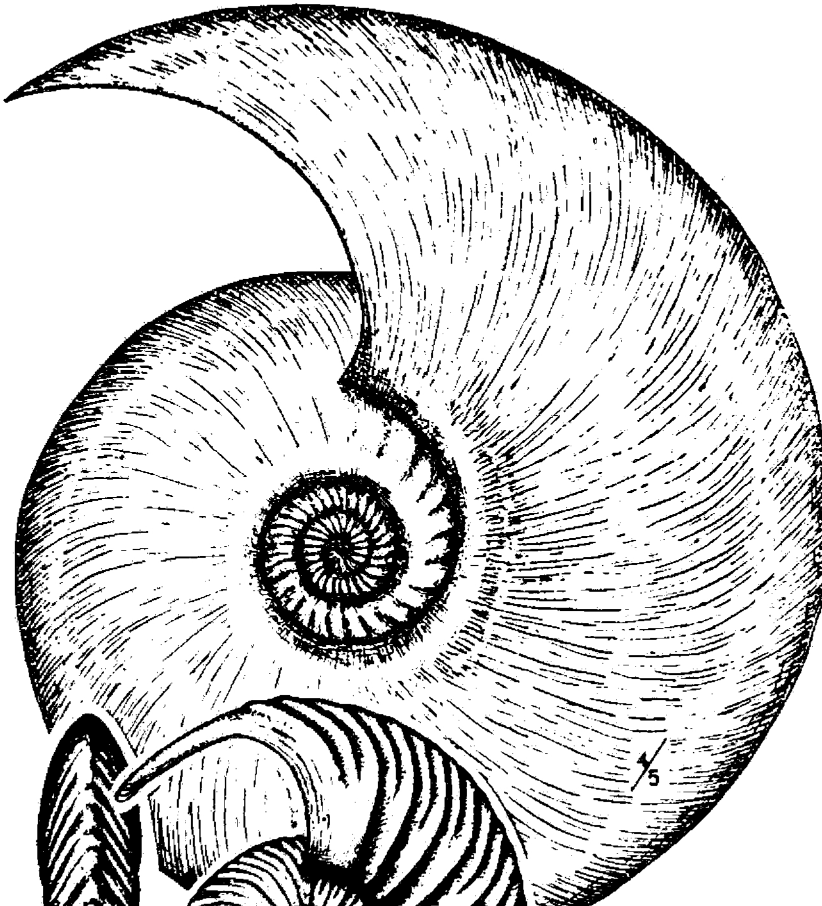

Fig. 4 *A Jurassic ammonite:* Quenstedtoceras henrici *Douvillé, 1912. Middle Jurassic, Callovian, Lamberti Zone, Henrici Subzone (see Fig. 6); Lukow, Poland (from Makowski, 1963[9]). Both specimens complete adults, forming a dimorphic pair, the larger (macroconch ×0.8) probably female, the smaller microconch, ×1) male. Family Cardioceratidae (see Figs. 10, 12, 14)*

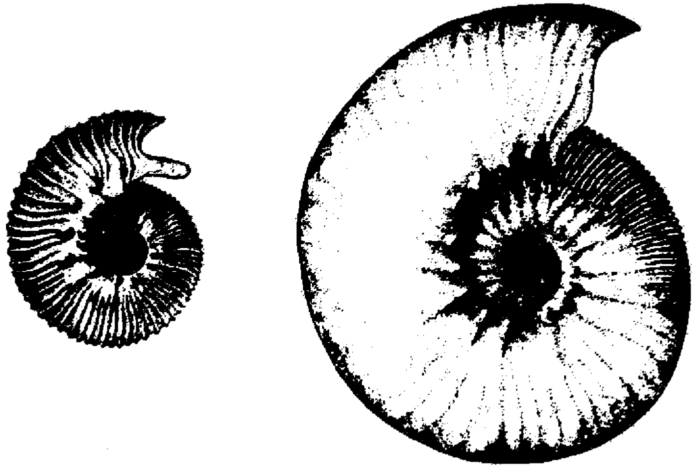

Fig. 5 *A Jurassic ammonite:* Kosmoceras jason *(Reinecke, 1818). Middle Jurassic, Callovian, Jason Zone and Subzone (see Fig. 6). Peterborough, England, level P7, 79–135 cm (see Fig. 9) (from Brinkmann, 1929).*[10] *Both specimens complete adults, a dimorphic pair (×0.5). Family Kosmoceratidae (see Figs. 9–11)*

The fossils are ammonites, and the Period is the Jurassic. The ammonites were a group of marine molluscs in the class of Cephalopoda which flourished during, and became extinct at the end of, the Mesozoic. The nearest living relative, and certainly the morphologically most closely homologous one, is the Pearly *Nautilus,* although the evolutionary branching-point lay somewhere low down in the Palaeozoic. Ammonites probably approach the ideal as guide-fossils more closely than any other group. They are certainly common and easy to recognise – the famous snake-stories of Whitby are known to almost every schoolboy; the giant ammonites of Portland are displayed in walls, gardens, and museums everywhere; and fine pictures of *Asteroceras obtusum* from Lyme Regis figure prominently in current advertisements promoting the sales of a certain brand of cigarettes, presumably as aesthetically appealing objects well known to all. In contrast to *Nautilus,* however, practically unchanged from the Trias to the present, some 250 million years, the ammonites evolved with very great rapidity for reasons that remain wholly mysterious. Their maximum sizes alone range from over a metre in the largest to less than a centimetre in the smallest known adults, corresponding to a ratio of bodyweights in excess of 10 million to one. Rapid morphological evolution means high stratigraphical resolving-power; and the ammonites and rocks of the Jurassic have been the testing-ground of stratigaphy since the earliest days of geology.

The way in which the geological column has been subdivided is illustrated in Fig. 6, in which a part of the Jurassic has been expanded to show the smallest units currently recognised in formal standard chronostratigraphy. The absolute

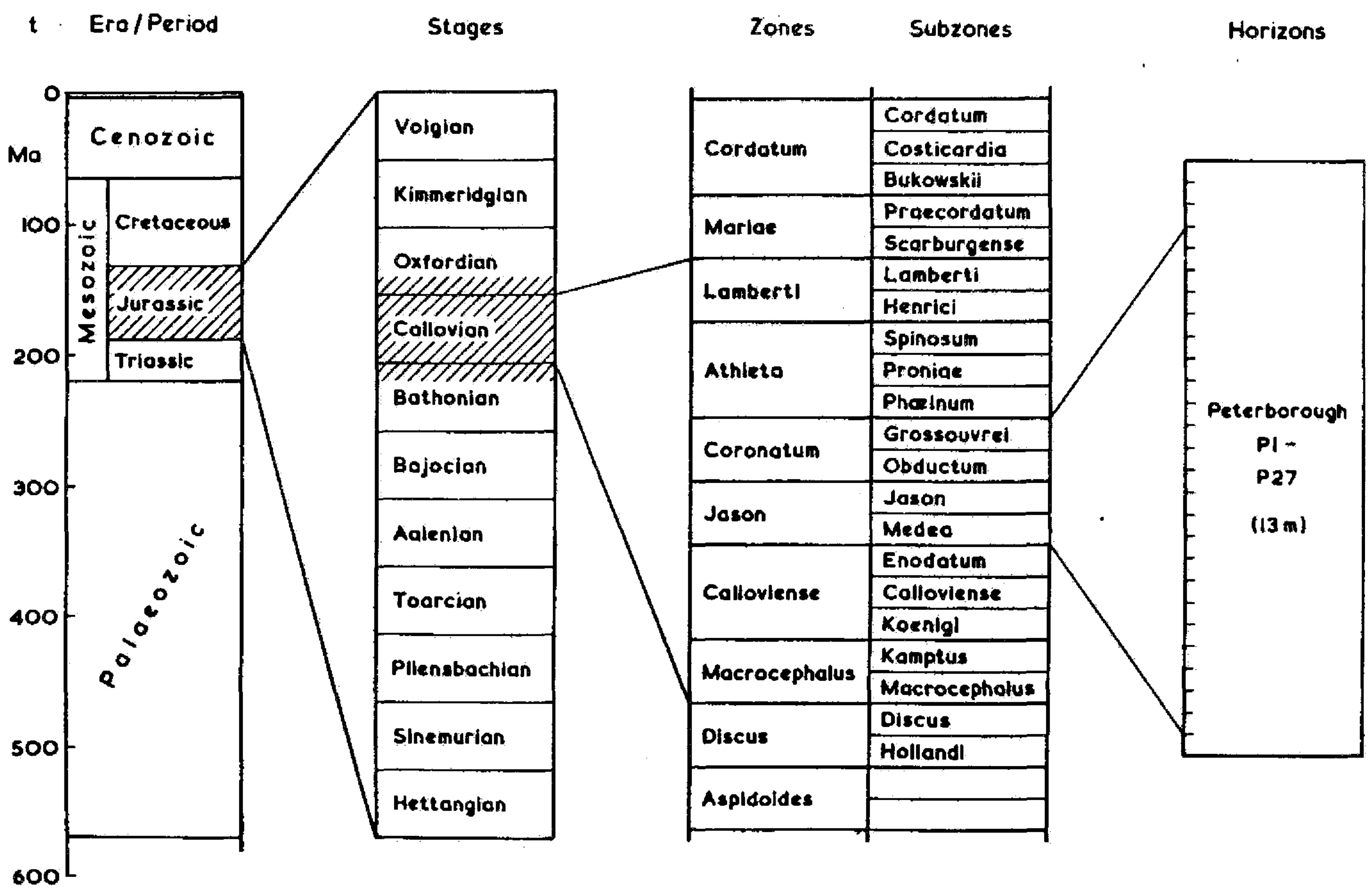

Fig. 6 *Subdivision of the geological column in the Phanerozoic. P1–P27: Peterborough (see Figs. 8, 9)*

time-scale in years shown at the left (*cf.* Fig. 2) is essentially the "Geological Society of London Scale" of 1964–71 (Harland *et al.*, 1971),[11] the minor changes recommended by Harland *et al.* (1982)[7] or Odin *et al.* (1982)[12] being questionable improvements. The division into the 11 major units, or Stages, shown here does not differ greatly from the scheme of 10 *étages* first put forward by d'Orbigny in 1850, each named after a locality in which rocks of the age in question were thought to be particularly well developed or well exposed.

The next step was taken by Oppel (1856–58) who, after extensive journeys through England, France, and Germany, arrived by means of fossils at a chronostratigraphic synthesis of the almost innumerable local beds and formations of the Jurassic rocks of this large area already named and described at the time, in terms of 33 Zones as shown in Fig. 7. These Zones constituted a continuous scale of units that could be recognised in practice in most, and in principle at least throughout the whole, of Europe, and represented therefore the first standard chronostratigraphic classification of the Jurassic down to the finest subdivisions then recognisable. Each Zone – a stratigraphical unit – had to be given a name, and, in contrast to the Stages, named after places, Oppel decided to name each Zone after one of its characteristic fossils – a zoological entity. This has caused much subsequent confusion, the temptation being to define the Zone in terms of the range of its nominal index-species. The latter is however only of limited interest, for the recognition of an Oppelian Zone rarely depends on finding the index-species itself. Each Zone is in general based on a whole assemblage of characteristic guide-fossils, among which the index is only one; and the known range of a single species may vary from year to year, depending on the state of knowledge, and from worker to worker, depending on his taxonomic interpretation of the species – a subjective, zoological matter having little to do with stratigraphy. This distinction between different usages of a Linnéan zoological name for different purposes is therefore indicated orthographically. In Fig. 6, for example, the Macrocephalus Zone is the name for all rocks lying between two time-planes fixed objectively by markers in geological sections, and is not the same as the (range-) zone of *Macrocephalites macrocephalus*, something currently a matter of great debate.

The pre-eminence of ammonites among Jurassic guide-fossils was already clear in Oppel's time, and the indices of 22 of his 33 Zones are ammonites species. Since his time, little has changed in principle but our classification of the Jurassic had undergone much refinement and continues to do so. The standard zonation shown in part in Fig. 6 now extends to some 76 Zones, all named after ammonites. The next step was to subdivide even the Zones into Subzones, and the number of these stands at present at about 154. The divisions are to a considerable degree arbitrary and dictated by convenience, convention, or historical accident. But they reflect also a limitation that is natural and real: the finer the stratigraphical unit differentiated, the more restricted the area in which it can be recognised. Time and distance behave here in some ways like conjugate variables in quantum-mechanics, their ratio (rather than product) being subject to an analogous Uncertainty Principle with its associated constant of scale (in

TABLE III. *Oppel's Table of Zones.* (1858)

Formationsabtheilungen.	Etagen *oder Zonengruppen.*	Zonen (*Lager oder Stufen, d. h. paläontol. bestimmbare Schichtencomplexe*).	Conybeare & Phillips. 1822. *England.*	Dufrénoy & Élie de Beaumont. 1848. *Frankreich.*
Oberer Jura oder Malm.	*Kimmeridge-gruppe.*	Zone der Trigonia gibbosa.	Upper Division of Oolites.	Ét. supér. du système oolithique.
		Zone der Pterocera Oceani.		
		Zone d. Astarte supracorallina.		
	?	Zone der Diceras arietina.	?	Étage moyen du système oolithique.
	Oxford-gruppe.	Zone des Cidaris florigemma.	Middle Division of Oolites.	
		Low. calc. grit & Scyphienkalke.		
		Zone des Amm. biarmatus.		
	Kelloway-gruppe.	Zone des Amm. athleta.		
		Zone des Amm. anceps.		
		Zone des Amm. macrocephalus.		
Mittlerer Jura oder Dogger.	*Bathgruppe.*	Zone der Terebr. lagenalis.	Lower Division of Oolites.	Étage inférieur du système oolithique.
		Zone der Terebr. digona.		
	Bayeux-gruppe.	Zone des Amm. Parkinsoni.		
		Zone d. Amm. Humphriesianus.		
		Zone des Amm. Sauzei.		
		Zone des Amm. Murchisonae.		
		Zone der Trigonia navis.		
		Zone des Amm. torulosus.		
Unterer Jura oder Lias.	*Thouars-gruppe.*	Zone des Amm. jurensis.	Lias.	
		Zone der Posidonia Bronni.		
	Pliensbach-gruppe. (Liasien d'Orb.)	Zone des Amm. spinatus.		
		Obere Z. d. A. margaritatus.		
		Untere Z. d. A. margaritatus.		
		Zone des Amm. Davöi.		
		Zone des Amm. ibex.		
		Zone des Amm. Jamesoni.		
	Semur-gruppe.	Zone des Amm. raricostatus.		Calcaire à Gryphées arquées ou Lias.
		Zone des Amm. oxynotus.		
		Zone des Amm. obtusus.		
		Zone des Pentacr. tuberculatus.		
		Zone des Amm. Bucklandi.		
		Zone des Amm. angulatus.		
		Zone des Amm. planorbis.		

Fig. 7 *Oppel's table of Zones (1858). (From Arkell, 1933)*[13]

quantum-mechanics, Planck's constant *h*). Thus, at the level of Eras and Periods, the units in Fig. 2 and 6 find application world-wide, as do all except the topmost of the Stages. The area in which the Zones of Fig. 6 can be used is much more restricted. The Jason Zone, for instance, can be recognised in a belt running eastwards from Greenland and Biscay north of the Alps as far as the Caucasus and Trans-Caspia, a distance of 6,000 km, but its characteristic ammonites are almost wholly absent, replaced by others, in Spain, only 500 km further south; in most of the Arctic; and in the whole of the southern hemisphere. The scale of Standard Zones shown in Fig. 6 has therefore to be qualified: it is part of the NW-European Standard Scale.

Other parts of the world have to construct and use alternative, parallel, scales of Standard Zones of their own. *A fortiori*, Subzones tend to be even more restricted. The Hollandi, Kamptus, and Phaeinum Subzones are recognisable so far only in England and northern France; but the Bukowskii Subzone can be followed from east Greenland through north and central Europe to Trans-Caspia; northwards across the Russian Platform to northern Siberia; and thence through the Canadia Arctic Archipelago *via* Alaska and British Columbia into Wyoming. But it, too, is wholly unrecognisable in the southern hemisphere.

Are these Subzones then at the limit of chronostratigraphic resolution? The answer is definitely no. Locally it is almost always possible to go even further. In what has become one of the classical studies in biostratigraphy of all time, Brinkmann (1929)[10] investigated the succession of ammonites of the genus *Kosmoceras* through the Oxford Clay as exposed in the brick-pits around Peterborough. Ground, pressed, and fired, these clays are familiar in the form of 40% of all the bricks made in this country, particularly the pink Fletton Stocks to be found on almost every building site. Less well-known is their richness in fossils, especially ammonites which, though crushed flat, are otherwise complete, beautifully preserved, and belong to groups that are highly ornate so that quite small changes of sculpture with time are immediately apparent to the trained eye. The pits at Peterborough expose typically some 15 m (50 ft) of what at first glance appears to be a featureless grey clay (Fig. 8). On closer inspection however it is seen to consist of a succession of beds of varying thicknesses and slightly differing lithologies separated by sharp boundaries representing non-sequences, just as in almost every other sedimentary succession. Brinkmann collected some 3,000 ammonites extending over 13 m of clays, recording their levels not only bed by bed but centimetre by centimetre. Some of his results are shown in Fig. 9. The succession is divisible into 27 beds. Each bed yields ammonites, and those from different beds differ in almost all cases by small but systematic amounts, often too small to be reflected in numerical measures of gross characters such as diameter or rib-density but immediately apparent to the human eye. (The power of the human eye as a device for pattern-recognition far outstrips any current combination of ruler, caliper, and computer; witness our ability instantly to recognise our nearest and dearest in a crowd of thousands.) Beds characterised by such distinguishable assemblages of fossils may therefore be referred to simply and purely descriptively as faunal *horizons*. Such a horizon may be

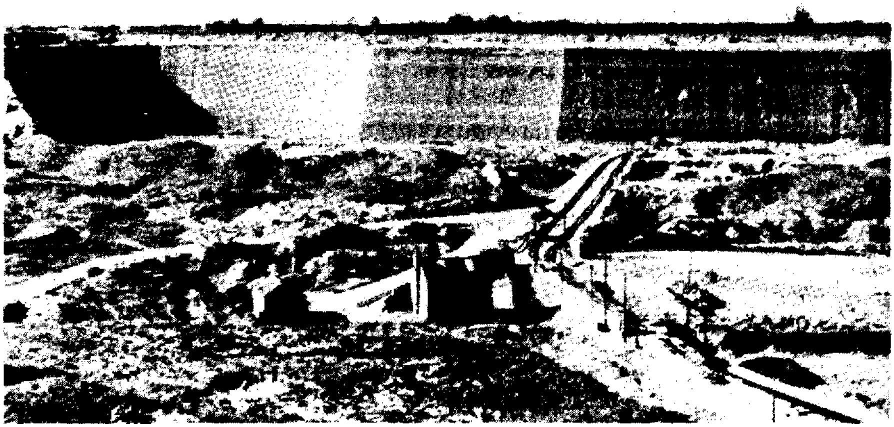

Fig. 8 *The Oxford Clay in the London Brick Company's pit at Whittlesea, near Peterborough*

distinguishable in only single quarry, or it may be recognisable quite widely. Brinkmann managed to distinguish over 25 horizons of *Kosmoceras* at Peterborough, extending over the six Subzones of two Zones and parts of two others. Many of these horizons can in fact be followed all over southern England,[14] down to the Dorset coast; and as one moves away from Peterborough south-westwards, the successions thicken and additional faunal horizons come in at levels thereby shown to be non-sequences at Peterborough. These faunal horizons are thus the ultimate building blocks of the geological record, and the very fact that they vary in number and thickness so rapidly from place to place attests to the existence of important geological processes occurring at rates that are significant on the time-scale of their formation.

What sort of absolute time-intervals then do our chronostratigraphical units represent? Some average values calculated from the standard radiometric time-scale are shown in Table 3. The average *time-resolution* $\langle\Delta t\rangle$ represented by Jurassic ammonite horizons turns out to be of the order of 100,000 years. Taking the mean age $\langle t\rangle$ of the Jurassic as 150 million years, the *secular resolving-power* R_t is therefore

$$R_t = \langle t\rangle / \langle\Delta t\rangle = 1{,}500$$

This is equivalent to being able to distinguish an event in the year AD 483 from one in the year AD 484, something not without its problems even in historic times.

A. Der Stamm *Zugokosmoceras*.

Tabelle 39 (hierzu Abb. 28 u. 29)[1]).
Die phylogenetische Entwicklung des Enddurchmessers im *Zugokosmoceras*-Stamm.

	Schichtgruppe cm	Anzahl	Mittelwert mm	Variationskoeffizient %
1	7—20	12	61,6 ± 1,5	8,7 ± 1,8
2	21—25	12	62,8 ± 1,5	6,2 ± 1,3
3	26—28	23	65,0 ± 1,9	10,6 ± 1,6
4	29—39	32	78,2 ± 0,9	6,4 ± 0,8
5	40—45	16	84,9 ± 1,4	6,6 ± 1,[illegible]
	46—50	9	88,5 ± 3,4	11,6 ± 2,8
6	56—78	19	105,8 ± 3,7	15,4 ± 2,5
7	79—90	8	109,3 ± 3,1	7,9 ± 2,0
	91—120	15	114,7 ± 2,2	7,5 ± 1,4
	121—135	9	119,0 ± 3,0	7,5 ± 1,8
8	136—160	9	95,6 ± 2,2	7,2 ± 1,7
	161—200	11	96,3 ± 2,4	8,2 ± 1,8
	201—240	5	94,6 ± 2,9	6,8 ± 2,2
	241—260	12	93,7 ± 2,1	7,6 ± 1,6
	261—300	7	95,7 ± 3,2	9,0 ± 2,4
	301—320	5	85,2 ± 4,0	10,5 ± 3,3
	321—340	14	91,0 ± 2,0	8,3 ± 1,6
	341—360	7	97,9 ± 3,7	10,0 ± 2,7
	361—380	7	93,7 ± 2,1	5,9 ± 1,6
	381—440	6	102,0 ± 2,8	6,7 ± 1,9
	441—460	12	99,8 ± 3,1	10,9 ± 2,2
	461—500	6	113,2 ± 4,5	9,7 ± 2,8
	501—520	19	110,9 ± 3,6	14,2 ± 2,3
	521—530	20	101,8 ± 2,0	9,0 ± 1,4
	531—539	13	106,1 ± 2,5	8,4 ± 1,6
9	540	36	112,8 ± 1,9	10,3 ± 1,2
	541—559	10	112,7 ± 2,5	7,1 ± 1,6
10	560	27	128,0 ± 1,5	6,0 ± 0,8
	561—680	15	126,7 ± 3,5	10,6 ± 1,9
11	681—690	13	130,4 ± 2,2	6,2 ± 1,2
12	691—759	13	117,7 ± 4,4	12,4 ± 2,4
13	760—780	16	131,3 ± 3,3	10,0 ± 1,8
14	781—792	8	144,1 ± 4,5	8,8 ± 2,2
15	793	31	146,6 ± 2,0	7,5 ± 1,0
16	794—854	6	129,2 ± 10,3	19,5 ± 5,6
17	855	23	129,1 ± 2,0	7,8 ± 1,1
	856—864	21	124,8 ± 3,1	11,3 ± 1,7
18	865	33	127,1 ± 2,5	11,1 ± 1,4
	866—880	7	140,9 ± 9,2	17,4 ± 4,6
19	881—894	7	132,4 ± 6,4	12,8 ± 3,4
	895	9	117,1 ± 3,7	9,6 ± 2,3
20	896—920	15	123,9 ± 3,0	9,4 ± 1,7
22	961—980	11	113,2 ± 2,4	7,1 ± 1,5
	981—990	12	109,0 ± 2,7	8,6 ± 1,7
24	1050—1093	22	115,0 ± 2,2	7,8 ± 1,5
25	1094—1120	14	121,7 ± 4,0	12,3 ± 2,3
	1121—1135	21	120,8 ± 2,9	11,0 ± 1,7
27	1270—1310	23	123,4 ± 3,2	12,4 ± 1,6

1) Die in den folgenden Tabellen nicht aufgeführten Schichten 921—960, 991—1050 u. 1136—1270 cm enthalten ebenfalls Kosmoceraten und wurden nur aus Zeitmangel nicht mehr abgesammelt.

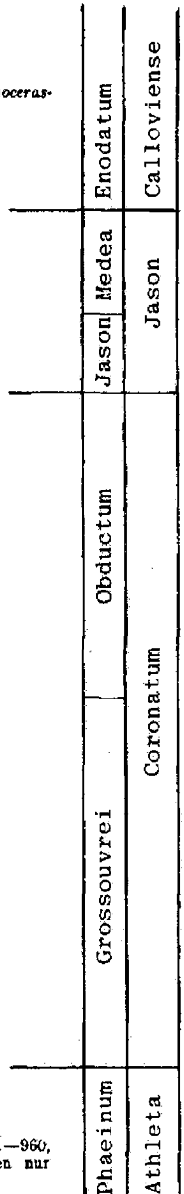

Fig. 9 The end-diameters of adult macroconch Kosmoceras *at Peterborough, after Brinkmann (1929).*[10] *Horizontal lines mark lithological boundaries between beds, labelled here 1–27. Zonal and subzonal classification of Fig. 6 shown at the right. The arrow of time in this table is downwards*

Table 3 *Estimates of time-intervals*

Unit	*Number of units*	*Average duration, <Δt>*
Standard Jurassic, N.W. Europe		
System: Jurassic	1	55 Ma (135–190 b.p.)
Stages	11	5.0 Ma
Zones	76	720,000 a
Subzones	154	350,000 a
Horizons	say, 450	120,000 a
Standard Aptian–Albian, S. England [15]		
System: L. Cretaceous	¼	17 Ma (98–115 b.p.)
Stages	2	8.5 Ma
Zones	14	1.2 Ma
Subzones	39	440,000 a
Standard Upper Cretaceous, N. America [15]		
System: U. Cretaceous	½	34 Ma (64–98 b.p.)
Stages	6½	5.2 Ma
Zones	60	570,000 a

An array of biostratigraphical time-scales analogous to those of Fig. 6 has been assembled for the other Periods of the Phanerozoic by Harland *et al.* (1982).[7] Although necessarily incomplete and taking the level of subdivision no further than something corresponding perhaps to the Zones of Fig. 6, it gives an impressive overview of the state of the art. As in all attempts to reconstruct history, we would expect the evidence to become more elusive as we go back in time. So it is with the fossils, but less than might have been feared. Thus, for instance, in the Carboniferous of western Europe, the Namurian (Millstone Grit) is zoned by means of goniatites, forerunners if not direct ancestors of the Mesozoic ammonites.[16] Subdivision can be carried to the level of distinguishable faunal horizons within Zones in a way very similar to the Horizons of Fig. 6. Accepting the older absolute timescale used elsewhere in this account,[11] the Namurian lasted from 332 to 319 Ma b.p. (million years ago). These 13 Ma are divisible into some 36 Horizons, of average duration $<\Delta t>$ 360,000 years; $R_t = 900$. In the Upper Devonian of Europe, the best guide-fossils are currently the conodonts. The 14 Ma from 366 to 352 Ma b.p. are divisible into 12 Zones[7] which incorporate some 29 faunally distinguishable horizons.[17] The time-resolution $<\Delta t>$ is thus some 500,000 years; $R_t = 740$.

This example also illustrates the point that to use fossils in biostratigraphy, it is not necessary to know anything about the organisms, once living, of which they are the partial remains. Conodonts are common, occur widely, and look like small teeth; but whether teeth, and the teeth of what, has been largely a matter of speculation. Suggestions have included scales, spines, or teeth of worms, molluscs, or boneless fishes. Only recently has a fossil of the whole animal been found.[18] It looks like a small chordate eel, and the conodonts were the teeth. Lastly, we may mention the graptolite zonation of the Silurian.[19] With a duration of 38 Ma, from 443 to 405 Ma b.p., it is subdivided into 30 Zones or Subzones. The average time-interval $<\Delta t>$ is 1.3 Ma, and $R_t = 340$.

4 The Rates of Some Terrestial Processes

As we have seen, it is the changes with time in the fossil record that allow us to reconstruct the Phanerozoic history of the Earth in great detail. Radiometric calibration allows us then indirectly to put dates on events in absolute terms, in years. Hence we can deduce also the absolute rates, both of the geological processes observed in crustal deformation, and of the biological processes that led to the changing fossil record, *i.e.* biological evolution.

The rates of geological processes

A deformation of the Earth's surface arises when one part of the crust moves relative to another. Such a strain may be resolved locally into its three orthogonal components: vertical; horizontal in the sense of tension or compression; and horizontal in the sense of shear. Of these, the commonplace observation in any mountain-chain of folded and faulted sedimentary rock-formations, of all thicknesses and at all angles or at all altitudes, attested since the earliest days to the power of vertical and compressional stresses and provided much of the stimulus for the development of dynamical geology. The realisation of the importance of tensional and shearing movements is much more recent.

The easiest geological processes to demonstrate are the vertical movements in the Earth's crust. Downward movements in a basin of sedimentary deposition directly influence rates of sedimentation; and it has therefore always been tempting, conversely, to take thicknesses of sediment as a rough indication of duration of time. But just how misleading this can be has been demonstrated over and over again, almost invariably by means of the fossils contained in the rocks. Thus, for instance, Jurassic limestones are known, particularly in Mediterranean regions, whose ammonites show that perhaps a metre of sediment spans some 30 ammonite Zones. Deposition was of course largely discontinuous, but this is not apparent from the lithology alone. In Dorset, a metre of Bajocian can contain all the ammonites of up to 10 Subzones. (It was pointed out just about 100 years ago that in some of these, the thickness of strata representing the Subzone was less than that of the ammonite used to date it!) In contrast, there are deposits in *e.g.* Oregon, Bulgaria, and the Caucasus in which it could be shown that 1,000–3,000 m of sediment span at most a single ammonite Zone. This represents sustained vertical synsedimentary movements of between 0.1 and 1 cm a year, which is the sort of figure that has been measured in historic times in *e.g.* local sinking of land at Naples, or the periodic depression of the southern North Sea basin that includes the London estuary and much of Holland, or the hydrostatic rise of central Scandinavia since the melting of the immensely thick ice-sheet that covered it during the last great glaciation. Clearly, such rates are entirely adequate to throw up whole mountain-ranges such as the Andes in the time-equivalent of perhaps 10 Jurassic ammonite Zones.

Horizontal movements are even more dramatic. It was first shown by Escher von der Lindt in 1840 that much of the structure of the eastern Helvetic Alps consists of large sheets of older rocks thrust northwards for long distances over much younger rocks. Subsequent biostratigraphy has mapped out in great detail the ages of the rocks and the times of thrusting. The horizontal movements can hardly have been less than 100 km and probably took no longer than 10 million years – an average rate of 1 cm a year. On the grandest scale, there is the evidence of the continents and the oceans themselves. It has long been known that the geologies of eastern North America and western Europe are most easily understood and best reconciled with each other if it is assumed that the North Atlantic is a relatively new ocean that did not open until about the end of the Jurassic. America has drifted some 2,000 km to the west in 100 million years, a speed of 2 cm a year. This figure was well-known to those of us who had kept faith in Alfred Wegener, long before geophysicists rediscovered continental drift by more physical techniques in the past 25 years. They estimate the rate from measurements (mainly geomagnetic) of sea-floor spreading in relatively recent times, and arrive at 1–5 cm per year. Translated into the Pacific, these figures are remarkably close to that given above for the migration of the Hawaiian volcanoes. They are also quite high enough to support what is perhaps one of the most startling geological discoveries of all in the past 25 years, that at least 70% of the igneous ocean floor of that immense ocean is of only post-Jurassic age, as revealed *i.a.* by the fossil-contents of the relatively thin sediments that cover it. Finally, the rates of shearing movement along wrench-faults are epitomised by the famous San Andreas fault in California, in which reconstructions of lateral displacements in recent times also indicate 2–3 cm a year.

Ammonites and the rates of biological evolution

"Individuals survive, species evolve" has been a basic tenet since Darwin's time. The discoveries of genetics, with its roots in molecular biology, and statistical theories of population dynamics have generated an enormous activity in the study of biological evolution. The ingenuity with which biologists explore the possibilities revealed by these discoveries to construct theories of evolution, while at the same time accommodating themselves to the constraints they impose, are most impressive. Paradigms and scenarios beset us on all sides, and there is much debate of gradualism *versus* punctuated equilibria, cladistics, and microevolution *versus* macroevolution. Practical studies are more difficult, for it is in their very nature that they take time. One can breed pigeons, or herds of dairy cattle, or fruit flies, or roses. But by far the greatest source of information remains the fossil record, and in attempting to discern in it examples of evolutionary lineages one always comes up against the same three basic problems. The first is that one cannot apply the essentially genetic tests of the ability to interbreed to an assemblage of fossils, to test whether it constituted a variable but monospecific, or even exactly contemporaneous population. There will always be basic taxonomic uncertainties attaching to the putative units in a fossil lineage, the species. The second is that the fossil record is highly incomplete in time. The best one can hope for is to see well-separated snapshots of an evolving lineage. The third is that the record is also highly incomplete in space. One is unlikely to find exact contemporaries of the instantaneous fossil population at one place anywhere else. Thus the common experience, in attempting to refine lineages, of finding breaks – jumps – which make it uncertain as to exactly what evolved from what, leading one to conclude that whatever did, did so somewhere else. A theory of evolution draws a picture; the fossil record is highly granular. The crucial question in using it to test or illustrate a theory is whether this granularity is fine enough to be treated as noise, perhaps blurring the picture a little but leaving it essentially recognisable; or whether the granularity destroys the picture. Most evolutionists of course bravely assume the former in whatever the example before them, usually without even discussing the problem explicitly at all. But as a biostratigrapher, I find such optimism more often than not misplaced, especially in the implied estimates of time. These points are brought out forcefully in attempts to reconstruct the evolution of the Mesozoic ammonites. Their very pre-eminence as chronometric guide fossils suggests that they might therefore be unusually good subjects for studies in evolution, and this has indeed turned out to be the case. Jurassic ammonites now provide us with what must be some of the most closely-documented evolutionary lineages we know.

The Jurassic ammonites proper, of the suborder Ammonitina, are divisible into eight major groups or superfamilies. One of these, the Stephanocerataceae, is illustrated in the form of a family-tree in Fig. 10. The time-scale on the left is the biostratigraphical one of Fig. 6 drawn to make Subzones equispaced. The branches represent divisions into units of lower rank, the families and subfamilies. These themselves are further subdivided into genera, and each genus is in general a grouping of the ultimate evolutionary building-bricks, the species. The 100 or so genera in the superfamily make up perhaps 20% of all Jurassic genera. The number of species is hardly worth estimating, for few of the nominal "species" that have been named and described correspond at all closely to species in the biological sense, of intrabreeding populations evolving with time. The number of nominal species certainly runs into many thousands. Two members of the Stephanocerataceae have been figured above. Fig. 4 shows one of the early Cardioceratinae from the Lamberti Zone; and Fig. 5, one of the Kosmoceratinae from the Jason Zone.

The first attempt to study an ammonite lineage at the limit of stratigraphical and hence temporal resolution was that of *Kosmoceras* by Brinkmann in the brick-pits of Peterborough already described in the discussion of biostratigraphy. He not only recorded the sequence of his 3,000 specimens most

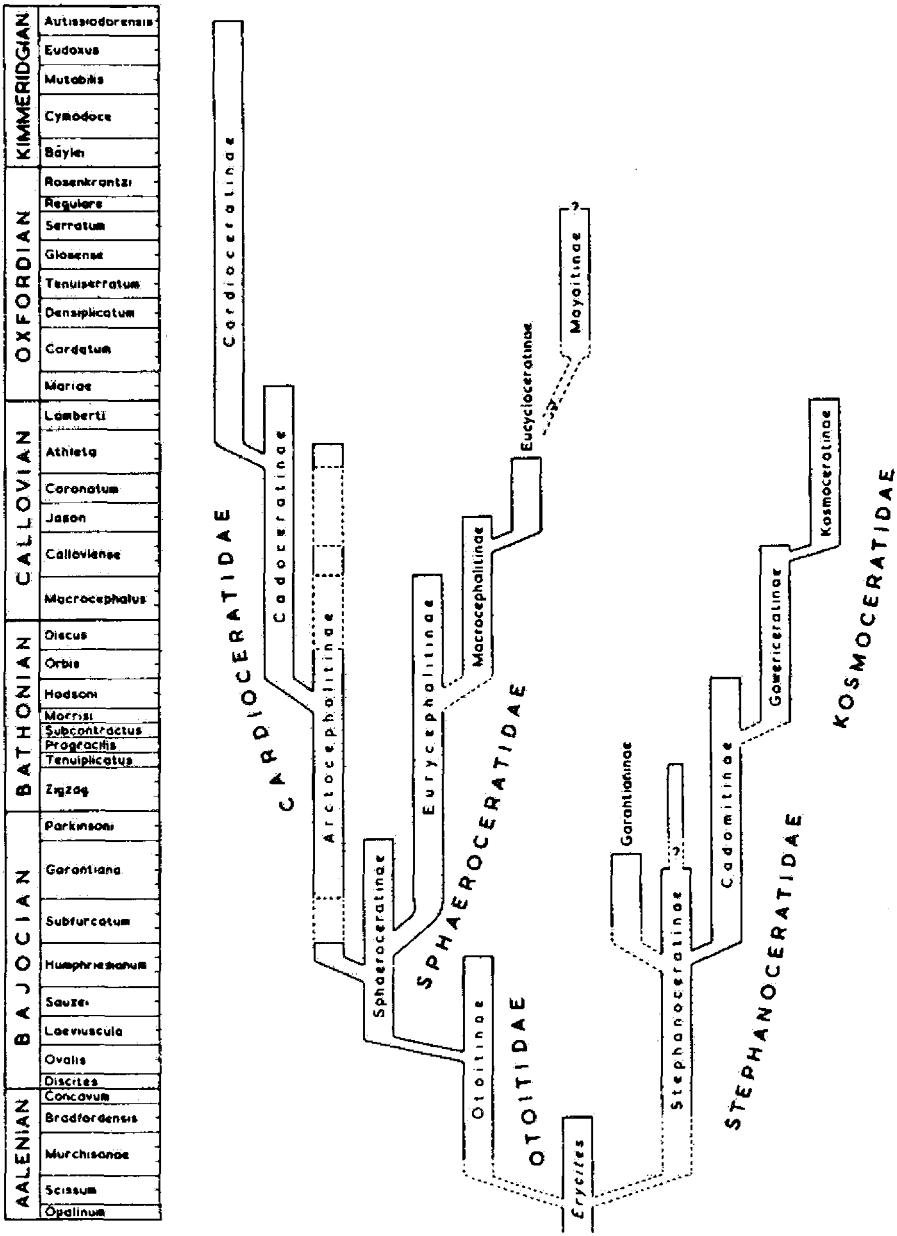

Fig. 10 *The phylogenetic classification of the ammonite superfamily Stephanocerataceae in the Middle–Upper Jurassic. Branches of*

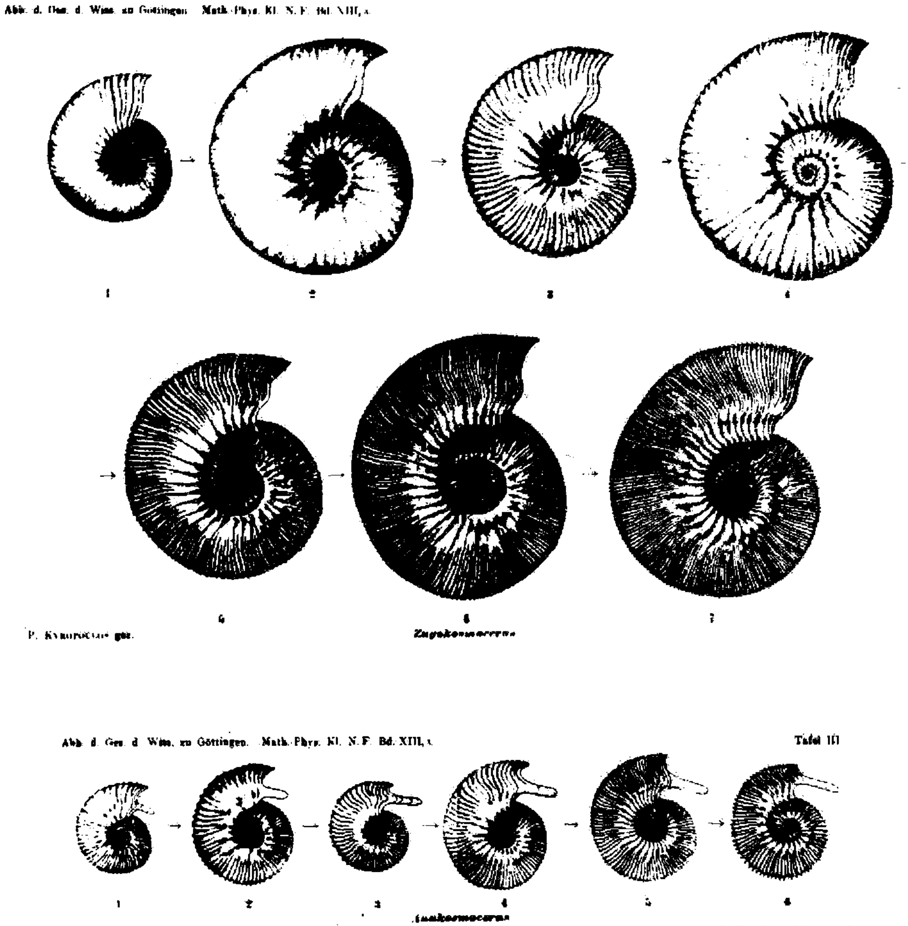

Fig. 11 *The evolution of* Kosmoceras *at Peterborough, after Brinkmann (1929).*[10] *Two sequences of shells represent the components of a single dimorphic lineage (×0.25). Levels are as numbered in Fig. 9. Upper series, large shells (macroconchs): 1–7: horizons 2, 7, 8, 10, 17, 21 and 27. Lower series, small shells (microconchs): 1–6: horizons 2, 7, 8, 9, 18 and 24*

precisely in the rocks but also examined the collection from each level biometrically (see *e.g.* Fig. 9). He concluded that these collections approximated to natural assemblages or biospecies, whose changes with time could, with minor exceptions, confidently be attributed to the evolution of just two parallel lineages. His illustrations of samples of these two lineages are reproduced here in Fig. 11. Today we interpret them as merely the sexually dimorphic components of a single lineage, the main clue coming from the recognition repeatedly of the appearance of new characters in the details of the ribbing and sculpture in both lineages simultaneously, showing they they were genetically linked. Note, for instance, the decrease in size in going from the second to the third shell in each line, which is real and significant. The overall differences between the first and last members of the lineages shown in Fig. 11 may not seem very startling, but the time-span they represent is not very great. It covers little more than the lower half of the branch shown as the Kosmoceratinae in the top right corner of Fig. 10. Changes in detail are certainly readily apparent, and taking as criterion for the minimum evolutionary change in a lineage the smallest morphological difference reliably detectable by the practiced eye, the 48 successive samples listed by Brinkmann in Fig. 9 represent some 24 resolvable *evolutionary* steps. Taking the time values of Table 3 for the five Subzones spanned by these 24 faunal steps, each step represents on average a time-interval of some 70,000 years. Fig. 9 also reflects the fact that the faunal steps are discontinuous and coincide with lithological breaks: within unit 8, for instance, the successive samples are not really distinguishable by eye. The implication is that the faunal discontinuities reflect breaks in sedimentation rather than evolutionary jumps, although in principle one probably cannot distinguish between these alternatives at this level of refinement. These discontinuities mark the ultimate granularity of the fossil record in this instance. Either way, however, the 15 levels within unit 8 must represent even shorter time-intervals, and making what is admittedly a gross assumption of uniform rates, 15 levels within a step interval of 70,000 years could represent an ultimate *sampling-interval* of only 5,000 years.

What do these figures mean in terms of reproductive steps? The life-span of ammonites remains highly uncertain, but for forms of the size of *Kosmoceras* it was certainly not less than one year and most probably not greater than 10. Taking for sake of argument a figure of five years, the sampling-interval quoted above of 5,000 years would then correspond to 1,000 generations, and the evolutionary step-interval of 70,000 years, 14,000 generations. If, as seems likely, the life-span to reproductive maturity of ammonites was less than five years, these numbers would be greater. It seems safe therefore to conclude that to produce a detectable evolutionary change in morphology took *Kosmoceras* at least 5,000 generations. This is gradualism by any standards, and moreover in a group of the animal kingdom renowned for the speed and diversity of its evolution. A modern stock-breeder would be disappointed to find himself without significant morphological changes after only 20 generations of selective (non-mutative) breeding, and genetic evolutionists seem to quote 1,000 generations as the minimum needed for significant changes in natural environments

We may mention briefly a second example of evolution which illustrates some other important general points. It consists of the family Cardioceratidae, shown as the left-hand branch of the Stephanocerataceae in Fig. 10. Some of the earliest and latest members are illustrated in Fig. 12; an intermediate form is shown in Fig. 14. The Cardioceratidae are common and long-ranging in the Jurassic rocks of nothern Europe, and include some of the most venerable of all ammonite species, sch as *Amm. cordatus, lamberti* (see Fig. 6), *serratus* and four others,

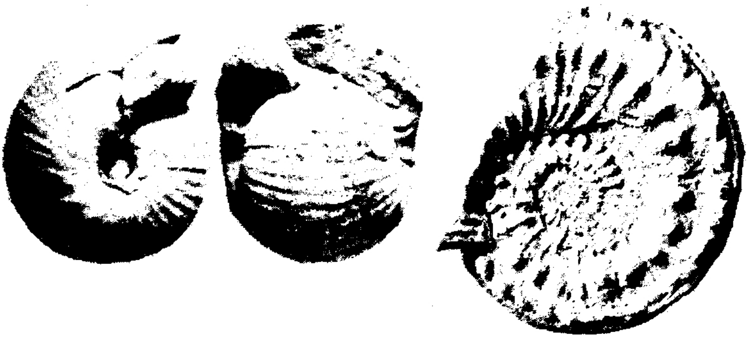

Fig. 12 *Early and late members of the family Cardioceratidae. Left:* Cranocephalites borealis *(Spath), Bajocian, Borealis Zone, E. Greenland, the earliest fauna. Right:* Amoeboceras decipiens *(Spath), Kimmeridgian, Eudoxus Zone, E. Greenland, one of the last. Both macroconchs.* $\times 0.5$. *Note the transformation from rounded, inflated, involute whorl-section to compressed, evolute coiling with keel, and the replacement of simple, subdued ribbing by rows of tubercles. An intermediate form is shown in Fig. 4*

described already by Sowerby in his *Mineral Conchology* (1813–1819). As knowledge of the group grew, so the evolutionary connections became apparent and the gaps were filled. But a number of problems persisted. There were some abrupt discontinuities that no amount of new material seemed to smooth out. The first discontunuity lay at the beginning of the family as it was known up to 1957. The Cardioceratidae appeared suddenly and in profusion all over northern Europe in the Calloviense Zone of the Callovian (see Fig. 10), but seemed to have no plausible immediate ancestors: a conspicuous example of cryptogenesis. Either they had made a sudden evolutionary jump from something else, or their sudden appearance merely reflected a rapid immigration from somewhere else, or both: an example of allopatric speciation and punctuated equilibria. The second discontinuity was of similar kind but less extreme, lying at the boundary between the Athleta and Lamberti Zones at the top of the Callovian. Here, ancestors (Cadoceratinae) and descendents (Cardioceratinae) were clearly discernible and even briefly coexisted, but there were no intermediates. The Cardioceratinae again made a dramatic appearance in Europe by flooding south in enormous numbers, in sharp contrast to the rather rare Cadoceratinae immediately before.

Both problems have been solved in the past 25 years in the course of an intensive geological exploration of the hitherto almost unknown regions of the Arctic, prompted largely by the search for petroleum. It transpires that the ecological habitat of the Cardioceratidae was confined to shallow shelf-seas in quite restricted biogeographical provinces, as were many other groups of ammonites and marine invertebrates, and as are most marine organisms today. The boundaries of these ammonite provinces could be surprisingly sharp, and

Fig. 13 *A palaeogeographic reconstruction of the Arctic in the Jurassic at about tl Middle–Upper Jurassic boundary. NWE: north-west Europe; RP: Russian Platform; M(Mongolian–Okhotsk geosyncline; SA: Sikhote–Alin geosyncline; NPC: North Paci Cordillera; WI: Westrn Interior basin of North America. Wavy lines represent megatecton sutures marking present-day plate boundaries. Reconstruction west of the Bering Straits a highly uncertain. It is also possible that the Boreal Sea was entirely a non-oceanic shelf sea the time. In any case, there was no ice-sheet (after Smith and Briden, 1977,[20] modified,*

fluctuated widely and rapidly with time. The proper home of the Cardioceratidae was in the Arctic. A reconstruction in about the Callovian is shown in Fig. 13. Before this, in the Bathonian, the sea-routes down the Viking Straits between Greenland and Norway were blocked at the southern end, in the northern North Sea, as were those west of and across the Urals into the Russian Platform (RP). The Boreal Sea was almost landlocked, and the early Cardioceratidae were confined to areas I–V (as far as about 100 km SE of the Shetlands, revealed by deep borings in the northern North Sea oil-fields) and the northern edges of areas VI–IX. The previously cryptogenic appearance in the classical areas of Europe then merely reflected a southerly migration following the removal of the obstructions in areas V and VI. The second break, between Cadoceratinae and Cardioceratinae, reflected the removal of the obstruction between the Russian Platform and area VII, in which the intermediate forms have since been found. The southerly spread of the Cardioceratidae reached its maximum in about the Oxfordian, extending as far as the northern margins of the Tethys in the Old World, and covering the whole of the Western Interior basin (WI) in the New, as far as about central California. The Cardioceratidae never entered the southern hemisphere.

This sort of ammonite history is typical and immediately points to a strong limitation in their use as guide-fossils for purposes of stratigraphical correlation. Biostratigraphy as outlined earlier in this account can only be done province by province, and wider correlations achieved in regions of provincial overlap. Here lies much work in the future. The example of the Cardioceratidae is again illustrated in Fig. 14, which shows how separate zonal scales have had to be constructed for the Middle–Upper Jurassic of the northern hemisphere. In much of this column, correlation at zonal levels remains quite impossible.

Fig. 14 also shows how well the Cardioceratidae have been documented as an evolutionary lineage. Each circle on the right represents a well-characterised faunal horizon that has yielded enough material to give a reasonable picture of biospecific variability. [M] and [m] once again refer to dimorphs. The lineage extends over 29 Zones and about 60 Subzones – some 21 million years according to Table 3. The number of Horizons is over a hundred, so the average time-interval between Horizons of 200,000 years is now rather greater than in *Kosmoceras* at Peterborough. On the other hand the length is 10 times longer, and there can be no doubt about the considerable magnitude of the evolutionary changes that have taken place: comparing the two shells shown in Fig. 12, it is not obvious that they should, or even might be, the end-members by lineal descent of but a single lineage. Neither, where so many intermediates are known, is there any simple answer to the question of whether they belong even to the same or different species. In both the Kosmoceratidae and the Cardioceratidae there are no natural breaks at which one species may be said to have ended and the next to have begun, other than as a convenient device for labelling. The question of what was the average duration of a species, often quoted as important in discussion of evolutionary rates, has here no meaning in any biological sense.

The general conclusions to be drawn from the ammonites are, then, that the

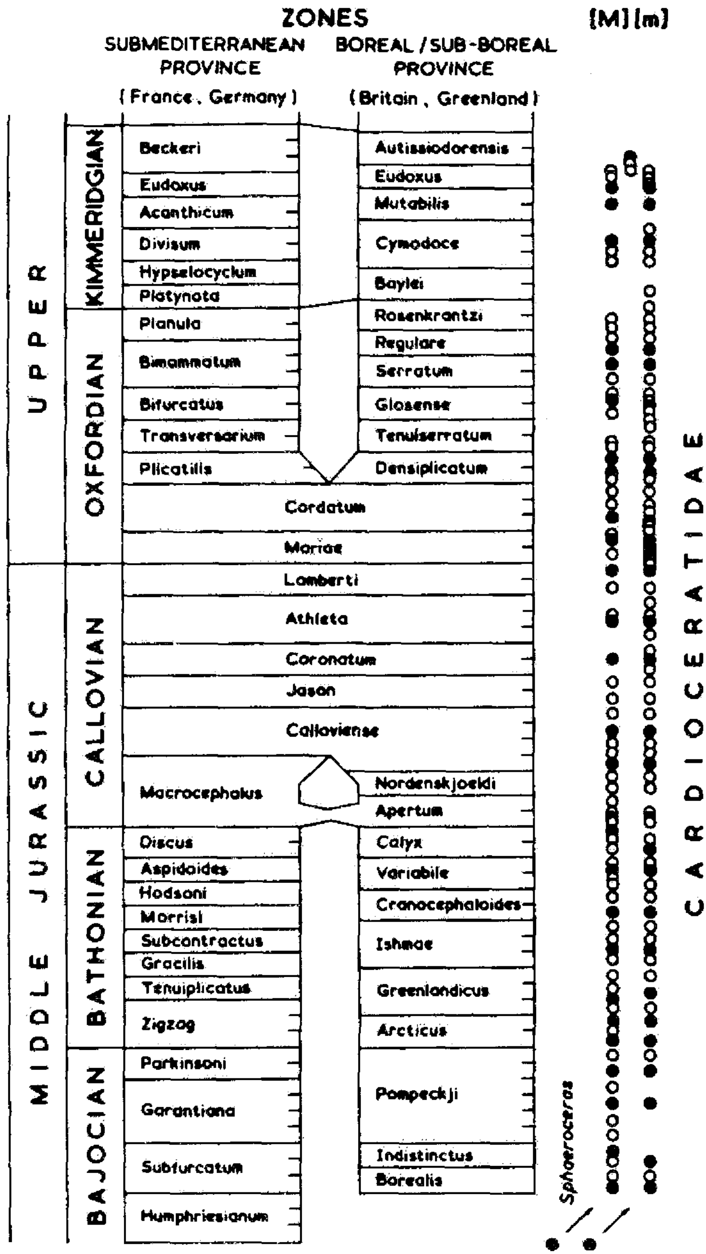

Fig. 14 *Faunal provinces, zones, and the faunal succession of the Cardioceratidae. The column on the left gives the standard zonation of central Europe, that on the right the zonation in the Arctic. In the Middle Jurassic, Britain follows the left-hand column; in the Upper Jurassic, that on the right. The columns of circles on the right represent the faunal horizons that have yielded distinguishable assemblages of Cardioceratidae; [M], [m] represent macro- and micro-conch dimorphs. In the last known forms of the lineage, dimorphism has become so inconspicuous that it has not yet been detected. The sex-ratio found in fossil assemblages can*

difference between smooth evolutionary changes ("gradualism") and discontinuous changes ("puncutated equilibria") is one of degree rather than of principle and probably more often apparent than real, depending primarily on the granularity of the imperfect fossil record both in time and in space. How do they compare with other groups of organisms?

The majority of case-histories debated in the evolutionary literature probably involve terrestrial vertebrates. The motivation lies in the fact that their morphologies are rich in information that can be interpreted functionally, involving the interaction with the environment. It is thus possible to ask, and try to answer, the question not only of *how* a series of organisms evolved, but also *why*. Vertebrate palaeontologists and comparative anatomists have become very successful in showing why organisms evolved the structures they did, but exactly how, along what evolutionary path, is often highly conjectural. For rarely in these cases, or for that matter in any others that are discussed, does the time-discrimination fall below intervals of a million years. The ammonites have shown that changes that appear abrupt at this level of sampling can be smooth at intervals of 100,000 years – geologically speaking, mere instants. Yet such instants are biologically quite long enough to fit in all the reproductive generations needed to produce the evolutionary changes observed without having to invoke any special causes. They are also quite long enough for major migrational changes of habitat to occur. An ammonite "cryptogenesis" resulting from a faunal migration of, say, 6,000 km in one Subzone of 300,000 years need represent a movement of no more than 2 km a century – hardly a catastrophic event in a group of marine organisms that must have been at least to some extent free swimmers, no matter how sluggishly.

A last word about ammonites. I have tried to indicate how they evolved rapidly, what we can learn from this, and how we can exploit it for chronometric purposes. But we know almost nothing about the detailed functional significance of the ammonite shell, why some had one shape and some another (Fig. 12). Hence we know even less why they should have evolved so rapidly into each other, and least of all the answer to that currently popular question of why they became extinct at the end of the Cretaceous, like the dinosaurs. All the criteria of "fitness" in the Darwinian sense that have been proposed – and there have been many: hydrodynamic, hydrostatic, predator-resistance, and others – are largely tautological and *ad hoc*, incapable of being tested independently. Hence the final comparison with the vertebrates: we know often why they evolved as they did, but not how. In the case of the ammonites, we now know in many cases exactly how they evolved, but have no idea why. The Pearly *Nautilus* has after all survived practically unchanged for 300 million years.

Evolution versus revolution

There remains a question hinted at before. Each geological period was unique and each System has its speciality. What marks out the Jurassic? Thirty years ago, the interest it excited was low. Its virtues seemed to be largely negative: in the middle of the Mesozoic, it seemed to have been a period of tranquility, geologically and biologically speaking, in the middle of everything and remarkable for nothing. All that was worth knowing seemed to have been discovered. The proper field for the display of geological virility lay in the Highlands, the Alps, the Andes.

Since the advent of plate tectonics, our views have subtly changed. The dominant factor is the twofold division of the Earth's crust into oceans and continents, the former highly mobile, the latter quasi-permanent, as in the picture of the scum of froth floating on the surface of a bubbling vat of boiling jam. Both the turn-over times of the oceans, and the duration of supercontinents between times of break-up and reassembly which we observe as continental drift, appear to be governed by characteristic time-constants presumably determined by the physics of convection in the deeper layers of the Earth, the mantle. These time-constants are of the order of 200–300 million years. Hence in the long term, geological history is cyclical, and each cycle destroys most of the evidence of the previous cycle – witness the Pacific Ocean today. So the primary task becomes the understanding of at least one cycle as completely as possible, from beginning to end. Fortunately, the Phanerozoic takes us back far enough to make this possible.

We seem to have been, very roughly, through about one and a half cycles. The first period of major continental drift that we can closely identify was reflected in the Caledonian mountain-building episode, around Ordovician–Silurian times. Amongst others, the North Atlantic (Iapetus Ocean) closed, and there was welded together the supercontinent Pangea, much as Wegener drew it. The second (Alpine) period, leading to the break-up of Pangea, including the reopening of the North Atlantic, began in the early Mesozoic. It gathered speed in the middle Mesozoic, *i.e.* the Jurassic, and is in full spate, as the events on Krakatoa and Mt. St. Helens testify, and as that fascinating *vade mecum*, the palaeocontinental maps by Smith and Briden,[20] plot out so dramatically. We are therefore anxious to map the dispositions of land and sea as closely as possible in the early stages of the cycle. In this respect the Trias is disappointing. It was a time when average worldwide sea-level was low, so very little marine shelf-sediment with its informative fossil-content is preserved. By the end of the Cretaceous major changes were already occurring rapidly. It seems the very tranquility of the Jurassic, with its shelf-seas of moderate and expanding widths, may make it the most informative period in which to follow the opening phases of the current cycle of continental rearrangements. This applies not only to the major continental units but also, and more particularly, to the smaller pieces that inevitably get scattered about. Some examples may be seen on the left in Fig. 13, in the collage of microcontinental terranes that make up the Western Cordillera of North America (NPC), whose palaeoreconstruction is currently a topic of hot debate. Another lies in the Pannonian Plain of Hungary, fringed by Jurassic rocks which indicate strongly that at the time it was much closer to Africa than to Europe, and that it had also rotated through 180° in the meantime. Finally, we understand why today's continental shelves are good places for finding oil, and it is cheering to know that both source and reservoir-rocks for many of the fields in the northern North Sea are Jurassic. So, its popularity restored, the Jurassic is alive and well.

5 Conclusion

As we look around us we enjoy the magic of the scenery and marvel at the profusion of life on Earth. I have tried to indicate how, with a little imagination, we may discern behind the surface the extra dimension of time, and learn to read the history of our planet. Using the fossils we plot the movements of the rocks, and using the rocks we follow the evolution of life, of what are now the fossils. It is an absorbing pastime that calls for little more than a hammer, some books, and perhaps a little travel-money. Anyone can join.

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