Fossils as geological clocks

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Abstract: To reconstruct the history of the Earth we need to know *what* happened and *when* – *events* and their *dates* – and we should like to know *how* it happened and *why* – *processes* and their *rates*. To date a historical event we need a timescale for reference – a *calendar* – and a means of placing events in this timescale – a *clock*. Direct access to the primary physical calendar, of time measured in years by means of elemental radiometry as clock, is possible in only a minority of geological problems. By far the richest historical source in the Phanerozoic Eon has been the stratigraphical analysis of sedimentary rocks by means of fossils, the approach pioneered by William Smith. The succession of fossil biotae found in the rocks is used to construct the calendar of *relative* time, the familiar geological calendar defining the standard chronostratigraphical timescale still in process of refinement today. Rocks are then dated through time correlations with this scale by means of their *guide* fossils (von Buch) as clocks. The power to measure the rates of geological processes then depends on the time *resolution* achievable by means of fossils, the time *intervals* between distinguishable events, the *finesse* of the calendar.

The present-day state of play is reviewed, both in the refinement of the geological calendar and the finesse that has been attained. Comparison of the geological calendar with our familiar human historical calendar reveals some illuminating parallels as well as some important differences. Illustrative examples are taken from the Jurassic Period (170 Ma BP) and its ammonites as clocks.

The last two centuries have seen the detailed exploration not just of the geological history of the Earth – of what happened, when and how – but also of the development of the timescales on which this history is based – the geological calendar – and of the methods of measuring geological ages – geological clocks. In the first of these two centuries, following the times of James Hutton and William Smith, the geological calendar, as it was described already by Buckman (1898), rapidly grew into the form in which we still use it today, filled with an ever more detailed chronology of events. It was a chronology largely based on the biostratigraphy of fossils as clocks. So the ages based on them were only relative; the rocks that could be dated were restricted to fossiliferous strata, which excluded the Precambrian; and the question of what were their 'true ages', in years, could lead to little more than speculation. The only positive outcome of the lively debate it engendered was to raise geological ages from the thousands into the realm of millions of years.

The discovery of radioactivity and its exploitation in radiometric age determination, forever coupled with the immortal name of Arthur Holmes, introduced a second class of geological clocks based on time-dependent physical properties and processes. These can lead to 'true ages' directly and things have not been the same in geology ever since. An increasing number of further physical methods, based on properties of rocks such as their remnant palaeomagnetism or the stable-isotope ratios of their elements, has given us today an impressive armoury of techniques for dating an ever-widening range of rocks and geological events. But, to what extent do newer methods replace older ones or merely complement them? And by what criteria may the relative merits of different methods be compared?

To do justice to this fascinating subject would take volumes and is far beyond the scope of these pages. I should like therefore to return here to a discussion of the original methods of dating rocks, those based on the stratigraphy of fossils in layered rocks pioneered by William Smith. The advent of physical methods has in fact in no way diminished the importance of biostratigraphy as a tool for geochronology. Intensive and sustained activity has greatly broadened the range of fossils drawn in as geochronometers, the types and ages of rocks that can be dated with them and the precision with which this can be done. To cover all these here in any detail is not possible. I shall therefore base the discussion largely on an example with which I am particularly familiar. The fossils are ammonites and the period in which they lived was the Jurassic. The

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arguments are, however, quite general and may be applied equally well to other groups and periods (with variable success). The emphasis will be on two leading criteria of merit: firstly, how precisely and geographically extensively can rocks be dated by means of fossils? And secondly, how closely in time can successive events be distinguished: what are the shortest time intervals that can be resolved? The biostratigraphy of fossils is, however, one step removed from the time factors derived from it – biostratigraphical ages are relative – and so it is worthwhile perhaps to begin with a brief review of the relationships between the conventional geological calendar and the primary physical timescale on which we like to express geological ages. Some of these relationships are subtle and perhaps not always appreciated.

Time, clocks and calendars

Time is one of the four physical dimensions in which we perceive the conscious world. To locate an *event* at a *point* in time, as the common expression has it, we must give the dimension a metric and scale – a *time-scale* – and to choose, or devise, a *clock* by means of which time can be *measured*. The clock that defines the scale is the *primary* clock and the scale that it defines is its *standard*, or *calendar*. A calendar is then the frame of reference for *dating* events and a record of events thus dated is their *history*. Dates are measures of relative time – relative in the calendar to one or more chosen *fixed points*. One of these fixed points is usually given the value zero, marking the *origin* of the scale. To determine the date of a particular event then requires a means of relating it to the calendar of the primary clock. Such means have to be observational devices – *secondary* clocks – whose kind can depend strongly on the nature of the event to be dated, whose *precision* is limited and whose relation to the primary clock is determined by *calibration*. A special case of time measurement commonly encountered is that of following the time *evolution* of a *system* relative to some arbitrary beginning, of its state at successive moments during a *period* of the 'passage of time' or, if the state remains constant during that period, of that period's *duration*. The time of a moment after the beginning of the evolution of the system is then its *age* at that moment. Finally, the precision with which a date can be determined by means of a secondary clock depends on its power of time *resolution*: the minimum interval between events that it is able to distinguish.

These points seem so obvious that to spell them out in such detail may appear pedantic. They seem obvious because we are so familiar with them from everyday experience and in the domains of our study of 'history' – history as preserved in human records or prehistory as deduced from archaeology. They become less obvious, however, when we stray outside the bounds of human experience into other historical domains, such as those of historical geology and its corollary, historical biology or palaeontology. The literature in these fields reveals the persistence of considerable confusion. It arises largely because of the nature of the clocks that have to be used in reconstructing their past. These clocks, both primary and secondary, differ fundamentally from those used in human history. Nevertheless, there are valuable insights to be gained from comparisons of the methods used in the different domains. They reveal some interesting analogies, as well as highlighting some important differences.

The historical calendar

Figure 1 shows a graphical representation of our traditional calendar and how a certain historical event is located in it. Setting aside the modifications introduced by modern physics and some relatively minor changes of convention, the calendar is based in fact on three primary clocks. They exploit three constants of solar planetary motion, characterized by highly regular and conveniently well-separated cyclical periods: the orbital motion of the Earth about the Sun – the year; the orbital motion of the Moon about the Earth – the lunar month; and the spin of the Earth – the day. The independence of the first and third is familiarly reflected in the need for leap-years, that of the second in the persistence of Easter as a moveable feast.

The periods of time of interest in human history vary over a very wide dynamical range of magnitudes. It becomes convenient, therefore, to subdivide historical time in a *hierarchy* of successively smaller units. A part of this hierarchy is incorporated in Figure 1 and its levels are numbered I–VII. The primary units lie at levels IV, V and VI. Larger units are then constructed as decadic multiples of the year, going up to the level appropriate for the chronicle of human history as a whole, the millennium (I). The decade (III) serves to enumerate human generations and the 'three score years and ten' of human lifetime. The year (IV) provides a convenient numerical metric in which the origin of the timescale is defined. Where placed is arbitrary and its

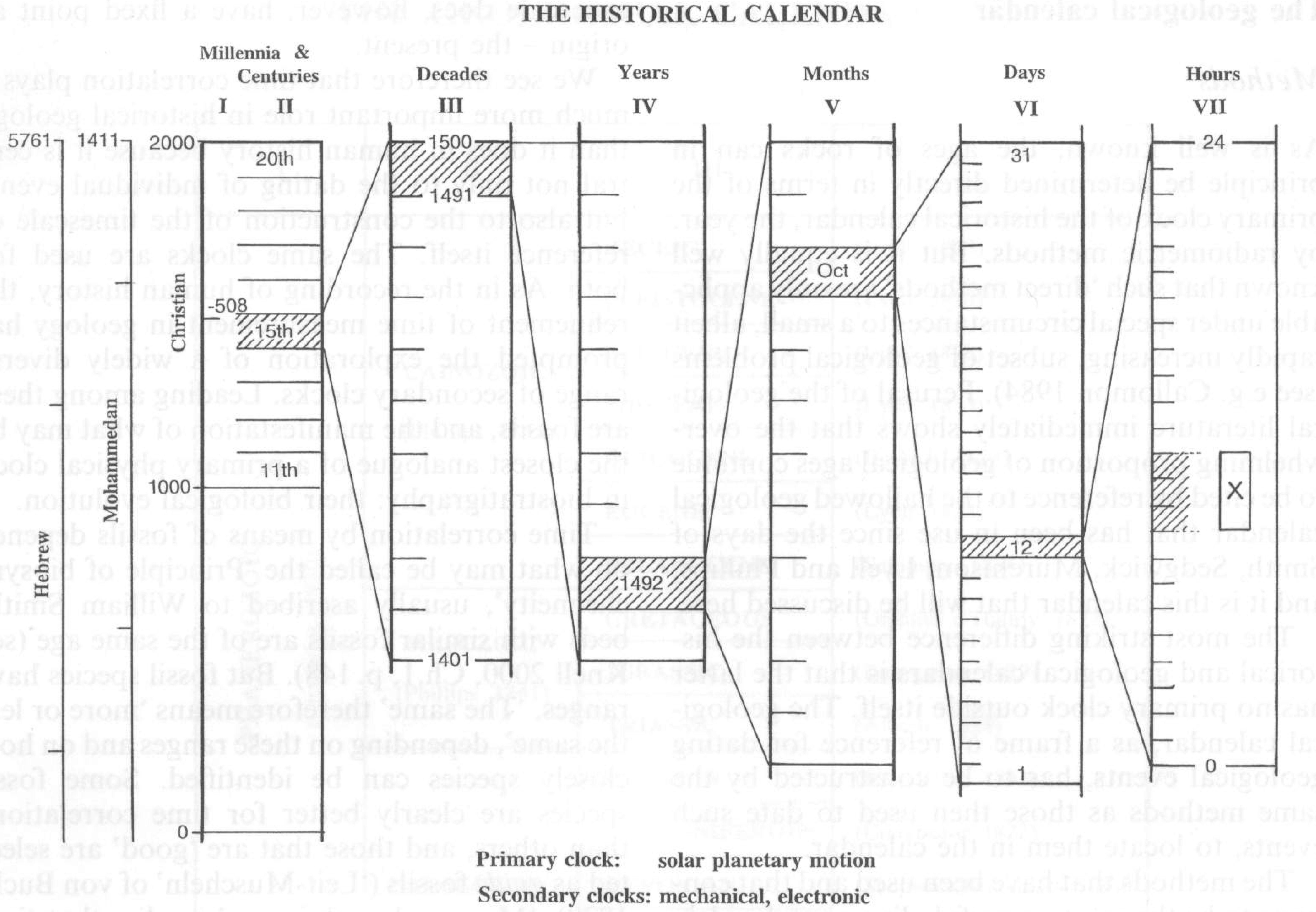

Fig. 1. The human historical calendar and its hierarchical subdivision. The two primary astronomical clocks still in practical use are based on the Earth's orbital motion, the year (level IV), and its spin, the day (level VI). The location in this calendar of a famous historical event (the late morning of 12 October 1492 (Julian calendar, local time), when Christopher Columbus landed in America) is picked out by diagonal shading.

positions at the BC/AD boundary in the Christian calendar relative to that of two other historical calendars widely used in the past are also indicated in Figure 1. These alternative calendars, together with others such as the Chinese, were also geographically separated, being used in different parts of the world. Yet they were all based on the same primary clock, that of the rotation of the Earth. Their time *correlation* therefore presents no special problems.

Smaller units in the hierarchy down to subdivisions of the day into hours are also shown, but further extensions into minutes (VIII) and seconds (IX) are of course familiar in everyday life. The second of time is appropriate for the description of the briefest events distinguishable by the human senses – the 'blink of an eye' or, more precisely, the persistence of vision, of about one-twentieth of a second, which governs the design of cinema and television projectors of moving pictures. (For physicists, the second is now also the primary SI unit of time, based on a natural internal oscillation of an atomic caesium clock having a period of 1.088×10^{-10} s. Modern technology enables us to measure times down to very small intervals, but the same principles as those outlined above apply. A radar speed-trap, to secure a conviction, has to measure a time difference between two periods of about one second with a precision of about one-thousandth of a microsecond).

Secondary clocks, essentials of our daily lives, are too diverse to enumerate but fall today into two classes: mechanical and electronic. The dynamical ranges of domestic timepieces vary from the simplest (and cheapest), a two-hands wristwatch telling the hours and minutes, to the more sophisticated, recording the years down to seconds, found in a personal computer. The accuracy of such a timekeeper is controlled by calibration against widely available broadcast time signals, but an important point to note is that it, and hence the accuracy of any event timed with it, depends also on the precision of its ability to measure time, which in turn depends on its temporal resolving power. A watch with a second-hand can tell the time to within only a second or so. This point becomes particularly important in geological time measurements, discussed below.

The geological calendar

Methods

As is well known, the ages of rocks can in principle be determined directly in terms of the primary clock of the historical calendar, the year, by radiometric methods. But it is equally well known that such 'direct methods' are only applicable under special circumstances to a small, albeit rapidly increasing, subset of geological problems (see e.g. Callomon 1984). Perusal of the geological literature immediately shows that the overwhelming proportion of geological ages continue to be cited by reference to the hallowed geological calendar that has been in use since the days of Smith, Sedgwick, Murchison, Lyell and Phillips, and it is this calendar that will be discussed here.

The most striking difference between the historical and geological calendars is that the latter has no primary clock outside itself. The geological calendar, as a frame of reference for dating geological events, has to be constructed by the same methods as those then used to date such events, to locate them in the calendar.

The methods that have been used and that continue to be the most powerful, diverse and widely applicable are those of stratigraphy, the study of successions of layered rocks. There are four steps in the argument. The first and basic *observation* is that of beds specified by relative heights in a succession – what lies above what. Description of their thicknesses and compositions is their *lithostratigraphy* and, if composition includes fossils, their *biostratigraphy*. The next step is to introduce Steno's (1669) 'Principle of Superposition', which states that in a normal succession of strata, the higher-lying are the younger. This transforms a static description of relative height into a dynamical one of relative time and is an *interpretation*. (Appearances can be deceiving, as in igneous sills intruded into sediments, or at imperceptible thrust-faults in fold-belts.) Specification of rocks in a stratal succession according to their relative ages is their *chronostratigraphy*. The third step involves the linking of local successions through time correlations These allow the ages of rocks at one place to be compared with those at another – the same, older or younger. The fourth step then becomes the synthesis of a standard time-ordered succession of rocks and its conjugate timescale, correlation with which allows any local rock to be dated in terms of the standard – the geological, chronostratigraphical calendar. This timescale is one of *relative* time. The age of any point on it is relative to those before and after. There is no *a priori* numerical measure either of time durations or of time intervals. The timescale does, however, have a fixed point as origin – the present.

We see therefore that time correlation plays a much more important role in historical geology than it does in human history because it is central not only to the dating of individual events but also to the construction of the timescale of reference itself. The same clocks are used for both. As in the recording of human history, the refinement of time measurement in geology has prompted the exploration of a widely diverse range of secondary clocks. Leading among these are fossils, and the manifestation of what may be the closest analogue of a primary physical clock in biostratigraphy: their biological evolution.

Time correlation by means of fossils depends on what may be called the 'Principle of biosynchroneity', usually ascribed to William Smith: beds with similar fossils are of the same age (see Knell 2000, Ch.1, p. 148). But fossil species have ranges. 'The same' therefore means 'more or less the same', depending on these ranges and on how closely species can be identified. Some fossil species are clearly better for time correlations than others, and those that are 'good' are selected as *guide* fossils ('Leit-Muscheln' of von Buch, 1839). 'More or less the same' implies that time correlations by means of fossils are approximations. 'Good' measures the minimum ranges of uncertainty in these approximations. Conversely, the degrees of approximation are set by the *temporal resolving powers* of the guide fossils, by the minimum time intervals between successive geological events that can be distinguished by means of such fossils. Then, to complete the circle, this leads back to the *finesse* of the standard geological calendar itself, constructed from the biostratigraphy of the guide fossils. This reciprocal interrelation of biostratigraphy and the construction of the standard calendar clearly form a basis for continual refinement. To claim that the two centuries since the days of William Smith have seen progress may sound trite. But how far have we come? How good is our calendar today? How closely can rocks be dated by means of fossils? And, finally, how well can our relative geological age determinations be correlated with their 'absolute' ages, in years, determined radiometrically? Should we today bother to retain our geological calendar at all?

The calendar

The standard geological calendar is shown diagrammatically in Figures 2 and 3. As in the historical calendar, periods of interest in the Earth's history also cover a very wide dynamical range of magnitudes. The total timespan from the present

THE GEOLOGICAL CALENDAR

I	II	III	
PHANEROZOIC (Chadwick 1930)	CAINOZOIC (Phillips 1841)	RECENT	(Lyell 1873)
		PLEISTOCENE	(Lyell 1839)
		PLIOCENE	(Lyell 1833)
		MIOCENE	(Lyell 1833)
		OLIGOCENE	(Beyrich 1854)
		EOCENE	(Lyell 1833)
		PALAEOCENE	(Schimper 1874)
	MESOZOIC (Phillips 1841)	CRETACEOUS	(Omalius d'Halloy 1822)
		JURASSIC	(Brongniart 1829)
		TRIASSIC	(Alberti 1834)
	PALAEOZOIC (Phillips 1840-41)	PERMIAN	(Murchison 1841)
		CARBONIFEROUS	(Conybeare 1822)
		DEVONIAN	(Sedgwick/Murchison 1839)
		SILURIAN	(Murchison 1833)
		ORDOVICIAN	(Lapworth 1879)
		CAMBRIAN	(Sedgwick 1835)
	skeletal macrofossils appear		
PRECAMBRIAN	PROTEROZOIC (Emmons 1888)		
	— (Gunflint Formation) —		
	ARCHAEOZOIC ARCHAEAN (Dana 1872)		

Fig. 2. The geological calendar at the top three levels in its hierarchical subdivision, drawn on an equal-Period/System approximation.

back to the earliest days of our Earth of which we have any record has therefore also been subdivided in a hierarchy of successively finer units and, for ease of reference, the levels of this hierarchy are again numbered, I–VII. Figure 2 shows the first three levels, I–III, and, as an example, one of the units at level III, the Jurassic, is taken in Figure 3 to the limits of time resolution attainable by means of one group of fossils – ammonites. (Level III also represents the limit to which the geological calendar has penetrated the body of public general knowledge, to be tested in television programmes such as *Mastermind* or *University Challenge*, or used to set the scene in films such as *Jurassic Park*.)

In looking at these figures, some important points should be noted. Firstly, the columns of boxes can be read in two ways, reflecting the conjugate representations of rock–time duality (Table 1). In the first representation, the vertical co-ordinates are in each case those of time and the horizontal lines delimiting the boxes, which represent periods of time, mark instants – turning points – of time. Although the representation

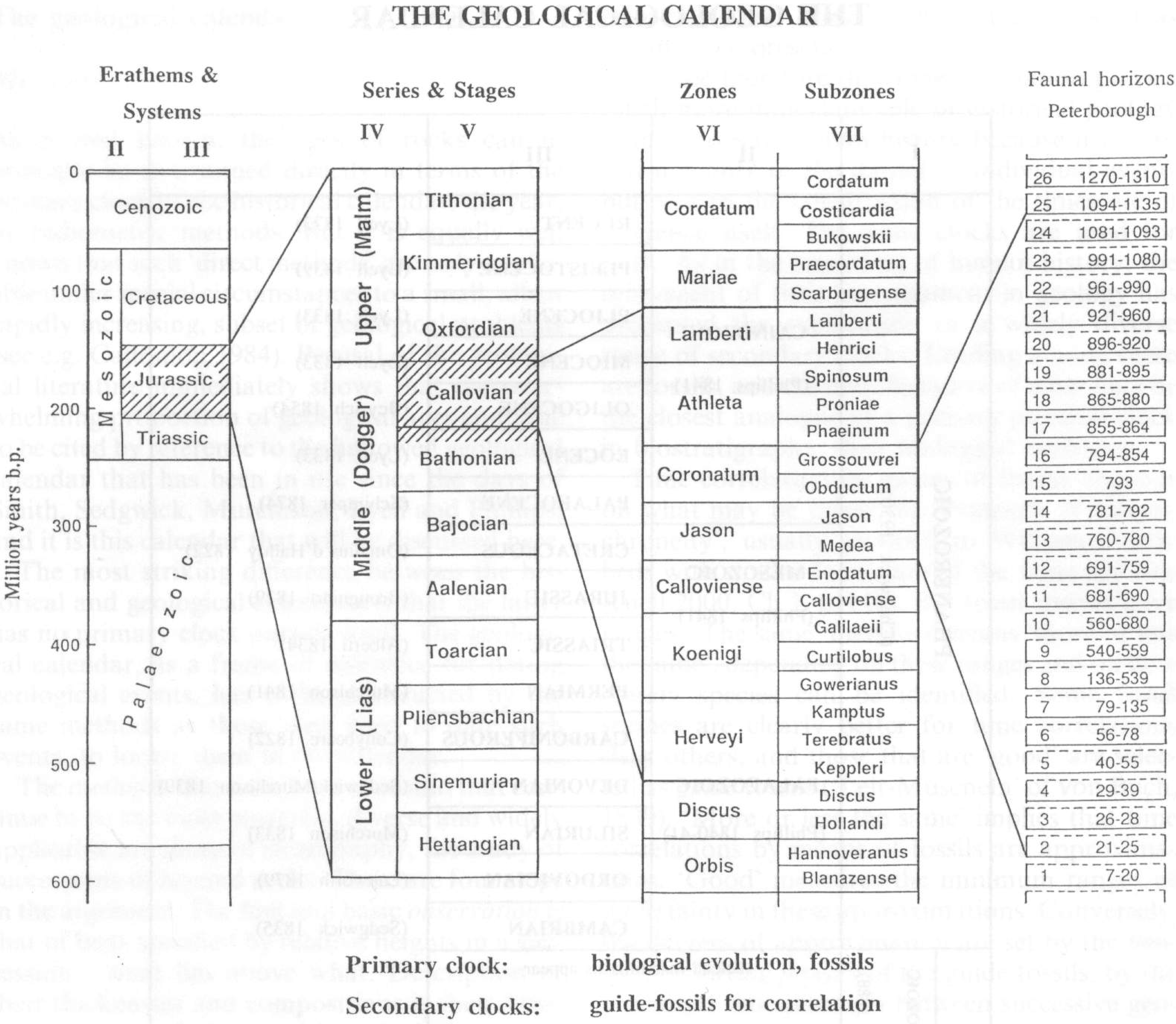

Fig. 3. The geological calendar and its finer subdivisions taken to the current limits of the standard hierarchy, at level VII Subzones/Subchrons, illustrated by an example in the Jurassic. The two principal columns are drawn at equal-Stage/Age and equal-Subzone/Subchron approximations. The column at the left is drawn on the geochronometric Cambridge timescale of Harland *et al.* (1990). The column at the right represents the distinguishable ammonite faunal horizons in the Oxford Clay of Peterborough recorded by Brinkmann (1929), drawn on an equal-time-interval approximation. They are labelled successively from 1 to 26 for convenience, together with their heights in centimetres above an arbitrary zero at the base of the section.

of time is continuous and complete, it has, with one exception, no scale: it is not linear, and relative thicknesses of time boxes are not proportional to real-time durations. The exception is the left-hand column in Figure 3, which incorporates *post hoc* information considered separately below. Column III in Figure 2 is drawn on an equal-Period representation, column V in Figure 3 on an equal-Age representation, and so on. On the evidence of chronostratigraphy alone, such representations are as valid as any other.

In the second of the dual representations, the columns represent what is commonly referred to as 'the standard geological column', a hypothetical stratigraphical column of rock whose formation was continuous and which therefore records the geological action of all time. There is of course no such complete succession at any one place, but discontinuous parts of it are what we observe at many places. The dividing lines between boxes do retain a clear meaning, however. They are ubiquitous *time planes* in the rocks. Whether we can identify one of them at any place other than at a type-locality, a section in which it has been typologically defined at some precise level in a stratified succession, is another matter: generally we cannot. But it must remain true that every piece of rock we collect in stratal succession must lie either below or above every time plane. If we can identify two time planes *between* which

Table 1. *Rock–time duality and the hierarchy of units of subdivision of standard chronostratigraphy and geochronology*

Level	Rock	Time
I	Eonothem	Eon
II	Erathem	Era
III	System	Period
IV	Series	Epoch
V	Stage	Age
VI	Zone	Chron
VII	Subzone	Subchron

a given piece of rock lies, we assign it to the chronostratigraphic rock-unit defined by those planes: we cite its age by the name of the unit. When we say *Tyrannosaurus rex* is Cretaceous, we say no more than that its remains are found in rocks that lie between the Jurassic–Cretaceous and Cretaceous–Tertiary boundaries. Similarly, standard chronostratigraphic units in general are identified in the field not by means of their defining boundary time planes but by means of what lies between them – such as guide fossils. Standard chronostratigraphic units are therefore all the rocks in the world lying between defining time planes, but their local representations are usually fragmentary and highly incomplete. And the '(in)completeness of the geological record' continues to preoccupy us in many geological and palaeontological problems, not least in mapping the phylogeny of biological evolution.

This distinction between the definition and recognition of standard chronostratigraphical units may present the apparent paradox that seems to puzzle so many members of commissions on stratigraphy (see e.g. Aubry *et al.* 1999, Remane 1996): that the ages of rocks can almost always be successfully determined by assignment to chronostratigraphical units of appropriate rank despite the fact that, of the vast number of these units in everyday use, the number so far formally defined in terms of typologically fixed bounding time planes is tiny. (You can usually tell, in finding your way to Burlington House, whether you are in Piccadilly or not without first having to find out where it formally starts and ends. Street-names helpfully displayed on placards at intervals can be useful guide signs.) And the corollary is that the closer together the time planes, the shorter the time intervals they define, the shorter the age spans of the rock-units between them, the more precise (less uncertain!) the dating of the rocks found in them.

Figure 2 shows the broader features of the geological calendar and brings out a number of points. Firstly, it indicates its early historical development. Previous classifications of rocks as Primary, Secondary and Tertiary, based largely on lithological characteristics only vaguely related to age, were largely abandoned as the results of more detailed mapping emerged. Emphasis shifted to litho- and biostratigraphy, and this is reflected in the names of the units. (Ghosts of earlier times linger in the frequent use of Secondary or Tertiary as exact synonyms of Mesozoic and Cainozoic (Cenozoic), with its subsequent extension to Quaternary.)

Secondly, it is remarkable how quickly the calendar stabilized into its present global form, following the relatively brief period of geological exploration spanning the first half of the nineteenth century: geological explorations, moreover, confined largely to a very small part of the Earth's terrestrial surface, that of classical Europe. Had the cradle of geology lain elsewhere, in North America, say, or in China, the calendar would have looked rather different. But the fact that later geological exploration of the rest of the world did not lead to the abandonment of the 'European' calendar at these higher levels, or even to any substantial modification of it, tells us that it conveys some geological truths about the Earth's history that are globally recognizable. And this universality rests today of course on the use of fossils as clocks.

Thirdly, at the highest level, the calendar makes use primarily of only one turning point in the Earth's history: that of the sudden appearance of macroscopic fossils at the base of the Cambrian. (A second, more recently recognized turning point was marked by the discovery of prokaryotic microfossils in the fine-grained cherty Gunflint Formation in the Precambrian Animikean rocks of southern Ontario, which for many years provided the oldest positive evidence of life on Earth.) The puzzle of what to do about the Precambrian persisted for a century and continues to challenge us today. Sparseness of interpretable evidence tended to reduce it almost to a footnote, a source of frustration and embarrassment. This is not helped by two relatively recent discoveries by radiometric methods that it accounts for seven-eighths of the age of the Earth, and by largely chemical methods that there was prokaryotic life already during most of it. And how sudden was 'sudden' also cannot be answered at the finesse of level III in Figure 2.

Refinements

Subsequent refinement of the geological column is illustrated in Figure 3 through the example of the level III System, the Jurassic, that has traditionally led the way in the development of the principles and techniques of bio- and chronostratigraphy that were needed. These were recently reviewed at some length (Callomon 1995) in yet another attempt to allay the confusion that persists (e.g. Whittaker *et al.* 1991). Levels IV and V were introduced by von Buch (1839) and d'Orbigny (1850) respectively and, most importantly, Zones (VI) by Oppel (1856–1858). The hierarchy of top-down subdivision has in the Jurassic gone one step further, to the level of Subzones (VII). As an illustration, the way the whole of the British Jurassic has now been chronostratigraphically classified down to this level may be seen in the Geological Society's correlation charts (Cope 1980*a*, *b*). A similarly detailed classification has been published for the Jurassic of France (Cariou & Hantzpergue 1997).

This degree of attainable time resolution owes its success to a special circumstance: the availability of exceptional guide fossils, the ammonites. The reason why they are so good depends on the fact that the morphology of their shells evolved over long periods of time more rapidly than that of almost any other marine organisms leaving fossil remains, for reasons that are still wholly unknown (Callomon 1985). (No environ mental selection pressure to which this evolution could be plausibly ascribed as an adaptive response has been identified. Recourse to 'genetic drift' as an explanation of last resort would probably also be tautological, but if in fact a viable cause, it would account for the observation that the exceptionally rapid evolution of Ammonoidea has been so constant, even across divergent phylogenetic clades, for so long – from the Devonian to the latest Cretaceous – but limited in range and largely iterative: similar forms occur repeatedly.) The shells are in the majority of cases also strongly sculptured, so that very small evolutionary changes, over short periods of time, are readily discernible. How the reliability of ammonites as time-diagnostic guide fossils can be assured and exploited has also recently been discussed in some detail (Callomon 1995). Because the chronostratigraphy at zonal levels is based almost exclusively on biostratigraphy, the units are named after characteristic index species found in them following the convention introduced by Oppel. Those shown in Figure 3 are named after species of ammonites. Stages (V) are named after places, a convention introduced by d'Orbigny.

Limitations and alternatives

There is a price to be paid for high-resolution chronostratigraphy based on fossils, which can restrict their usefulness. There are commonly three possible causes. The first is bioprovincial endemism of the guide fossils even within an accessible and otherwise physically compatible environment, limiting their geographical distribution. The second is unsuitability of facies, e.g. non-marine sediments in the case of ammonites. The third is constraints imposed by available methods of sampling, e.g. in the exploration of subsurface formations by means of continuously chip-drilled boreholes, which rule out macrofossils.

The best-known example in the Jurassic of the first cause lies in its topmost Stage, the Tithonian. Its ammonites, equally prolific, became segregated in Europe into three faunal provinces so mutually exclusive that the zonation (levels VI–VII) constructed in any one of them is wholly unrecognizable in the other two. We have therefore three parallel standard calendars of Zones in three more or less contemporary Stages: the Tithonian, for central and southern Europe broadly south of the Alpine fold-belts; the Portlandian, for NW Europe and into the Arctic; and the Volgian, for the Russian and north Siberian platforms. Correlation of these three calendars continues to be problematic, but their temporal finesses are comparable. The selection of one as *primary standard* become a matter of convention. Generally speaking, recognition of most Stages by means of ammonites can be done globally. Ammonite Zones are recognizable over continental distances, more or less; and Subzones over formerly connected shelf-sea sedimentary basins, distances of from hundreds to a few thousand kilometres.

As illustration, two favourable cases are shown in Figures 4 and 5. Figure 4 samples the distribution of the characteristic species of the basal Keppleri Subzone of the Callovian (Fig. 3), *Kepplerites keppleri* (Oppel, 1857). Figure 5 shows some of the known occurrences of *Cardioceras martini* Reeside, 1919 (type from Alaska) and its more widely used synonym *Cardioceras bukowskii* Maire, 1938 (type from Poland), characterizing the Bukowskii Subzone of the Lower Oxfordian Cordatum Zone (Fig. 3). Both genera are bioprovincially restricted to the Boreal Realm, which occupied the higher temperate to polar latitudes in the northern hemisphere, and are wholly absent from the Jurassic equatorial belt and southern hemisphere, replaced there by other groups.

Problems of the second kind, of inimical facies, can be less tractable. Most acute is that of terrestrial sediments, such as the Carboniferous Coal Measures, the Red Beds of the Germanic Trias, or the Karoo of Mesozoic Gondwana. All one can say here is that one must use whatever there is, but that it is unlikely to be very good.

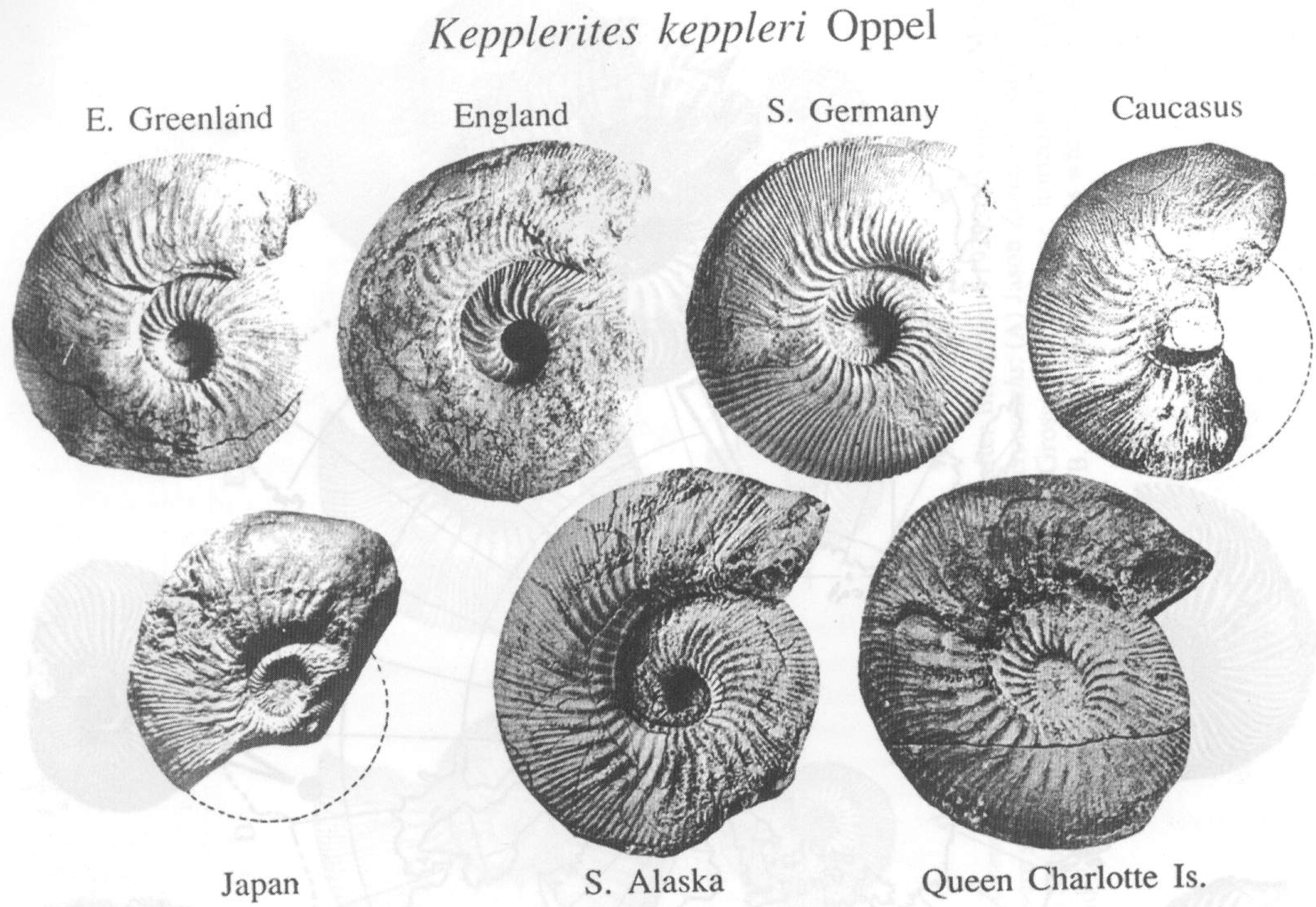

Fig. 4. Correlation by means of ammonites: the recorded distribution of the index of the Keppleri Subzone at the base of the Callovian Stage (Fig. 3). Recent additions include the Volga Basin on the Russian Platform.

Time resolution at level IV may be the closest attainable, or level V with luck.

Thirdly, the methods and problems of dating borehole logs are well known. They have spawned the immense multinational industry of oil-company micropalaeontology. Many chronostratigraphical calendars based on foraminifera, calcareous nannofossils, palynomorphs and pollen have been constructed. An interesting comparative compilation has been published by Cox (1990). (The problems of correlating these zonations are largely circumvented by the fact that most of them continue to be unpublished, if not confidential.) The time resolutions attained usually lie at Stage or Substage level, level V or a little better.

The limits of time resolution by means of fossils

Mesozoic ammonites

Does the time resolution implied by the lowest hierarchical level in the standard calendar represent the limit of what can be achieved by means of fossils? The answer is 'No'. Even within the timespan of a Subzone, further successive distinguishable evolutionary steps in an evolving lineage – the *transients* – can often be recognized. The strata providing these ultimately resolvable temporal snapshots of the state of the fossil clock, recording their closest resolvable *moments* of time, have come to be called simply characteristic faunal, floral or fossil *biohorizons* (Callomon 1964), characterized by a transient fossil taxon or assemblage. But the basic idea and its application go back to a landmark in the history of biostratigraphy set by S. S. Buckman (1893), who coined the term *hemera* for a moment of time distinguishable in the record of evolution of ammonites (or, more generally, in 'palaeobiology' as he termed it). His fundamental contributions and their subsequent development were also reviewed recently (Callomon 1995).

What continues to be one of the earliest and finest examples of the application of these ideas is a classical biostratigraphical analysis by Brinkmann (1929) of the evolution of the ammonite genus *Kosmoceras* through the Lower Oxford Clay exposed in the brick-pits around Peterborough. He collected some 3000 ammonites centimetre by centimetre through 13 m of finely stratified sediment and analysed their morphological characters biometrically. The main result

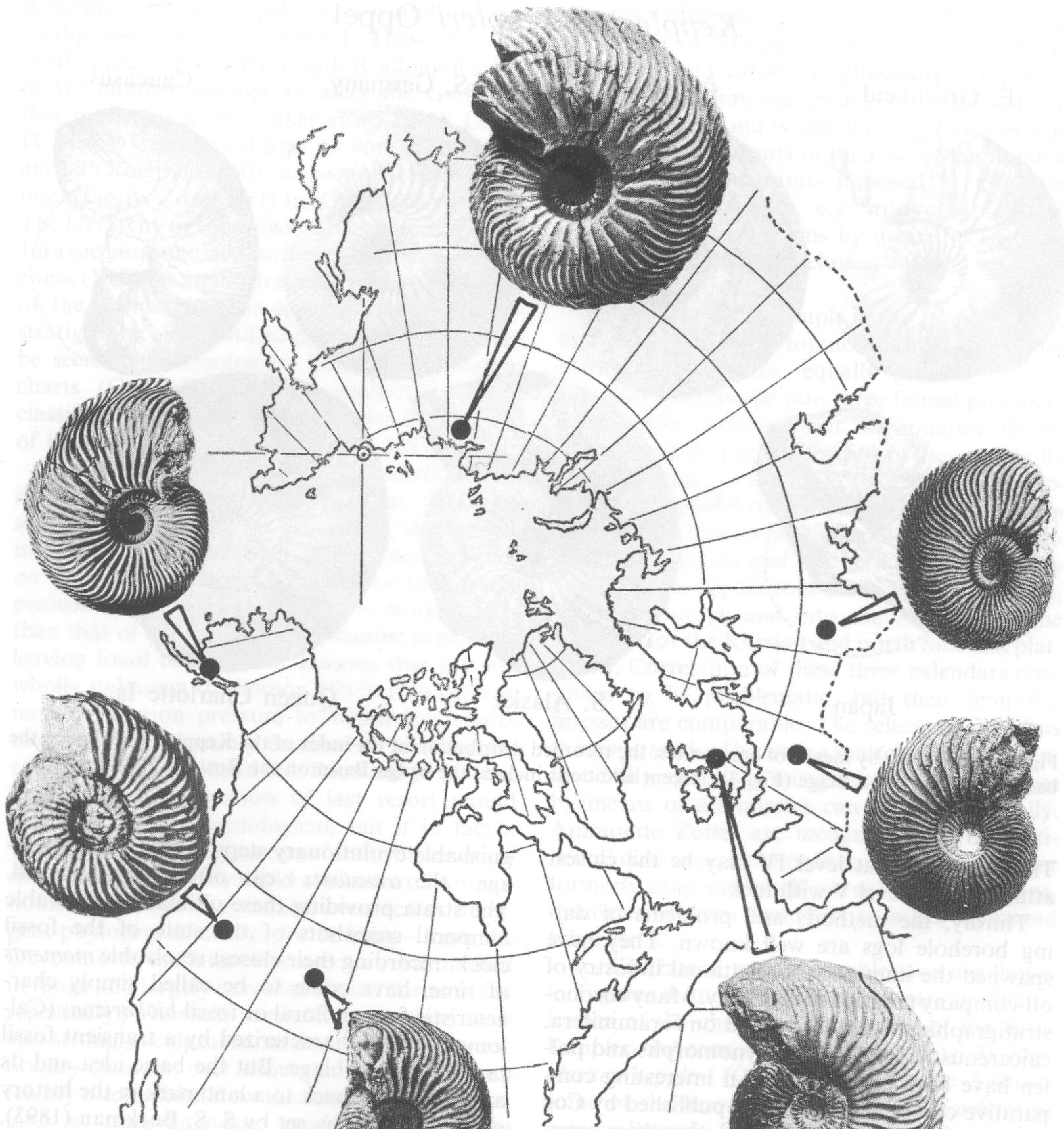

Fig. 5. Correlation by means of ammonites: the recognized distribution of the Bukowskii Subzone of the Cordatum Zone of the Oxfordian Stage (Fig. 3).

of interest from the present point of view was that the succession could be resolved into some 26 beds, sharply bounded by lithological discontinuities, each with an ammonite assemblage that can be distinguished visually and in part biometrically from its neighbours. These 26 faunal horizons are indicated on the right in Figure 3, labelled by their heights in centimetres in the section; and pictures of their characteristic ammonites at some of these levels are shown in Figure 6. How these horizons fit into only four subzones is also indicated. That they are not only of purely local significance is reflected in the fact that many of them, perhaps as many as half, can be traced across country over considerable distances, to Dorset in the southwest, and in some cases as far as Brora on the east coast of Sutherlandshire in the north. Conversely, additional

Fig. 6. Illustration of six transients in the evolving lineage of the ammonite genus *Kosmoceras* at Peterborough (see Fig. 3: after Brinkmann 1929, drawings by Mme P. Kyropoulos). In common with most other Jurassic ammonites, the shells of this genus were strongly sexually dimorphic. *Macroconchs*: (**A**) Jason Zone, Medea Subzone, horizon 4 (Fig. 3); (**B**) Jason Subzone, horizon 7; (**C, D**) Coronatum Zone, Obductum Subzone, horizons 8 and 10; (**E, F**) Grossouvrei Subzone, horizons 17 and 23. *Microconchs*: (**a**) horizon 1; (**b**) horizon 7; (**c, d**) horizons 8 and 9; (**e, f**) horizons 18 and 24. Note the marked change from B, b to C, c: this reflects what is probably a considerable non-sequence at level 135 cm at Peterborough.

horizons become inserted as the succession thickens southwestwards, to Oxford and beyond, showing that this rich succession is still incomplete even at Peterborough.

Faunal horizons are in general still a long way from being a continuous sedimentary or evolutionary record and are separated by time gaps of unknown durations. They are therefore shown in Figure 3 not as further top-down subdivisions of subzones as parts of a continuous column, but as rock equivalents of disjointed time slices of unknown but probably short durations. The gaps between them are still there, waiting to be filled by new discoveries. The process of inserting new faunal horizons as they are discovered, hence adding to the number of distinguishable events in the timespan of a subzone, is one of bottom-upward synthesis. One of Buckman's most significant discoveries was that in fact the more complete the fossil record becomes, the more incomplete the sedimentary record turns out to be. The ultimate paradox is that fossils can show not only the ages of the rocks that are present in a section but, perhaps even more importantly, the ages of the rocks that are *not* present – the gaps in the record. And the ability to do so depends strongly on the temporal resolving power of the guide fossils used. Some comparative examples were discussed in a review of Buckman's contributions (Callomon 1995). The temporal resolving power of ammonites is sufficient to have revealed the presence of major time gaps – major on the timescale of their temporal resolution – in almost every sedimentary succession in which they have been closely studied. (This prompts another interesting comparison between the historical and geological records. Sparseness of dated events in the historical calendar always implies failure to record, not the presence of time gaps in history. Sparseness of dated geological events can in certain circumstances be ascribed positively to gaps in the stratigraphical record, the all-too-common disconformal non-sequences.)

Radiometric calibration of the geological calendar

Radiometric dating of rocks within the domain of applicability of the method has become routine and revised 'absolute' timescales of the Phanerozoic appear almost annually. One of these, chosen arbitrarily, the 'Cambridge timescale' of Harland *et al.* (1990), is shown at the left of Figure 3, and the Systems/Periods of the Mesozoic at levels II and III of the hierarchy are drawn with vertical thicknesses now probably very closely proportional to their true time durations.

When we descend the hierarchy, however, the picture becomes less cheerful. Figure 7 shows an excerpt from a recent compilation (Palfy 1995) of timescales that have been proposed for the stages of the Jurassic by various authorities in the last 15 years. Clearly, we are still some way from finality. The rise and fall of the Callovian (Fig. 3), CLV in this chart, is typical. The reason for these uncertainties is that the number of securely dated points to which these timescales are anchored in the Mesozoic, and in the Triassic–Jurassic in particular, are so far still very few. The rest is done by interpolation in one way or another, not excluding simply counting the numbers of Zones or Subzones in a stage (Fig. 3). The appearance in print of a numerical scale, sometimes quoted even to one decimal place in Ma (units of a million years), as for example, in Harland *et al.* (1990) and the widely used instructional charts based on the 'Exxon' global scales of Haq *et al.* (1988 and revisions) can raise an illusory sense of accuracy in the minds of the unwary (see discussion by Miall 1997, Ch. 13, 14). But no harm is done as long as it continues to be associated with a representation of the standard chronostratigraphical calendar as primary frame of reference. A temptation to assume that numerical scales can now be used by themselves as life-simplifying substitutes for the bewildering plethora of arcane names that adorn the calendar can, however, be counterproductive. A valuable recent review (Howarth & McArthur 1997) of a powerful new method for dating marine sediments by means of the stable-isotope ratio $\rho(87:86)$ of their contained strontium shows fine curves of the change with time of this ratio in the interval from Recent to Jurassic. The temporal resolving power of this method can, in the Mesozoic, approach that of ammonites, level VI or even VII, and the samples used to construct these curves, largely made up of belemnites, were themselves collected from beds precisely dated at level VII. Yet the timescales plotted on the abscissae are all given linearly in millions of years (Ma): their chronostratigraphical ages are not shown at all. Only a casual sentence reveals that the numerical ages used were those of Gradstein *et al.* (1994), not reproduced. To use the curves, therefore, to date a new rock sample in familiar terms, one has first to obtain a copy of this timescale to convert back to the practical units in common use with which the curves were constructed in the first place.

Rates of geological processes

The precise values of radiometric ages are in fact not of much practical interest in stratigraphy.

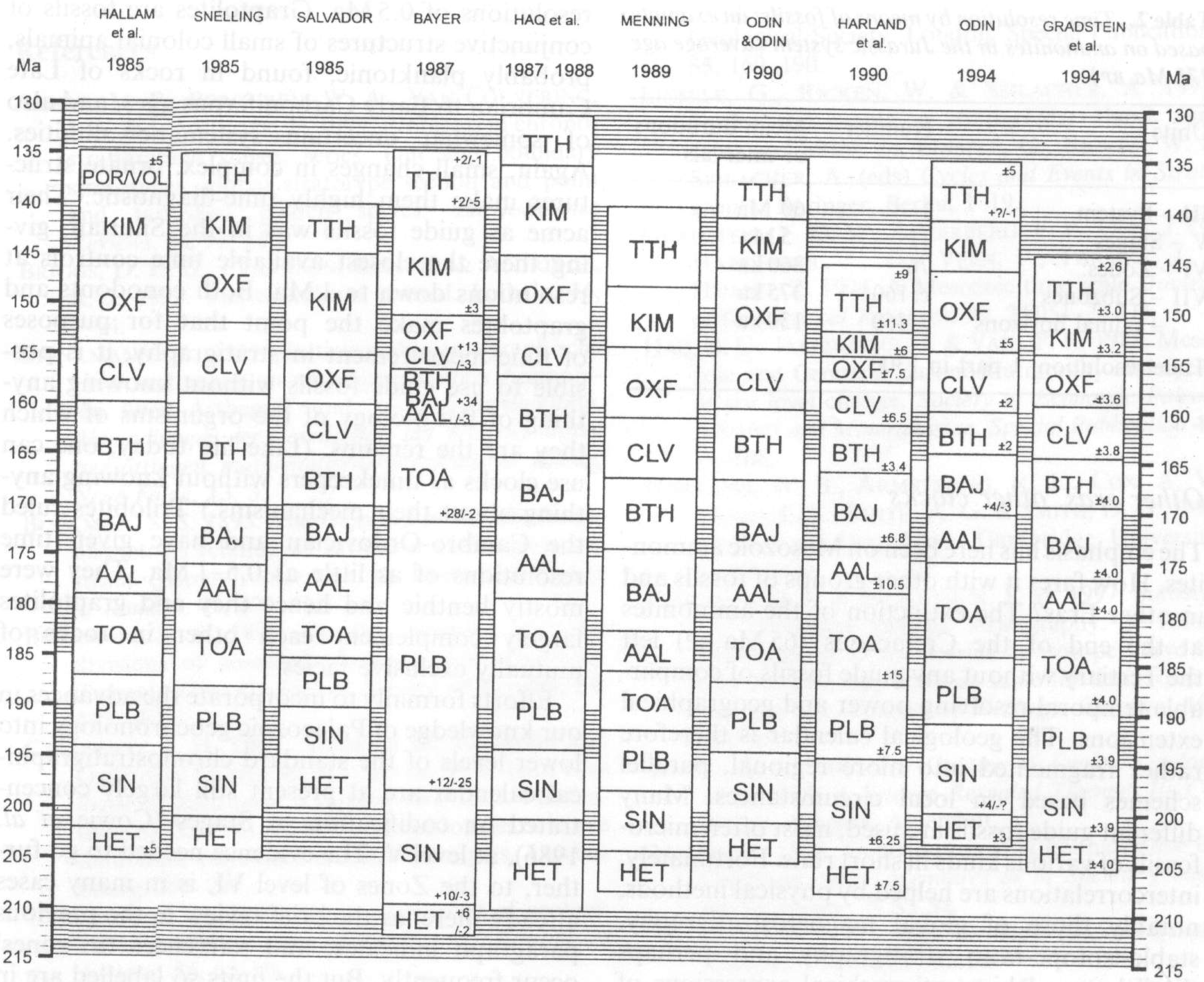

Fig. 7. A comparison of ten radiometric timescales for the stages of the Jurassic proposed in the last 15 years (from Pálfy 1995, with permission; an updated version may be found in Palfy *et al.* 2000).

It matters very little, for instance whether the horizon of *Kepplerites keppleri* defining the base of the Callovian (Fig. 3) is thought to lie at 157 Ma BP (Fig. 7: Haq *et al.* 1988) or at 165 Ma BP (Gradstein *et al.* 1994) – a difference of 5%. What are interesting are average values of time *intervals* – age differences. The ammonites of the Jurassic are again taken as an example, in Table 2. The reason is that these averages allow us to estimate the rates of many of the innumerable processes that make the geological structures we see. Most of these processes are cyclic or repetitive and so a hierarchy of orders of cyclicity was introduced by Vail *et al.* (1977), roughly in powers of ten of time duration in years. A useful classification of processes was compiled by Einsele *et al.* (1991) and is reproduced by Miall (1997, Ch. 3). Major continental rearrangements, such as the assembly and subsequent dispersal of Pangea, and their associated orogenic phases, such as those that dominated the study of geology a century ago – Caledonian, Hercynian, Alpine – are first-order processes. Long-ranging cycles of world-wide (eustatic) sea-level change that governed the characteristic sedimentary histories of whole systems, such as the Triassic–Jurassic–Cretaceous triplet of the Mesozoic, at level III in the chronostratigraphical hierarchy, are of second order. Processes at third to sixth order take us down the range from a million years (1 Ma) to a thousand years (1 ka), and in this range the shift of interest is more and more towards sedimentary processes determining increasingly local lithostratigraphy and its interpretation in genetic basin analysis, now called sequence stratigraphy. In this field, time controls are crucial and Table 2 indicates how good guide fossils can provide such time controls down to fourth-order processes. And, as already mentioned, one of the discoveries has been that already at this level of time resolution, the sedimentary record is often far less complete than the proponents of sequence stratigraphy would like us to believe. Finally, sedimentary records of tidal flow take us off-scale to Tuesday afternoon events, lasting 10^{-3} years.

Table 2. *Time resolution by means of fossils: an example based on ammonites in the Jurassic system (average age 175 Ma BP)*

Units	Number	Mean durations or intervals
III – System	1	60 Ma
V – Stages	11	5 Ma
VI – Zones:	76	860 ka
VII – Subzones	*c.* 160	375 ka
– faunal horizons	*c.* 450	130 ka

Time resolution: 1 part in 1300

Other eras, other clocks

The emphasis has here been on Mesozoic ammonites. How fares it with other groups of fossils and in other Eras? The extinction of the ammonites at the end of the Cretaceous (65 Ma BP) left the Tertiary without any guide fossils of comparable temporal resolving power and geographical extensions. The geological calendar is therefore rather fragmented into more regional, parallel schemes based on local circumstances. Many different guide fossils are used, most often microfossils of various kinds in short runs. Fortunately, intercorrelations are helped by physical methods, notably those of global magnetostratigraphy, stable-isotope-ratio stratigraphy and perhaps the litho- and biostratigraphical expressions of Milankovič cyclicity. Overall time resolutions and correlations can come down to 0.5–1 Ma in favourable circumstances, perhaps a little better locally. In the Palaeozoic (see a compilation in Callomon 1995), ammonites hold the lead as far down as the Devonian. The goniatites of the Carboniferous can in parts of it resolve 0.8 Ma; the ammonoids of the Middle–Upper Devonian, 0.4 Ma. But the most striking advances in the last half-century have been in the high-resolution biostratigraphy of three other groups: conodonts, graptolites and trilobites.

Conodonts have been known for 150 years: they are common, occur widely, range from mid-Cambrian to latest-Triassic, and look like small teeth (*c.* 1 mm). But whether they were teeth, and if so the teeth of what, remained a mystery until only some 20 years ago (Briggs *et al.* 1983). The animal to which they belonged was probably free-swimming, looked like a small chordate eel, and the conodonts were its teeth. The assemblages are rich in morphology and hence the ability to follow small collective changes with time also makes them powerful guide fossils. Their zonation in the Upper Devonian can give time resolutions of 0.5 Ma. Graptolites are fossils of conjunctive structures of small colonial animals, probably planktonic, found in rocks of Late Cambrian to Early Carboniferous ages, and also of somewhat uncertain systematic affinities. Again, small changes in complex, ornate structures make them highly time-diagnostic. Their acme as guide fossils was in the Silurian, giving there the closest available time controls at resolutions down to 1 Ma. Both conodonts and graptolites make the point that for purposes of time measurement in stratigraphy, it is possible to use guide fossils without knowing anything of the biology of the organisms of which they are the remains. (Like life today, one can use clocks as timekeepers without knowing anything about their mechanisms.) Trilobites ruled the Cambro-Ordovician and have given time resolutions of as little as 0.5–1 Ma. They were mostly benthic and hence they and graptolites largely complement each other in rocks of mutually exclusive facies.

Efforts formally to incorporate the advances in our knowledge of Palaeozoic geochronology into lower levels of the standard chronostratigraphical calendar are at present still largely concentrated on codification of Stages (Cowie *et al.* 1986), at level V. The evidence needed to go further, to the Zones of level VI, is in many cases already there, as the brief review in the previous paragraph indicates, and references to 'zones' occur frequently. But the units so labelled are in most cases best regarded as being still no more than in the category of biohorizons rather than standard chronozones.

Conclusion

The measurement of geological time has come a long way since the days of William Smith's *Strata Identified by Organized Fossils* (1816–1819). Many new methods of dating rocks based on their non-biostratigraphic, physical attributes have been discovered, and in unravelling the longest, Precambrian part of the Earth's history they provide the only means we have. In this brief review I have tried to indicate how at the same time the Phanerozoic geological calendar based on the use of fossils as clocks has also been refined. Although the new physical methods may increasingly claim to challenge traditional biostratigraphical methods even in the Phanerozoic, they do not yet surpass or displace them. Our venerable geological calendar seems safe for the foreseeable future.

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