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Time from fossils: S. S. Buckman and Jurassic high-resolution geochronology

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Abstract: Chronostratigraphical classification of rocks can be approached from two directions. The first is a 'top-down' process of subdivision of the geological column in a hierarchy of successively finer units. These units are therefore *defined* by their boundaries, which are time-planes, and form complete continuous series or scales. They are chosen to be widely *recognizable*, and hence correlatable, by means, in the Phanerozoic, of their contained guide-fossils, *i.e.* by their characteristic biozones. This was the approach of d'Orbigny and Oppel in the Jurassic, leading to a *standard chronostratigraphy* down to Subzonal level notably espoused by Arkell and widely adopted today. The second approach is one of 'bottom-upwards' integration: the assembly into time-ordered sequences of the most minutely distinguishable local faunal horizons—distinguishable in the sense of evolutionary change—which may or may not subsequently be found to have more widespread value for time-correlations and biochronology. This was the method introduced by Buckman a hundred years ago to describe the ammonite biostratigraphy of the Inferior Oolite of Dorset, in response to the need for the finest attainable time-resolution in phylogenetic palaeontology. The time-equivalents of such faunal horizons were termed *hemerae*.

Polyhemeral chronostratigraphy went into abeyance with Buckman's death in 1929, but its equivalent, in terms of the faunal horizons themselves, has been revived. A faunal horizon is defined as a stratigraphical entity within which no further biochronological subdivision can be made, so that the bed or beds embodying that horizon must, on the evidence of the fossils alone, be regarded as internally isochronous. A succession of faunal horizons becomes the record of well-spaced instants: the record is presumed *a priori* to be full of gaps of unknown duration waiting to be filled by new discoveries. The measure of chronostratigraphical finesse is the average time-interval between the moments represented by the faunal horizons, $\overline{\delta t}$, the *secular resolution*. The relative ability of groups of guide-fossils to resolve time-intervals δt in rocks of age t is their *secular resolving-power*, $R = t/\delta t$.

The current state of Jurassic chronostratigraphy is reviewed. The guide-fossils of choice are the ammonites, whose secular resolving-power exceeds that of any other group and which can give time-resolutions of 150000 years in rocks of age 150 million years ($R > 1000$). These figures are compared with those attainable elsewhere in the Mesozoic and Palaeozoic. Resolution-analysis of the Jurassic shows that, at the level of resolution of ammonite faunal horizons, the geological record is highly incomplete, nowhere more so than in the Inferior Oolite. As Buckman concluded, the more complete the fossil record of a system becomes, the more incomplete turns out to be its lithochronology. This has important consequences in sedimentology, and in sequence stratigraphy.

Rock-time duality

The history of the Earth is recorded in the rocks around us. To reconstruct this history we need to measure the ages of the rocks. This allows us to present the history as a compilation of what has occurred, and such compilations make up the greater part of text-books on historical geology. But perhaps even more interesting today, it allows us to estimate the *rates* of underlying *processes*—tectonic, plutonic, metamorphic, sedimentary and biological. These rates range over many orders of magnitude, and being derivatives with respect to time, the ability to measure them depends not so much on the measurements of the ages themselves as on the ability to measure small *differences* in ages, to resolve time-*intervals*, to distinguish closely-spaced moments in time. Alas, as we all know, although we now have powerful methods of directly dating rocks through the measurement of radioactive decay, they are applicable to only a minority of cases.

In taking stock of the present position in the geochronology of fossiliferous sedimentary rocks, on which so much of our history of the Earth is based, it is relevant to recapitulate five steps in the argument. The first and basic *observation* is that of beds specified by heights in a succession, thicknesses and compositions: their *lithostratigraphy* and, if composition includes fossils, their *biostratigraphy*. The next step introduces Steno's Principle of Superposition (1669), which states that in a normal succession of sediments the higher lying are the younger. This transforms a static description in terms of height into a dynamic one in terms of local time—relative time—and is an interpretation. Specification of rocks in a stratal succession according to their relative ages we refer to today as their *chronostratigraphy*, although this term appears to have been first explicitly introduced only by Hedberg (1954). 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 fourth step then becomes the synthesis of a *standard* time-ordered succession of rocks, correlation with which allows any local rock to be *dated* in terms of its relative position in the implied conjugate chronostratigraphic time-scale. Only in the fifth and final step is this standard chronostratigraphic time-scale calibrated in absolute terms, in years, by radiometric methods.

So much for principles. In practice, everything depends on successful time-correlations. But, being a matter of interpretation, how can they be assured? How precise can they be made?

In the early stages of the evolution of our geological time-scale, correlation was largely lithostratigraphic, for sediments with bedding-planes are clearly at least locally synchronous. Formations were characterized, mapped and placed in succession. Such successions give the impression of being regionally complete but discretely subdivided records of geological time, for in their very nature non-sequences, representing time-gaps at formational boundaries or partings between beds, are not readily evident. There evolved therefore the concept of 'the standard geological column' as a complete and continuous record of geological time, subdivided into a succession of distinguishable segments. The outline of its major features was substantially complete a century and a half ago and is shown in Fig. 1. (For a recent review from a Palaeozoic viewpoint, see McKerrow this volume.) It continues to provide part of the basic vocabulary of our subject even today and calls for only a few comments.

Firstly, it can be read in two ways. On the one hand, the boxes represent slices of the geological column: Systems, rocks. In this representation, the horizontal lines delimiting the boxes signify time-*planes* in the rocks. On the other hand, the boxes represent durations of time vertically (Eras) and the horizonal lines represent time-markers (instants) in a vertical time-*scale*. This rock-time duality may seem obvious, but failure to remember it can still cause confusion, for it is vital to one aspect of the all-important act of time-correlation implied in dating a rock. Whereas the time-markers and their conjugate time-planes *define* the chronostratigraphic units to which we assign rocks when we date them, the *recognition* of the unit to which a rock belongs is by means of what lies between the planes, not of the planes themselves; for, except perhaps very locally, time-planes can generally not be recognized other than at the point in a section at which they have been defined. The corollary is that all stratigraphical time-correlations are *approximations*.

Table 1. *Rock-time duality and the hierarchy 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

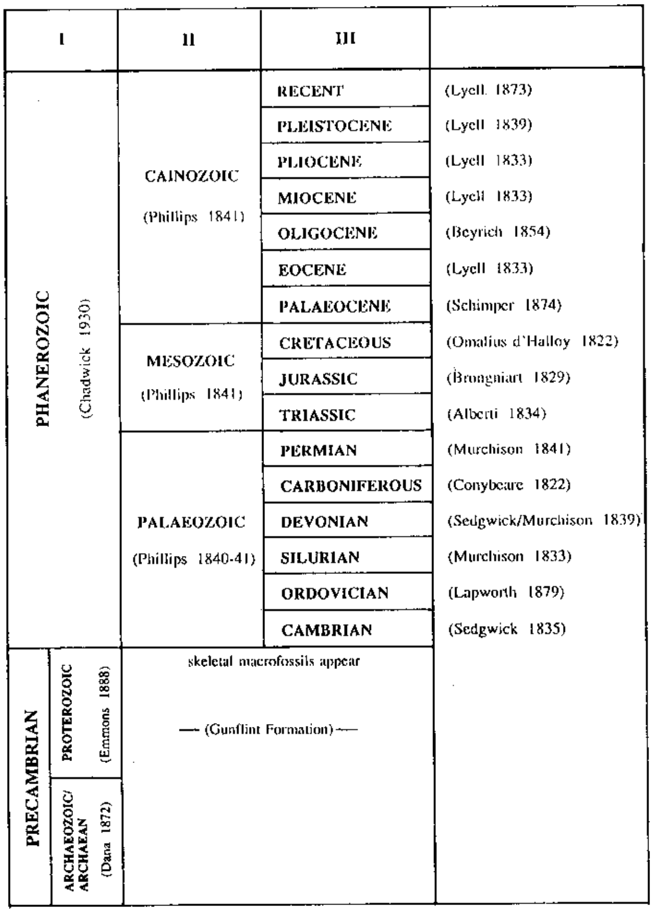


Fig. 1. The standard geological column at the highest three levels of the chronostratigraphic hierarchy. Additional categories intermediate between levels II and III in use today include subdivisions of Cainozoic (Cenozoic) into Tertiary (as redefined by Lyell in 1833) and post-Pliocene Quaternary (Morlot 1854).

Secondly, the figure shows a classification that is made up of the top three tiers of a *hierarchy* of successive subdivision (Table 1): Eons (I), Eras (II) and Periods (III). Such a process of refinement can clearly be taken further.

Thirdly, the foundations of this classification were predominantly lithostratigraphic—formations and their superposition. That individual formations had their own characteristic fossil assemblages was fully recognized and these assemblages were described in considerable detail. But, with some exceptions, their use as important tools in time-correlation came later.

Biostratigraphy and time-correlation: William Smith to Leopold von Buch

The limitations of lithostratigraphy in attempts to refine and extend time-correlations were soon recognized. Not only were rocks of similar lithology not necessarily of the same age, but also, conversely, rocks of the same age could be of different *facies* (Gressly 1838). The first practical use of fossils for time-correlation is usually attributed to William Smith (1816). It is based on what might be called the Principle of Biosynchroneity: rocks containing similar fossils are of the same age. But fossil species have ranges. 'Same' therefore means 'more or less the same', depending on these ranges, and on what is understood by species and how closely they can be identified. Some fossils are clearly better for correlation than others, and those whose distributions (biozones) approximate most closely to synchroneity were called 'Leit-Muscheln' by von Buch (1839, p.64): the *guide*-fossils of today.

The context was a review of the Jurassic of Germany and Switzerland. He comments (p. 61) on earlier attempts to classify the German succession by means of correlations with the then much better-known succession in England, based on claims to have recognized a lithologically similar order of formations. For instance, lithological comparisons led Murchison (1831) to assign the 'slates' of Solnhofen and those of Stonesfield to the same 'geognostic horizon' [*sic*] and to conclude therefore that the equivalents of the whole of the Upper Oolites of England must be missing in Germany. Such correlations were refuted by the 'zoological character' of the formations, 'which alone should decide the identity [equivalence] of the formation'. What was needed was a catalogue of reliable guide-fossils, and these von Buch proceeded to enumerate. At the same time he refined the standard classification by subdividing the Jurassic further, into the three universal parts of Lower, Middle and Upper Jura. These correspond to our Series of today, at level IV of the standard hierarchy. Of the 102 species of guide-fossil he lists for the Jurassic, 30 are ammonites. The pre-eminence of ammonites as guide-fossils in the Jurassic gave that System a lead in the development and testing of the techniques of chronostratigraphical refinement through biostratigraphy that it has maintained to the present day.

Standard chronostratigraphy: d'Orbigny, Oppel and beyond

The next step was taken by d'Orbigny (1850, *Résumé géologique*, p. 600). He subdivided the Jurassic into ten Stages ('étages', 'Stufen' in German). The importance of this work and some of its shortcomings in execution were reviewed by Arkell (1933, p.8), who also provided an English translation of the key passages in the introductory pages of the classical *Résumé*. Arkell's analysis reads as freshly as when it was written but two points are worth re-emphasizing. The first is that the Stages are undoubtedly what we would today call chronostratigraphic units. They explicitly represent the record in rocks of 'successive distinct geological epochs', recognized by their characteristic fossils. The second is that they are subdivisions of a larger continuous unit, slices of the geological column, defined by the dividing time-planes. They are therefore standard chronostratigraphic units, the rock-equivalents of a standard geological time-scale, and constitute the next level downwards in the hierarchy of classification by subdivision, level V. Arkell makes great point, implicitly perhaps rather than explicitly, of this difference between d'Orbigny's Stages as part of a standard classification and numerous other entities masquerading under the same title as 'stages' already in the literature at the time, such as Marcou's Vesulien, Argovien and Sequanien, variously interpretable as local litho-, bio- or even chronostratigraphical units—a list that had grown in 1933 to over a hundred for the Jurassic alone. Standard classifications generate standard nomenclatures; and it is the analogy between stratigraphical and zoological nomenclatures that guided Arkell in his subsequent proposals (1946) for a Code of Rules of Stratigraphical Nomenclature, analogous to those of Linnéan zoological nomenclature, in which d'Orbigny's *Résumé géologique* of 1850 marks the starting-point for a Rule of Priority in naming Stages in the same way as Linnaeus' *Systema Naturae*, 10th Edition (1758) does for naming species in zoology.

Finally, Oppel's Zones (1856–58). In the introduction to his seminal work, Oppel made it quite clear that he was following the principles laid down by William Smith and Leopold von Buch, but taking the refinement of the chronological classification of the Jurassic of NW Europe even further, down to the level of Zones. And although there can be few works on Jurassic stratigraphy during the past century in which 'zones' are not used, professedly in the Oppelian sense, there has been a longstanding uncertainty as to precisely what it was that Oppel meant by the term, an uncertainty that has caused much confusion in the past and that persists even today (e.g. Harland *et al.* 1990, p.21; Guex 1987). As Arkell wrote (1933, p.16): 'It is remarkable that Oppel nowhere defined what he meant by a zone. He is frequently credited with the first use of the word, but it had in fact been employed by several French geologists before him [including d'Orbigny, as alternative to "étage"], and a definite meaning was already attached to it. Oppel adopted the term and accepted its meaning and no doubt it seemed to him in consequence unnecessary to give a definition.... If he had given a definition... it would have been in fact superfluous, for his meaning is apparent on almost every page of the book'. Apparent, perhaps, but clearly in different ways to different readers.

For an authoritative second opinion, however, nothing could have been clearer than the re-statement by Oppel's student, Waagen. In the introduction to his article defining and characterizing 'die Zone des Ammonites sowerbyi' in the lower Middle Jurassic (1867, p. 511–13), he explains the purpose to be achieved. It is not merely to give detailed descriptions of any particular bed or of the organic remains it contains: rather, by means of such descriptions, 'ein neues, bestimmt fixiertes Glied in der Zeitskala des Bildungsprozesses des Jura nachzuweisen'—to demonstrate the presence of a new [i.e. hitherto unrecognized] segment of the time-scale of the formation of the Jurassic. He makes no claim either that this segment can always and everywhere be distinguished from those adjacent, or that its characteristic fauna will never be found mixed with those below or above; but he confidently asserts that whenever a bed with this fauna by itself is found, it will always lie at the same relative position in the succession. And finding this to be the case in most of central Europe, are we not justified, 'diese Schicht als einen Zeitabschnitt to betrachten,... als solchen für sich besonders zu beschreiben und als Zone mit einem Namen zu belegen': in regarding this stratum as [equivalent to] a time-interval to be explicitly described and named as a Zone? And in our attempts to refine ever further the zonation of the Jurassic in the face of variable lithologies ('Bestand') and localized or migrating faunas and their individual species, how are we to arrive at firm conclusions? 'Das Mittel ist... die Feststellung einer Normal-Schichtenreihe, nach welcher die Bildungen in anderen, entfernter liegenden Distrikten beurtheilt werden können': the answer lies in the determination of a standard succession [*sic*] with which formations at other, more distant localities can be compared, i.e. correlated. And 'ein solches Glied der Normal-Schichtenreihe möchte ich denn in der Zone des *A. sowerbyi* festzustellen suchen': it is as such a member of the standard succession that I seek to recognize the Zone of *A. sowerbyi*. '[It] falls into the time-interval [*sic*] between the occurrence of *A. murchisonae* and the appearance of *A. sauzei*.... The Zone is therefore bounded below by the beds containing *A. murchisonae* and above by those with *A. sauzei*'. (Waagen's Sowerbyi Zone spans today a succession of 15 distinguishable ammonite faunal horizons, see below).

Oppel's meaning of 'Zone' is brought out unambiguously by careful attention to definitions in stratigraphical nomenclature (e.g. Callomon 1985*a*). There are two sources of confusion. The first has already been alluded to, and derives from the distinction between *definition* of a unit (here an Oppelian zone) and its *recognition* and use in correlation. The definition is clear from the numerous tables to be found throughout Oppel's book, but particularly in the summaries in table 63 (p. 822, reproduced in part by Arkell, 1933, p.18, Table III) and table 64. The Zones are continuous subdivisions of d'Orbigny's Stages, which are themselves subdivisions of the three parts, Lower, Middle and Upper, of the whole of the Jurassic. Their definition lies in their bounding time-planes, which we are attempting today to fix objectively and typologically by means of markers ('Golden Spikes') in type-sections. Their function is to provide a standard scale of reference against which all the known formations of Europe could be classified (correlated) according to their relative ages. Oppel's Zones are therefore standard chronozones. Their recognition is by means of the guide-fossils they contain, i.e. the biozones of the fossils. In general, the biozones used are concurrent-range assemblage biozones, in modern parlance, for the simple statistical reason that, in handling approximate data, the larger the data-set the closer the estimate of the quantity to be determined from it, in this case geological age.

The second source of confusion has been the failure to distinguish between guide-fossils and *index*-fossils. Whereas d'Orbigny's Stages were named after places, Oppel chose to name his Zones after species of fossils (p.813), to emphasize the biostratigraphical basis of his classification. 'I have named individual Zones each after one of its more important [*sic*] species. . .'. He immediately goes on to warn against the subconscious bias that the choice of one particular species to label a Zone might introduce into our interpretation of it, carrying over to the Zone as a whole what might have been largely a local accident of range or relative abundance. 'Important' is a relative concept. He discusses briefly the alternative of place names, as for Stages, but concludes that the dangers of bias arising from the association of a zonal name with its particular development at the eponymous locality are even greater. The function of the index is purely name-giving. It helps if it is at the same time a good guide-fossil, but this is not essential. All that is required as a minimum is that it at least occurs, and preferably that its type horizon lies, in its nominal Zone. Unfortunately, Oppel's remarks have been widely ignored, especially in Germany. There has resulted an often impenetrable confusion of zonal nomenclature as authors changed the choice of index every time they thought another was more appropriate. Often, the index-species has become *the* guide-species, i.e. what purports to continue to be a standard chronozone has become transformed into a single-taxon total-range biozone. The subjective and ephemeral nature of such biozones has been stressed elsewhere (Callomon 1985*a*). Their use in standard chronostratigraphy is almost as unsatisfactory as is that of lithostratigraphical units. And it was mainly the need to bring order into this nomenclatural confusion that led Arkell to propose his Code of Stratigraphical Nomenclature (1946), the first attempt at what has become a flourishing multinational industry.

Such, then, was the legacy of the founding fathers. The number of standard Zones into which the Jurassic had been divided at the end of *Die Juraformation* in 1858 was 33, of which 22 were named after ammonites. The tragic death at the age of 34 of Albert Oppel, the Mozart of the Jurassic, cut short a career that would have given us many further contributions to Jurassic stratigraphy. The problems of biogeographic provincialism among the ammonite guide-fossils, for instance, were becoming apparent as his interests spread further afield, to the Mediterranean and the Himalayas, indicating limits to the applicability of the standard classification he had created. The process of refinement was however carried forward by his successors and continues at the present day. As we have seen, it is a process of subdivision through the insertion of new boundary time-planes, reflecting the incorporation of new discoveries. This can be done in two ways: by delimitation of new Zones, or by splitting of existing Zones into finer subdivisions at a yet lower level in the standard hierarchy, level VII: Subzones. Oppel himself already introduced the category of Subzone a number of times, albeit somewhat tentatively, and their popularity has grown. The distinction between Zones and Subzones is largely a matter of choice, and taken by most authors to reflect the interrelation between the finesse of stratigraphical resolution that can be attained and the areal extent over which it can be recognized. By and large, the category of standard Zone is retained for units that can be recognized over at least sub-continental distances, whereas Subzones may be recognizable over lesser but still useful extents. At least one *International Stratigraphic Guide* (Hedberg 1976) makes provision for yet further subdivisions, as Zonules, but these have not been widely used. A modern example of an analysis of standard chronostratigraphy down to the level of Subzones, taking into account an assessment of biostratigraphy, correlation and Arkell's Rule of Priority in nomenclature, may be seen in the seminal classification of the Lias of NW Europe by Dean *et al.* (1961). It stops short only of the final step, the typological definition of the subzonal boundaries.

Two further technical points remain to be made. The first is orthographic. Standard Oppelian chronozones and fossil biozones, including those of chronozonal index species, being conceptually different entities, the difference should be apparent from the way they are written. I have therefore strongly advocated (1985*a*) the retention of, or the return to, or, especially outside the Mesozoic, the adoption of a convention consistently followed by Arkell (e.g. 1956), even if perhaps not invented by him. He indicates standard chronozones named after an index-fossil by writing the Linnéan name of the fossil in non-italicized, ordinary roman letters, with capital initial and, similarly, initially capitalizing 'Zone' and 'Stage' when used in standard chronostratigraphic sense. Thus, the Upper Jurassic Cordatum Zone and *cordatum* zone are not the same thing. The latter lies within the former, to an extent depending on the interpretation of a zoological entity and the state of knowledge. The former is (or will be) defined in terms of two bounding time-planes fixed in type sections.

The second point relates to the definition of standard chronostratigraphic units. Standard chronostratigraphy having a hierarchical structure, units at higher levels in the hierarchy should be defined in terms of those at the levels below them, as in zoological nomenclature (Callomon 1965). The ultimate and only unambiguous fixed point is that at the lowest level. A genus rests ultimately on the type specimen of the nominal sub-species of the type species of the nominal sub-genus. Similarly, a standard Stage should be defined in terms of the standard Zones and Subzones it contains.

Standard units being now, by general agreement, defined by their bases, the ultimate typological anchor of a Stage should be the basal time-plane, defined in a type section, of the lowest Subzone of the lowest Zone in the Stage; and so on, through Series and Stages upwards. A recent set of *Guidelines* from the International Commission of Stratigraphy (Cowie *et al.* 1986) purporting to advise numerous Boundary Stratotype Working-Groups on procedure, makes no mention of hierarchy and its consequences.

The present state of subdivision of the Jurassic is illustrated in Fig. 2. It shows how its standard chronostratigraphical classification has evolved by a process of *analytical, hierarchical top-down subdivision*. The number of Zones recognized today in the classical areas of Europe is about 76, the number Subzones about 155. All are named after ammonites as indices. It is a process that may have worked exceptionally well in the Jurassic through the fortunate circumstance of its ammonites as guide-fossils, but the principles apply to all Systems whose chronostratigraphy is based on biostratigraphy.

Does this process of refinement then take us to the limits of time-resolution that can be achieved? The answer in the Jurassic is no, but further progress calls for a different approach. The first to introduce this was S. S. Buckman in the Geological Society's *Journal* a hundred years ago.

The limits of biostratigraphical time-resolution: the hemerae of S. S. Buckman and the classification of the Inferior Oolite

Sydney Savory Buckman (1860–1929) was a remarkable man. The oldest son among five siblings, he was born in Cirencester where his father, James Buckman, was Professor of Geology, Natural History and Botany at the Royal Agricultural College, and an enthusiastic naturalist in the great Victorian tradition. Resigning from his post in 1863 after prolonged conflicts with a recently newly appointed Reverend Principal, conflicts arising almost certainly from James Buckman's overt support of Darwin's recently published theory of evolution (Torrens 1988), the Buckmans moved to Bradford Abbas, 5 km WSW of Sherborne Abbey in Dorset, to take up farming at what is now East Farm. James' wife (née Savory) died when Sydney was only five years old, so that the boy was brought up largely under the

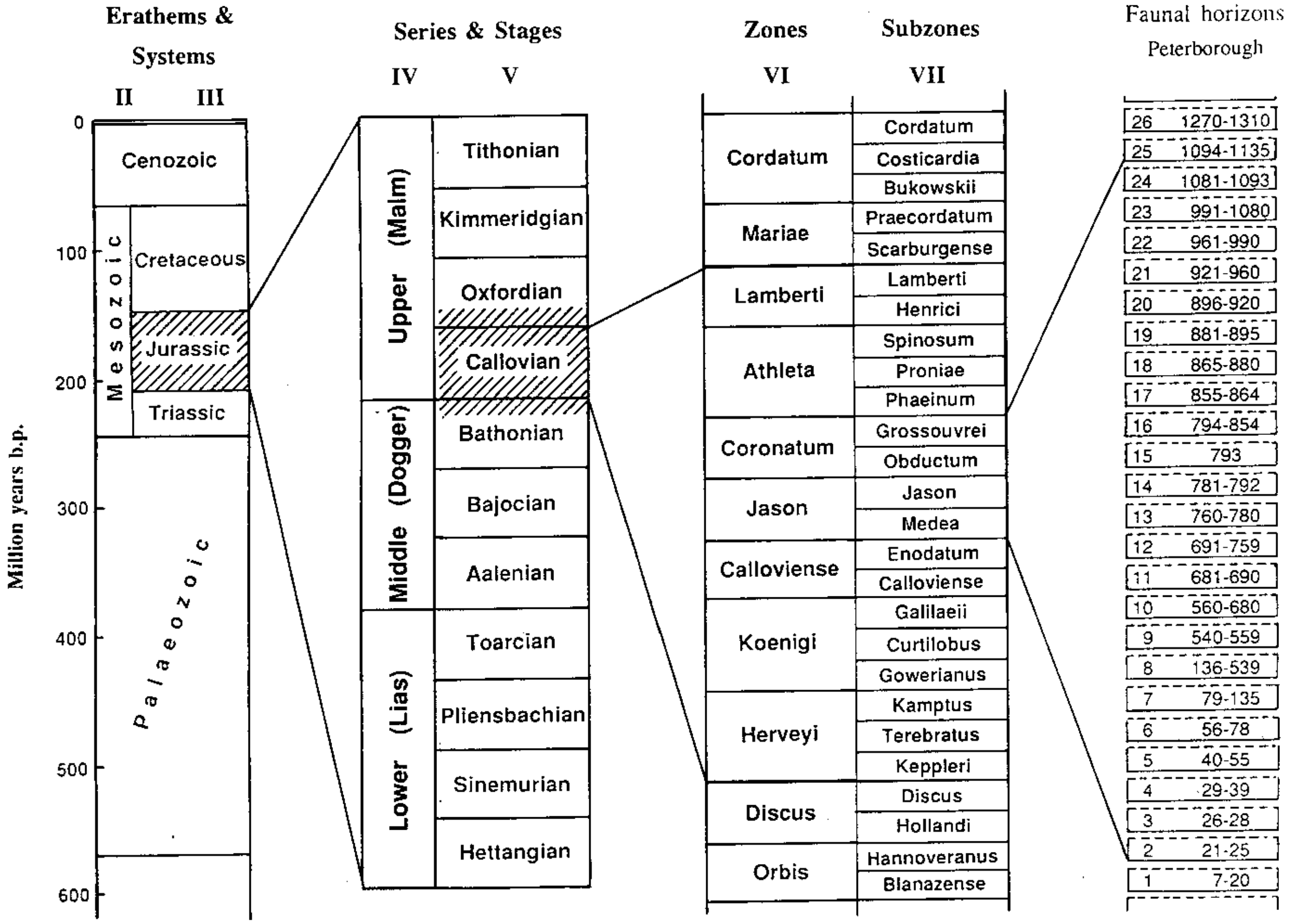


Fig. 2. The subdivision of the Jurassic down to the lowest level of the standard chronostratigraphic hierarchy, the Subzone (VII), and thence to the limit of biochroological resolution in the example of the ammonite faunal horizons of the Oxford Clay at Peterborough as described by Brinkmann (1929; see also Fig. 6): numbers refer to stratigraphic heights in centimetres. The Stages are often further subdivided at a level intermediate between V and VI into Substages. Sometimes these are separately named, e.g. as in the Domerian (upper) and Carixian (lower) Substages of the Pliensbachian, but Lower, Middle and Upper are more usual. Time-scale at left from CTS89 of Harland *et al.* (1990).

influence of his remarkable father. He was sent for his secondary schooling to nearby Sherborne School (1871–78), which, through the enthusiasm of some of its teachers, was building up strong interests in natural history and, given its location, in geology in particular. In this it was strongly supported by Buckman senior, co-founder in 1875 and first Honorary Secretary of the Dorset Natural History and Antiquarian Field Club (Torrens 1978). But besides nurturing his interest in geology, the school clearly gave young Buckman an excellent basic education, strong after the manner of the times in reading, writing and the classical Greek and Latin languages, a familiarity with which is apparent in much of his own later writings. Original intentions to follow school by University and then to enter the Church came to nothing and, encouraged by his father-in-law, he set off for a year's study and travel on the Continent, to see whether he might find an interest in chemistry, the basis of the occupation as pharmacists in London of his mother's family and even originally of his own father, who had started his working life as a pharmacist in Cheltenham. Sydney Buckman was therefore enrolled for two semesters in the Chemical Laboratory of the University of Wiesbaden, but it, too, was not to his taste. It marked the end of any further attempts at formal higher education and he returned to Dorset in 1880. He did however later acknowledge the value of having learned the German language (Davies 1930*b*).

Buckman's subsequent career continued to be as varied and turbulent as had that of his father. After two years studying to become a land-agent, he married in 1882 and and took up farming near Andoversford, east of Cheltenham. 1889 saw the beginning of a new career as novelist, living near Stroud ('James Corin', as in Corinium, Roman Cirencester). In 1894 the family moved to Charlton Kings, today a part of Cheltenham, and in 1904, following a break-down in health, the Buckmans, now with five children, moved to Thame, SE of Oxford, where they lived for the rest of Sydney's life until his death in 1929. Although his strenuous field-work, much of it by bicycle, came to an end in 1904, his geological writings continued undiminished. The list of his publications runs to over 200 titles. His most famous work, started from Thame in 1909, must be the monumental *Type Ammonites* (1909–1930), running to seven volumes with over a thousand plates which, whatever may be said about its systematics, continues to be the most comprehensive description of British Jurassic ammonites. His active geological career spanned half a century. During this period, although he undertook occasional paid work for the Geological Survey and earned something from the sale of fossils, he never held a position of employment as a geologist either in a Survey, in industry, or in an academic institution.

In retracing Buckman's career as a stratigrapher we can see how the development of his ideas was influenced by a combination of circumstances. Firstly, under the influence of his father, he had early become familiar with the general principles of stratigraphy, systematic palaeontology and the application of biostratigraphy to the unravelling of geological time. Secondly, the region in which he grew up provided almost unrivalled opportunities to apply these principles to innumerable quarries and outcrops that yielded an abundance of fossils from almost every bed. Thirdly, leading amongst these fossils were the ammonites. He was aware of their renown as guide-fossils through his father both directly and indirectly, for he had become familiar with the literature, including Oppel. His acute sense of observation therefore quickly led him to appreciate the points stressed by Oppel, that just how good ammonites were for correlation and hence for time-resolution depended crucially on two factors: on how closely their species could be identified, and on how precisely their stratigraphic horizons were recorded.

The first of Buckman's many papers to appear in the *Quarterly Journal of the Geological Society* (1881), published at the age of 21 and only his second publication, is prophetic. Under the innocuous title of 'A descriptive catalogue of some species of ammonites from the Inferior Oolite of Dorset', it begins firmly with a stratigraphical introduction, setting up a framework to which the systematic discussion of the ammonites is then referred. This framework has two parts. The first consists of field observations in the form of detailed sections and their ammonite faunas. The second is a chronostratigraphic classification in terms of the standard Zones of Oppel and Waagen, from the Zone of *Harpoceras murchisonae* to that of *Amm. parkinsoni*. But the notable observations relate to the thicknesses of some of the Zones and hence, conversely, of just how carefully a section has to be recorded. Writing of the Zone of *Stephanoceras humphriesianum* (p. 588), he notes: 'At Oborne,... its thickness is about 5 feet, while at Louse-Hill and Wyke quarries this zone is only represented by two thin layers,... the two being only about 6 inches thick, but containing nearly all the species that one finds at Oborne...'; and of the Inferior Oolite of Sherborne as a whole, that it 'can be very well divided into four zones, which are extremely well marked, but vary greatly in thickness at different localities; and it is probably this variation in thickness, and sometimes *almost complete absence* [his italics] of a zone, that has led to very much confusion.' In other words, ammonites can reveal not only those zones that are present but also those that are missing: they can reveal significant sedimentary non-sequences—the incompleteness of the geological record. This point was to assume ever more significance in his later work.

Buckman's next major stratigraphical paper, also published in the *Journal* (1889*a*) was concerned with an old problem: the age and classification of the Cotteswold, Midford and Yeovil Sands of Gloucestershire, Somerset and Dorset respectively. These formations lie between the clays of the Upper Lias below and the limestones of the Inferior Oolite above: to which should they be assigned? They consist throughout their outcrop of very similar yellow, unfossiliferous fine-grained micaceous sands 30–50 m thick, interspersed with thin, harder bands of sandstone containing fossils, including occasional ammonites. These ammonite 'horizons' (p. 442) revealed a succession of clearly distinguishable faunas. While not all were found at any one locality, whenever several did occur they always did so in the same relative sequence. Their homotaxis therefore indicated synchronism. Their number and distinguishability showed that ammonite biostratigraphy could achieve time-resolutions that were much finer than those indicated by the lithostratigraphy. Hence it should be able to provide a way of analysing the problem: 'Now the questions arise, Do these series of Sands begin on the same horizon, and, including the Cephalopoda-bed, do they end on the same horizon?... Are the sands all on one horizon, as stated by Wright; or are they on two different horizons, as Oppel and my father thought?'.

The answer to the first question was emphatically no.

Buckman showed, firstly, that both the lower and upper boundaries of the Sands were highly diachronous; secondly, that the lowest and highest ammonite horizons found in the Sands at one locality could pass laterally into Upper Lias clays or Lower Inferior Oolite limestones respectively; and thirdly, that the thicknesses of the sands associated with or lying between adjacent faunal horizons could vary from 1 to 50 m. Hence, in his own words:

> It has been observed that attention to lithology is likely to ensure success in the matter of correlation. I am bound to confess, however, that my experience of Jurassic rocks tells me that in many cases this observation is quite incorrect. Within the limits of one basin it may happen that the same horizon can often be identified by the similarity of lithology;... while in correlating the strata of one basin with those of another, such an idea will probably lead to very decided errors. The strata now to be discussed have suffered singularly in the matter of correlation from this similarity of lithology.... The celebrated Dr Oppel, who visited this country about 1855, comprehended the position of these sands with his usual acute perception; and had our English geologists given to his work the attention which it deserves, it ought to have been impossible for the discussion to have ~~be~~ been maintained.

As we would say today, lithostratigraphy can be a poor guide to chronostratigraphy. But this had been the central tenet both of d'Orbigny and of Oppel before him: the idea that a given faunal horizon or zone could transgress facies boundaries was hardly new. Was Buckman doing anything more remarkable than importing an idea already well established abroad, albeit perhaps into the culture of a somewhat sleepy and sceptical, local Establishment? In principle, probably not. But in practice, and perhaps implicitly rather than explicitly, yes: the important point is that 'diachroneity' implies a *time-scale*, that of attainable time-*resolution*. And the diachroneity of the boundaries of the Midford Sands became apparent only through a considerable refinement of the ammonite biostratigraphy. Where Oppel had divided the Upper Lias and lowest Inferior Oolite into only three Zones, those of *Posidonia bronni, Amm. jurensis* and *Amm. torulosus*, Buckman was able consistently to distinguish seven successive ammonite faunal horizons (still variously called 'beds' and 'zones'). His proposal henceforth to abandon lithology as the primary character in stratigraphic classification in favour of faunal successions based on ammonites was certainly quite definite, even if the word 'time' was not explicitly mentioned. And the drive to refine the ammonite record and to extend the refinement over the whole of the Jurassic was to become one of his main motivations during the rest of his life.

These ideas surfaced explicitly in Buckman's famous paper on the Inferior Oolite of Sherborne (1893), whose appearance just a century ago this chapter commemorates. Buckman was by now well launched into his monograph on the ammonites of this formation (1887–1907). It had started very much along conventional lines, as little more than a descriptive, typological catalogue of the wealth of beautifully preserved specimens that had accumulated over the years, largely in the collections of his father and friends. But in looking for a more natural basis of classification, Buckman became increasingly aware of evolutionary connections, both through his own observations and through his increasing familiarity with the literature. The latter included, fortunately, the seminal work of Waagen (1869) and, less fortunately, that of Hyatt (1889 and earlier: see Donovan 1973). His complete conversion to phylogenetic classification appeared in print almost simultaneously in part (iii) of his *Monograph* (March 1889, 'Classification by descent', p. 125–41) and yet again in this *Journal* (1889*b*, November, 'The descent of *Sonninia and Hammatoceras*'). There was therefore now a second, palaeontological need for the closest possible dating of rocks, and of those of the Inferior Oolite of Dorset in particular. The purpose henceforth of stratigraphy became primarily to provide geochronology, and the classification of strata was to be according to their ages—chronostratigraphical.

Buckman immediately realized the need of a dual nomenclature: one for rocks, another for their ages. He also understood the nature of Oppel's Zones, that they were rock-units, the distinguishable sedimentary expression of durations of time in a standard scale; that these durations of time should in principle be, and in his experience were, further subdivisible through refinements of biostratigraphy; and that there existed no technical term for the smallest time-units thus discernible. For this he introduced the word 'hemera' (as in 'ephemeral'). It is worth quoting the critical sentences again:

> *On Zonal Correlation.*—The geological unit for the correlation of strata has hitherto been the 'zone'. Gradually, however, it has been felt that either the zones must be increased in number, or some modification adopted, if the true faunal sequence is to be expressed with that accuracy that is now necessary....
>
> *The term 'Hemera'.*—Its meaning is 'day' or 'time'; and I wish to use it as the chronological indicator of the faunal sequence. Successive 'hemerae' should mark the smallest consecutive divisions which the sequence of different species enables us to separate in the maximum development of strata. In attenuated strata, the deposits belonging to successive hemerae may not be absolutely distinguishable, yet the presence of successive hemerae may be recognized by their index-species, or some known contemporary; and reference to the maximum development of strata will explain that the hemerae were not contemporaneous but successive. The term 'hemera'... is designed as a chronological division, and will not therefore replace the term 'zone' or be a subdivision of it.

Taken by itself, as Arkell remarked, it would be difficult to imagine anything stated much more clearly than this. But Buckman went further, driven by the palaeontological considerations alluded to above. Right at the beginning he states:

> I may, however, remark that the division of the Jurassic period on palaeontological grounds... is a necessity. Ammonites have been chosen as the indicators of horizons [*sic*], and their rapidity in development [evolution] makes them peculiarly suitable. Therefore, as far as possible, the chronological unit and the Ammonite-species should go together: and any system of grouping the chronological units should depend on the epacme, acme, and paracme of Ammonite-families.

And later:

> The term 'Hemera' is intended to mark the acme of development of one or more species. [It] will therefore enable us to record our facts correctly; and its chief use will be in what I may call 'palaeo-biology'.

Buckman then proceeded to describe and analyse the strata around Sherborne. He took into consideration some 20 quarries over a distance of only 12 km of outcrop, recording 17 of them with their fossils, bed by numbered bed, down in some cases to thicknesses of only 1–2 inches (3–5 cm). The frame of reference for correlation was now a succession of 12 hemerae in place of the 4 Oppelian Zones used previously. The interesting conclusions were as follows. Firstly, the thicknesses of the 'strata deposited during the ... hemerae' (p. 493) could vary dramatically: those of the *Garantianae* hemerae, for instance, represented by 6 m (20 feet) of Sherborne Building Stone north of the town, had shrunk to a mere 5 cm (2 inches) at Bradford Abbas, only 6 km away. Secondly, what appears to be a single bed in one section can contain the faunas of several hemerae—a case of what today we would call a condensed deposit. The example Buckman quoted was the famous Fossil Bed of Sandford Lane, a single solid bed of limestone only 45 cm thick. Thirdly, strata representing one or several hemerae could be absent altogether in a section, and a common reason for this was synsedimentary erosion, sometimes directly reflected in the spectacular erosion-planes for which the Inferior Oolite of Dorset has become famous. 'The "incompleteness of the record" and the attenuation of the deposits are especially noticeable' (p.484). In either case, a faunal condensation or a total stratal non-sequence at one locality can be demonstrated only by correlation with the succession at another at which it is more complete. The logical conclusion of this argument, which Buckman seemed to wish to indicate in his introductory sentences quoted above, with their reference to 'the maximum development of strata', is that we can only be sure that our hemeral succession is complete when we have pieced together the complete stratal succession. The dilemma is immediately obvious: but how do we know when the stratal succession is complete?

The further Buckman cast around for correlations the less complete the succession around Sherborne turned out to be. The hemeral succession of Sherborne could be successfully carried over to the outliers of Inferior Oolite at Dundry, near Bristol, and to the Cotswolds, with further dramatic changes of facies and thicknesses. They could even be identified in continental Europe. His observation (p.494), that in the Sandford Lan~~d~~ Fossil Bed 'no other locality in England yields the same fauna as the lower part of this bed', remained true until two years ago; and his recognition that it does occur around Gingen in southern Swabia in sections described by Waagen (1867) was a brilliant act of correlation. (For the first modern description of the Swabian succession, see Oechsle 1958. The definitive guide-fossil (p. 105) is *Shirbuirnia* [sic] *stephani* (S. Buckman, 1882)). In what were to be his last two papers on the Inferior Oolite based on his own field-work, he takes in the successions of the Dorset coast and nearby localities. In the first of these papers (1910*a*, table III), the number of hemerae in the Inferior Oolite has grown to 18. But what is probably the most important general conclusion to emerge from the whole study of the Inferior Oolite is summarized in the introduction to the second paper (1910*b*, p. 90):

> A schoolboy once defined a net as a series of holes strung together, and the Dorset Inferior Oolite might be defined as a series of gaps united by thin bands of deposit.... the deposits are so local, the deposits of one place correspond to the gaps of another. Therefore many localities have to be placed together to produce the full tale of the Inferior Oolite.

To paraphrase the introductory motto on the fly-leaf of Vol. III of *Type Ammonites* (Buckman 1923), the more complete the faunal record becomes, the less complete the sedimentary record turns out to be.

Buckman's field observations have stood the test of time down to the smallest detail (see e.g. Parsons 1974, 1976, 1980). Almost the only changes have involved even further refinement rather than revision—the number of successive ammonite faunas now recognizable in the Inferior Oolite has grown from the original 12 of 1893 to over 40 (Callomon & Chandler 1990). Buckman's analysis stands as one of the all-time classical landmarks of stratigraphy. Its wider contributions to the subject as a whole were two-fold. Firstly, it showed how detailed biostratigraphy of ammonites could be used to resolve geochronology across a complex mosaic of disparate *lithological* units formed in a tectonically quiescent regime, that of Jurassic southern England. This evokes the interesting parallel with the contemporary achievements of Lapworth (recently reviewed by Fortey 1993), who showed how the biostratigraphy of graptolites could be used to resolve geochronology across a complex mosaic of disparate *tectonic* units in a monotonous sedimentary regime, that of the Siluro-Ordovician Southern Uplands. Biostratigraphy succeeded where lithostratigraphy had failed. Secondly, it had shown how the time-resolution of the geological record could be carried well beyond the conventional limits of Oppelian standard zonal chronostratigraphy.

It remains only to make one further important point. This concerns the basic principles behind the refining of time-resolution by polyhemeral analysis. As was shown in the introduction, conventional refinement of standard chronostratigraphy proceeds by successive subdivision of a geological column that is regarded from the outset as being always complete. The act of delimiting additional smaller units within larger ones by inserting newly-defined time-planes does not enlarge the duration of geological time being classified. It merely provides ways of characterizing that which was assumed to be already there, even if it had not been previously recognized. In contrast, polyhemeral refinement proceeds through the new discovery of hemerae that are then *inserted* into the previously known succession. It makes no assumptions as to what might be there before it is discovered: the implication is in fact the opposite, that the record is *a priori* incomplete, the gaps waiting to be filled. There is no theoretical limit to the number of hemerae that could in principle be discovered. The process is therefore one of successive additions rather than subdivisions, of what might be called *bottom-upwards synthesis*. This leads immediately to the question of the time-duration of a hemera, and this is discussed further below.

Polyhemeral chronology: difficulties and objections

Buckman's paper of 1893 started a vigorous debate that was to last for 40 years, terminating in another masterly and comprehensive review by Arkell (1933, pp. 17–37). Most of this debate is now of little more than historic interest.

There were objections based largely on misinterpretation, or non-comprehension, of what Buckman had written. Some of these are to be found in the reports of discussions following the reading of Buckman's papers at the Society's meetings. Their only residual value is as entertainment. Mr H. B. Woodward had some difficulty with the concept of a zone (Buckman 1889*a*, p. 473, repeated in Woodward 1892, p.298): 'Zones are assemblages of organic remains of which one abundant and characteristic form is chosen as index'. To which Buckman is said to have replied that the fossils in a museum would fit this definition. Professor Blake (*in* Buckman 1893, p. 522), on learning of the highly attenuated beds assigned to a zone or hemera in some sections, thinner than the ammonite that was its index, foresaw that in such cases the ammonite would have some difficulty in fitting into its own zone. Buckman duly showed how this trick could be done by producing a specimen of an ammonite, probably of the same species of cadicone *Teloceras* that can still be collected at Oborne today, planed off by the same erosion-plane that had attenuated the bed (Davies 1930*b*, p. 227, and see Fig. 4 below). Even more telling would have been the pebble lags made up largely of rolled, bored and epifaunally encrusted ammonites found at numerous horizons, evidence of hemerae whose former sediments had been totally removed, probably by winnowing. Mr A.J. Jukes-Browne (1903) and others unnamed had a general difficulty with time-rock duality. Buckman tried to come to their help (1902, 1903) by appeal to every-day experience, including the famous parable of the Dorset labourer whose lunch—the tangible manifestation of lunch-time—had been eaten by a dog: would we have said, 'My dinner is gone: one o'clock is absent'? Further complaints at this level of discourse clearly reached him from the editors of journals (ours included) in the form of anonymous referees' comments, for Hugh Torrens has discovered a previously unpublished epigram in Buckman's papers that we both feel should be shared by a wider public, especially in the climate in which we toil today:

> Speak kindly of the referee
> Forgive him if he teases
> He doesn't do it to annoy
> He really thinks it pleases.—S.S.B.

(A not altogether dissimilar passage is to be found in Dodson 1865).

An illuminating account of the contemporary state of geological opinion on zonal palaeontology that Buckman so robustly invaded, has been given by Davies (1930*b*).

More serious criticisms arose from two causes: incompleteness, in a failure to follow arguments to their conclusion and to realize their implications; and over-specification. This led to contradictions and uncertainties, some of which persist in the practice of stratigraphy to this day.

The main misunderstanding stemmed from the failure to distinguish explicitly between the time-*duration* of a hemera and the time-*intervals* between hemerae. It lies at the heart of the distinction already made above between refinement by subdivision of a continuum and refinement by addition through insertion into a discretely-spaced series. Trueman (1923) realized that even after lengthy debate there was still no term for the rock-equivalent of a hemera. He therefore introduced the term *epibole*, which has led to further confusion that need not be reviewed here.

Then, how to recognize hemerae? Hemerae of what? Here we come to problems generated by overspecification. Buckman referred his hemerae explicitly to the 'acme of development of one or more [ammonite] species' (see quotations above). How are such species defined? Few attempts at zoological classification can have aroused greater controversy at the time than had Buckman's own taxonomy of ammonites. In successive species of the same lineage, phyletic classification in palaeontology runs into well-known problems arising from the dimension of time, discussed for instance by Bather (1927) who introduced the useful term *transient* for a segment of a phyletic chronospecies (see also the discussion of a particular case among thre ammonites by Callomon 1985*b*, p. 557). And what is meant by the 'acme' of an evolving species? And even if we could define it, how would we recognize it in the rocks? All we can see are 'ammonite horizons': beds containing ammonites. And if successive acmes involved members of different co-existing lineages, could such hemerae overlap? These points were taken up by Trueman and others. Some beds contain ammonites, many do not. Could the absence of ammonites be due to ecological factors? In other words, could biostratigraphical gaps reflect not only stratigraphical but also faunal non-sequences? Could fossil horizons be diachronous? In which case, would the hemera of a species become something that varied from place to place, and hence merely a synonym of a local range biozone? Or would what we see at one place be merely a local manifestation of part of a hemera, a sort of 'teil-hemera'? And how long, in years, was the duration of an ammonite hemera and how long the intervals between them? And why only ammonites? And so on.

It was uncertainties such as these that contributed to the demise of further attempts to develop Buckman's polyhemeral methods in Jurassic geochronology. But the greatest contributor must have been Buckman's attempts in his last years to extend them over the rest of the Jurassic. This made him depend almost entirely on the field observations of others, when available, or on his own intuitive deductions of phyletic relationships based largely on Hyattian 'biogenetic laws' when not. Morley Davies' final compilation of all the hemerae coined by Buckman, published in an editorial appendix to the last volume of *Type Ammonites* (Davies 1930*a*), lists some 375. Unfortunately, most of them, particularly in the Upper Jurassic, are not based on established fact. As Arkell wrote (1933, p. 36): 'It is one of the great misfortunes for Jurassic geology that when increasing age and frailty prevented Buckman from continuing active field-work, he lost sight of the distinction between results obtained with hammer, collecting bag and field notebook, and those arrived at by speculation and deduction from matrix at home. ... the two kinds of results are almost inextricably interwoven in his later published works. Only those with intimate local knowledge of the English Upper Jurassic rocks can hope to distinguish the two'. Like the clock that struck thirteen: an event not only raising disbelief but also casting doubt on all that went before. Arkell's epitaph in effect brought to an end a chapter in the development of methods of geochronological refinement.

The limits of biostratigraphic time-resolution: characteristic faunal horizons

Although Buckman's presentation of geochronology based on biostratigraphy may have been faulty, his methods of recording field observations, both of rocks and of fossils, were admirable. So was his primary goal: to 'mark the smallest consecutive divisions [of time] which the sequence of different species enables us to separate'; and the purpose to which he wished to apply the results, the analysis of evolutionary 'palaeo-biology', seems more appealing than ever (see the apposite reviews by Paul (1985) and Fortey (1985)). The needs for high-resolution chronostratigraphy have only widened (e.g. Hailwood & Kidd 1993), for instance in the combination of sedimentology and sequence stratigraphy as analytical techniques in the study of basin evolution tied to the history of eustatic sea-level.

Interest in the refinement of Jurassic chronostratigraphy to the limits attainable by means of ammonite biostratigraphy, following Buckman's methods, was revived 30 years ago (Callomon 1964), when the idea of a characteristic faunal horizon as the ultimate time-diagnostic infra-standard-subzonal stratigraphical unit was explicitly reintroduced. It has therefore been a relatively simple matter to revive the core of Buckman's methods, stripping away what is unnecessary and filling in what had been missing. The basic approach, already outlined above, is a positivist one: to start with the record of what is observable in the field as stratigraphy and then to interpret it with minimal assumptions of time. The argument that follows has been generalized to apply not only to Jurassic ammonites, but equally to other groups of fossils, with modifications that depend on their time-diagnostic characteristics. The greatest contrast is probably to be found between the nekto-benthic ammonites and planktonic micro- and nannofossils, and their applications to stratigraphy have been compared elsewhere (Callomon 1994).

(1) *Rocks and stratigraphical horizons*. The rocks continue to provide the basic observations from which all else must be derived, including time. (This is the opposite of Buckman's approach, in which the epiboles were derived from the hemerae). A succession of strata in a section define the *stratigraphical horizons* at which fossils are found. All sedimentary successions are at one scale or another lithologically discontinuous and it is usually convenient (but not essential) to break them up into distinguishable units, or *beds*. How beds are differentiated in practice is a matter of lithostratigraphical judgment and need not concern us here.

(2) *Fossils and faunal horizons*. Fossils, singly or in assemblages of taxa and individuals, may occur at many horizons in a section at one locality. Taking the taxa one by one, their *known* ranges span the strata that are their *local range biozones*. ('Known', because we have resolved to exclude from the argument that which is unknown. Hence biozones change with the state of knowledge (Callomon 1985*a*). The 'total range biozone' much cited in theoretical discussions, which is represented in a section by a local partial-range biozone, or teilzone, can never be known). Local range biozones of different taxa usually begin and end at different levels. Local *concurrent-range* biozones are therefore shorter than individual range biozones, and *total-assemblage concurrent-range* biozones are the shortest.

Every first and last appearance of a taxon in a section then marks the boundary of a total-assemblage concurrent-range biozone (the *unitary association* biozone of Guex 1987) and the faunal succession (or floral: but faunal hereafter for short) as a whole becomes a time-ordered sequence of distinguishable, non-overlapping total-assemblage concurrent-range biozones. Conversely, applying the Principle of Biostratigraphic Synchroneity, all the stratigraphical horizons (parts of a bed, a whole bed, or several beds) making up such a biozone are, *as far as can be judged from the fossils alone*, effectively *of the same age*. They may therefore be treated as equivalent to a single, faunally indivisible bed representing the sediments of a short period of time—a geological instant. They may therefore be called simply a *faunal horizon*. The local biostratigraphical succession has become a quantized, time-ordered sequence of distinguishable faunal horizons.

But what makes successive faunal assemblages distinguishable? And which distinctions are of interest?

(3) *Guide-fossils and characteristic faunal horizons*. Not all faunal horizons as defined above are of practical value for geochronology. We are interested only in the subset of fossil taxa in an assemblage that we believe to be of value for at least regional time-correlations between sections and hence for the construction of a regional geochronology—the guide-fossils. But how do we know which they are?

Distinctions between fossil assemblages may be ascribed to five factors. The first two are experimental.

(a) *Quantity and quality of available material*: quantity includes total absence–collection-failure. Deficiency on both counts can be made good by more work: improving the state of knowledge.

(b) *Taxonomic skill*: the observer's ability to distinguish taxa.

The next two are ecological.

(c) *Ecoenvironmental factors*: those factors that determine habitat, seen in changes of faunal compositions of fossil assemblages (relative numbers of different species, sexes or ontogenetic stages), including the limiting case of total absence.

(d) *Ecophenotypic factors*: environmental factors that can induce somatic changes in organisms seen as changes of shape in fossils.

Both ecological factors are time-reversible and likely to be local; fossils of organisms sensitive to either of them are *facies*-dependent. Lastly, and most importantly,

(e) *Genotypic evolution*: seen as the phenotypic time-evolution of the morphological characters of the fossils we collect. It is effectively irreversible (although the evolution of some characters may be reversible, leading to homoeomorphies) and likely to be widely independent of geographical distributions, hence of greatest value in the selection of guide-fossils.

The identification of time-diagnostic guide-fossils is an art and proceeds by trial and error, the trials including tests to assess the importance of all five of the factors enumerated above. Such trials usually involve tests of conjectural regional correlations and depend on the characteristics of the fossil group under consideration. Once the guide-fossils have been selected, we apply to them the same arguments as before and describe their successions in terms of their own effective faunal horizons: the concurrent-range biozones of restricted subsets specified by the guide-fossils. These faunal horizons of guide-fossils are therefore the sought-for minimally chronologically distinguishable regional stratigraphical units in the stratal succession. They may be referred to as *characteristic faunal horizons*—characteristic of the specified group of guide-fossils:

> *A characteristic faunal horizon is a bed or series of beds, characterized by a specified taxon or assemblage of time-diagnostic guide-fossils, within which no further stratigraphical differentiation of the fauna can be made.*

A characteristic faunal horizon may be recognized in a single section if its guide-fossils are already known. It may be recognized further afield:

> *Two local faunal horizons at different places are effectively of the same age if their guide-fossil faunas cannot be distinguished.*

This is the Principle of Synchroneity restated in terms of faunal horizons and, as before, forms the basis of all biostratigraphic time-correlations. Such correlations are clearly subject to the uncertainties of 3(a-b) above, which are what make them approximations.

(4) *Characteristic faunal horizons and geochronology.* Faunal horizons as defined above are rock-units in the same class as other types of biozone. The periods of *time* represented by their fossils and sediments are *a priori* unknown. They are the shorter of either the minimum time needed for one characteristic fauna to have evolved into another distinguishable one, within the experimental uncertainties implied by factors 3(a-b) above, or of the times of formation of the sediments. Any realistic estimates of what the periods actually were must come from other sources. The periods of time between faunal horizons cannot be deduced from the fossils alone either. It becomes important, therefore, to distinguish clearly between (i) the time-*duration*, δt_i, represented by the ith faunal horizon, and (ii) the time-*interval*, δt_{ij}, between the times of *formation*, t_i, t_j (the *ages*), of the horizons i, j.

There seem to be as yet no technical terms for precisely these quantities, although there is no shortage of terms that come close. A selection was given by Arkell (1933, pp. 21–22). All of them are deficient in one way or another, but this is not the place to add to them. Buckman's 'hemera', stripped of references to 'species' and 'acmes' conveys the right spirit; but I am attracted by the term 'biochron' introduced by Williams (1901). It seems sufficiently general to encompass what is required: the *biochron* (δt_i) of a faunal horizon.

An interval δt_{ij} represents a non-sequence or sedimentary hiatus: stratigraphical, faunal, or both. Geochronology deduced from successions of faunal horizons makes no *a priori* assumptions, however, concerning the relative magnitudes of durations δt_i and intervals δt_{ij}, least of all the special assumption that δt_{ij} is zero, that the faunal record is complete and that δt_{ij} therefore represents the evolution-time of distinguishable fossil assemblages. Refinement of biostratigraphic geochronology proceeds in two ways: reduction of the experimental uncertainties inherent in the characterization of faunal horizons; and discovery of new horizons and their insertion into hitherto unrecognized gaps in the sequence. We can never know when the process is complete, but is useful to devise some measures of success, some indices of geochronological finesse, for comparing the power of one technique with that of another. There are two that come to mind: (i) the *secular resolution*: the smallest time-interval δt in the geological record that can be resolved; and (ii) the *secular resolving-power*, R_t: the inverse of the secular resolution as a fraction of the age of the rocks in which the time-interval is being resolved,

$$R_t = t/\delta t$$

In the geochronology of faunal horizons we assume the duration ~~dti~~ δt_i is negligible and that what we resolve is δt_{ij},:

$$R_t \text{ (faunal horizons)} = t_{i,j}/\delta t_{ij},$$

Some estimates are given below.

In summary, the construction of a biostratigraphical geochronology based on the differentiation of characteristic faunal horizons differs very little from what Buckman actually did in practice, as, indeed, have many others, even if not articulated in these terms. It is a universal method, one that proceeds from the minimal premise of an incomplete record that is to be refined by addition at the lowest levels of observation—the process of bottom-upward synthesis.

Jurassic ammonites as guide-fossils

Many fossil groups have been successfully used for high-resolution geochronology in the Jurassic, but almost always only as substitutes for ammonites when these fail. What are the factors that combine to make ammonites such pre-eminent guide-fossils?

Firstly, an average, individual, well-preserved specimen, treated as an ideogram, is rich in morphological characters that convey a lot of information. It is the ability to grasp minute distinctions between such ideograms that singles out the human eye as a device for pattern-recognition, far outstripping any combination of ruler and computer currently available in digitized biometry. This is why passports continue to carry both the photographs and signatures of their legitimate bearers. It follows that even among ammonites, strongly sculptured forms such as *Kosmoceras* are better guide-fossils than smooth, featureless ones. But for its potential to be realized, the human eye has to be trained, and the limit of what can be achieved with ammonites as guide-fossils thus depends strongly on the taxonomic skill of the stratigrapher, perhaps more so than in many other groups (3(b) above).

Secondly, the number of specimens hence needed to characterize a stratigraphically diagnostic assemblage is relatively small. The specimens found at one level can usually be readily divided into groups differing strongly in morphology, assigned to different families or genera and belonging to separate lineages. Phyletic diversity is usually low, and more often than not the time-diagnostic forms are those of a single genus or family. The distinguishable taxa making up the characteristic assemblage tend in fact to be the variants of single biospecies, the transients of a single lineage (Callomon 1985b), but such an assignment to a particular zoological category is irrelevant for stratigraphical purposes. Typically, in ammonites, 5–10 specimens, if well-preserved, should suffice to characterize a faunal horizon, and a similar number to recognize it. Very often, even a single specimen can limit the possibilities to a very narrow range.

Thirdly and most importantly, the changes of morphology with time seen in successions of assemblages are determined almost entirely by genotypic evolution (3(e) above), which, for reasons still entirely unknown, was so much more rapid in ammonoids, from their earliest days in the Palaeozoic, than in any other group of invertebrates (except perhaps monograptids). The changes one is looking for are now the smallest detectable changes in the composite ideogram of whole assemblages of variants of transients of an evolving lineage, not just of individuals. Sometimes the changes involve no more than a shift of the centre of gravity of the distribution of the variability. At others, they can affect mainly one character, such as adult size, in all variants. Often, however, they involve nuances of sculpture too subtle to quantify. This point was well brought out in an attempt to apply Buckman's descriptions of one of the dominant family of ammonites from the lower Inferior Oolite, the Graphoceratidae, to their biostratigraphy in the much more complete successions of southeastern France (Caloo 1971).

Such delicate changes in morphology can only be relied upon as time-indicators if alternative explanations can be ruled out. The most likely would be ecophenotypic (3(d) above), but ammonites appear to have been remarkably resistant to such influences. The disproof again comes from homotaxial correlations, in finding the same successive changes at localities sufficiently far apart for identity of biofacies to have been highly unlikely, and this is almost invariably what has been observed. Ammonite successions of a single lineage are found to be the same within the whole of a biogeographic province, which means over distances of at least 1000–2000 km. I know of only one indisputable example of ecosomatic modification of Jurassic ammonites, found in the Bajocian pelagic carbonate sea-mount facies of the Venetian Alps (Sturani 1971) and perhaps the related fills of Neptunian dykes in Sicily (Wendt 1971). It takes the form of dramatic dwarfing, the fully mature adults being only half or a third as large as usual elsewhere. Yet, remarkably, this is the only effect. The normal course of their anatomical ontogeny, including the considerable modifications seen in their sexual dimorphism, is retained intact—as are all the morphological nuances characterizing their faunal horizons.

More serious are ecoenvironmental factors. These can be local or distant. Locally, the relative compositions and abundances of assemblages can vary rapidly from place to place and level to level, as Buckman discovered. In many of the well-bedded epeiric or shelf-sea sediments with which most ammonite biostratigraphy has been concerned, ammonites are in fact rare or absent. Ammonites were therefore strongly facies-dependent in their local distributions. The problems this creates can be largely overcome by hard work, as Buckman also showed, relying on the converse of the Principle of Synchroneity: if assemblages at two nearby localities are of similar composition but morphologically distinguishable, it implies that they are of different ages.

On the intercontinental scale, a further problem emerges. Ammonites were all more or less provincial in their habitats. Bioprovincialism could be extreme, when evolving lineages were restricted to regions of endemism, such as those traditionally referred to as Boreal or Tethyan. In such cases, long-distance interprovincial correlations rarely go beyond the level of zonal precision. But there are many other groups of so-called cosmopolitan ammonites in whose evolution rough parallels can be perceived all over the globe, down to generic level, yet which persistently differ in details of just the kind that would, within a province, be ascribed to small differences in age. Here we are almost certainly concerned with geographic subspeciation. Hence if two distant assemblages differ slightly in aspect, e.g. in the Lower Lias of Britain and the Andes, the explanation could be either age-difference, or geographic subspeciation, or both, and the two factors may never be separable. Such uncertainty imposes limitations on the use of ammonites for correlation.

In summary, time-resolution down to the finesse of ammonite faunal horizons can be achievable within the areal extent of a faunal province but not beyond—distances of a few hundreds or thousands of kilometres. Hence, each faunal province has to have its succession of faunal horizons worked out separately.

Ammonite faunal horizons of the Jurassic

Biostratigraphy by faunal horizons was actively taken up in France by Gabilly in an important and wide-ranging review of stratigraphical methods at the second Luxembourg Colloquium in 1967 (not published till seven years later: Gabilly 1974) and systematically applied by him to a revision of the Upper Liassic Toarcian Stage at its type-locality at Thouars (Gabilly 1976). Since then, the method has been increasingly adopted in the Jurassic both of Europe and further afield. It can often be applied equally well also to a re-analysis of older stratigraphical descriptions, many of which have never been fully evaluated. Few major regional reviews in recent times have ended without a zonal synthesis of one kind or another, although precisely what kind is rarely stated: usually presented in tabular form to resemble a continuous, standard, chronostratigraphical, Oppelian scale but, more often than not, revealed by the text to amount to no more than a succession of selected local biozones of unknown chronological extent or completeness. Such stratigraphical information can be recast in the form of a succession of faunal horizons with no loss of information. Some selected examples of stratigraphical analyses based on characteristic faunal horizons are listed in Table 2. There is room to expand briefly on only two of them: the Inferior Oolite where it all began, and the Oxford Clay at Peterborough, made famous by Brinkmann (1929).

The Inferior Oolite of southern England

The list of faunal horizons characterized today is shown in Fig. 3. It is set against a standard zonation that is becoming widely accepted, although none of it has yet been formally defined in terms of boundary stratotypes ratified by international agreement. The Dorset Inferior Oolite spans the Aalenian and Bajocian Stages, and the basal Bathonian. The number of faunal horizons now stands at 56, compared with Buckman's 18 of 1910 (and the 55 hemerae, largely conjectural, in the final compilation by Davies in 1930). Horizons Aa-1–Bj-3 are based on the evolutionary transients of one family, the Graphoceratidae; Bj-4–Bj-12, on Sonniniidae; Bj-13–20, on Stephanoceratidae; and Bj-21 - Bt-1, Garantianinae and Parkinsoniinae. The list is even now incomplete, for there are indications both in Britain and abroad of further assemblages and horizons to be differentiated. The faunal succession of the Garantiana and Parkinsoni Zones, for instance, has so far received little more than cursory attention. Figure 3 therefore summarizes the *biochronology* of the Inferior Oolite based on ammonites, presented, as we have seen, as a series of effectively instantaneous, well-separated snapshots. But how instantaneous, and how well separated? How complete is the record of geological time? To attempt to answer these questions required evidence from other sources, such as sedimentology.

Table 2. *Some Jurassic chronostratigraphical classifications down to characteristic ammonite faunal horizons*

	Standard				
	Stages V	Zones VI	Subzones VII	Faunal horizons	Notes
Europe					
L Jurassic, Sinemurian	1	6	17	61	1
L. Pliensbachian	$\frac{1}{2}$	2	6	18	2
Toarcian	1	6	15	22	3
M Jurassic, Aalenian (a)	1	3	4	11	4a
(b)	1	5	9	16	4b
Bajocian	1	8	17	37	5
Bathonian	1	8	11	16	6
L. Callovian	$\frac{1}{3}$	3	8	16	7
M. Callovian	$\frac{1}{3}$	2	4	21	8
Callovian	1	6	14	23	9
U. Jurassic, Kimmeridgian	1	6	11	28	10
Arctic					
M Jurassic, U. Bajocian–L. Callovian	2	12	—	37	11
U Jurassic, U. Callovian–M. Volgian	3	28	—	46	12
M–U Jurassic, U. Bajocian–Kimmeridgian	$4\frac{1}{2}$	29	—	100+	13
America					
M–U Jurassic, U. Bajocian–Oxfordian	$3\frac{1}{2}$	—	—	47	14
U Jurassic, Oxfordian–Tithonian	3	—	—	22	15

(1) Page (1992): Great Britain. Traditionally one of the most finely subdivisible and widely correlatable parts of the Jurassic, now probably approaching the attainable limits of time-resolution. Many of these horizons can be recognized all over Europe west and north of the Alps. The number of Zones and Subzones is unchanged from those of Dean, Donovan & Howarth (1961).

(2) Phelps (1985): Ibex–Davoei Zones of Britain and France. Analysed in terms of 'zonules', here interpreted as faunal horizons. Areal extent as note (1). Approaching completeness.

(3) Gabilly (1976): western France. Standard zonation differs in detail from that adopted in Britain by Dean *et al.* (1961), summarized in slightly revised form by Howarth (1992); number of Zones and Subzones almost the same. Still scope for further refinement.

(4a) Contini (1970): eastern France. Most horizons identical with those of Dorset, with some additions and omissions; close to complete.

(4b) Callomon & Chandler (1990). For comparison, the number of Buckman's hemerae in 1910 was 6. Extent as note (1), especially Scotland and Iberia.

(5) Callomon & Chandler (1990) with additions: southwestern England. Most horizons recognizable here and there all over Europe, but successions elsewhere indicate still considerable gaps in the English succession.

(6) Westermann & Callomon (1988). A compilation and review based on the works of many authors all over Europe, reflecting unusually sparse and scattered occurrences of ammonites. Scope for considerable further refinement in the Middle and Upper Bathonian.

(7) Callomon, Dietl & Page (1989), Page (1989). The standard Subboreal succession as seen in Britain and Germany, based on the evolution of only two lineages, the Macrocephalitinae and Kosmoceratidae; probably now close to the attainable limit.

(8) Brinkmann (1929), as reinterpreted by Callomon (1984a). Subboreal based on the evolution of the Kosmoceratinae. See Fig. 2.

(9) Cariou (1985): Submediterranean, western France. Widely recognizable at this level of resolution, especially in Iberia, but still scope for considerable further refinement.

(10) Hantzpergue (1989): western France, Aquitaine Basin. Faunal provincialism in ammonites became acute from this level upwards; analysis of the immensely rich successions of faunal horizons in the Subboreal Province (including Britain) and the Rhodano-Franconian Submediterranean Province (including the classical White Jura of the Jura, Swabia, Franconia and southern Poland) has hardly begun.

(11) Callomon (1993*b*): East Greenland. Independent standard Boreal zonation still not closely correlatable with that of Europe, but applicable over the whole of the Arctic. Subdivision into Subzones not yet attempted.

(12) Callomon & Birkelund (1980, 1982); Birkelund, Callomon & Fürsich (1984): East Greenland. Partly Subboreal and Boreal Provinces.

(13) Callomon (1985*b*). The faunal horizons of all the known transients of a single lineage, the Cardioceratidae, wherever found in the Boreal Realm, arranged in time-ordered sequence.

(14) Callomon (1984*b*): western North America, spanning the craton and at least three allochthonous terranes in the Cordillera. An almost extreme case of highly discontinuous, fragmentary successions at widely scattered localities, yet providing a quite respectable Jurassic biochronology in terms of ammonite faunal horizons. Scope for almost unlimited

(a)

		Standard zonation	
	LOWER BATHONIAN	Zones	Subzones
Bt-3	*Oxycerites yeovilensis*	Zigzag	Yeovilensis
Bt-2	*Morphoceras macrescens*		Macrescens
Bt-1	*Parkinsonia convergens*		Convergens
	UPPER BAJOCIAN		
Bj-28	*Parkinsonia bomfordi*	Parkinsoni	Bomfordi
Bj-27c	*Parkinsonia pseudoferruginea*		Truellei
Bj-27b	*Parkinsonia parkinsoni* β		
Bj-27a	*Strigoceras truellei*		
Bj-26b	*Parkinsonia rarecostata*	Garantiana	Acris
Bj-25	*Garantiana tetragona*		Tetragona
Bj-24	*Garantiana dichotoma*		Garantiana
Bj-23	*Leptosphinctes davidsoni*	Subfurcatum	Baculata
Bj-22	*Caumontisphinctes polygyralis*		Polygyralis
Bj-21	*Caumontisphinctes aplous*		Banksi
Bj-20	*Teloceras banksi*		

(b)

	LOWER BAJOCIAN		
Bj-19	*Teloceras coronatum*	Humphriesianum	Blagdeni
Bj-18	*Teloceras blagdeni*		
Bj-17	*Stephanoceras blagdeniforme*		Humphriesianum
Bj-16	*Stephanoceras gibbosum*		
Bj-15	*Stephanoceras humphriesianum*		
Bj-14b	*Chondroceras wrighti*		Romani
Bj-14a	*Chondroceras delphinum*		
Bj-13	*Stephanoceras umbilicum*		
Bj-12	*Stephanoceras rhytum*	Sauzei	
Bj-11b	*Nannina evoluta*		
Bj-11a	*Otoites sauzei*		
Bj-10	*Witchellia laeviuscula*	Laeviuscula	Laeviuscula
Bj-9	*Witchellia ruber*		
Bj-8b	*Shirbuirnia trigonalis*		Trigonalis
Bj-8a	*Witchellia nodatipinguis*		
Bj-7b	*Witchellia connata*		Sayni
Bj-7a	*Witchellia gelasina*		
Bj-6c	*Witchellia "pseudoromani" MS*	Ovalis	
Bj-6b	*Fissilobiceras gingense*		
Bj-6a	*Euhoploceras zugophorum*		
Bj-5	*Witchellia romanoides*		
Bj-4	*Bradfordia inclusa*		
Bj-3	*Hyperlioceras subsectum*	Discites	
Bj-2b	*Hyperlioceras rudidiscites*		
Bj-2a	*Hyperlioceras walkeri*		
Bj-1	*Hyperlioceras politum*		

Fig. 3. The ammonite faunal horizons of the Inferior Oolite of Dorset–Somerset. (**a**) Upper Inferior Oolite; (**b**) Middle Inferior Oolite; (**c**) Lower Inferior Oolite. Note: the labelling of some horizons with additional letters a, b, c . . . reflects the insertion of further horizons recognized since the first list was drawn up in 1990, so as not to have to change the main framework of numbering introduced in that list. The letters imply no reduction or other inequality of rank and importance.

(c)

		Standard zonation	
	AALENIAN	Zones	Subzones
Aa-16	*Euhoploceras acanthodes*	Concavum	Formosum
Aa-15	*Graphoceras formosum*		
Aa-14	*Graphoceras concavum*		Concavum
Aa-13	*Graphoceras cavatum*		
Aa-12	*Brasilia decipiens*	Bradfordensis	Gigantea
Aa-11	*Brasilia gigantea*		
Aa-10	*Brasilia bradfordensis, similis*		Bradfordensis
Aa-9	*Brasilia bradfordensis, baylii*		
Aa-8	*Brasilia bradfordensis, subcornuta*		
Aa-7	*Ludwigia murchisonae*	Murchisonae	Murchisonae
Aa-6	*Ludwigia patellaria*		
Aa-5	*Ludwigia obtusiformis*		Obtusiformis
Aa-4	*Ancolioceras opalinoides*		Haugi
Aa-3	*Leioceras bifidatum*	Scissum	
Aa-2	*Leioceras lineatum*		
Aa-1	*Leioceras opalinum*	Opalinum	

Fig. 3. (*Continued.*)

What the faunal horizons look like in the field may be seen in Fig. 4, which illustrates three sections in weathering profile. Their details provide the evidence for the reconstruction of a long and complicated *lithochronology*, the residual record left by many competing processes, each with its characteristic rate acting for a specific duration, often in cyclic and repetitive sequences. Some important processes are listed and categorized in Table 3. The Inferior Oolite shows records of all of them, although no systematic analysis appears yet to have been published. Unfortunately, in any attempt to assess the durations (δt) the effects of the destructive processes dominate, largely erasing those of the constructive processes. Although the successions are all well bedded, in almost no beds have any of the finer sedimentary structures survived intensive bioturbation by deep burrowers (S7). It is therefore often not possible even to claim that the top of a bed must be younger than the bottom, and all of it must be regarded as effectively synchronous with the last bioturbational turnover. The effects of S9 and S10 are reflected in the sharp partings and erosion-planes that separate beds, but again, there is no way of estimating their durations. Attempts to assess the 'stratigraphic completeness of the record' in the Inferior Oolite sedimentologically by such methods as those proposed by Schindel (1980, 1982) or Sadler & Strauss (1990), which base their time-scales on sedimentation-rates (S1 and S2), are therefore inappropriate.

How the succession has been built up from the records of individual sections is shown in Fig. 5. The 'gaps united by thin bands of deposit' are evident. The time-durations that left no record (S8) or whose records have been destroyed (S9, 10) are often greater than the time intervals δt_{ij}, between the biochrons of adjacent faunal horizons. What is less evident, however, is any coherent relationship between the lengths of the gaps and their positions, such as might be explicable by simple sequence stratigraphy—and this across a distance of only 80 km in a single basin. A large non-sequence at one locality may be correlated with several

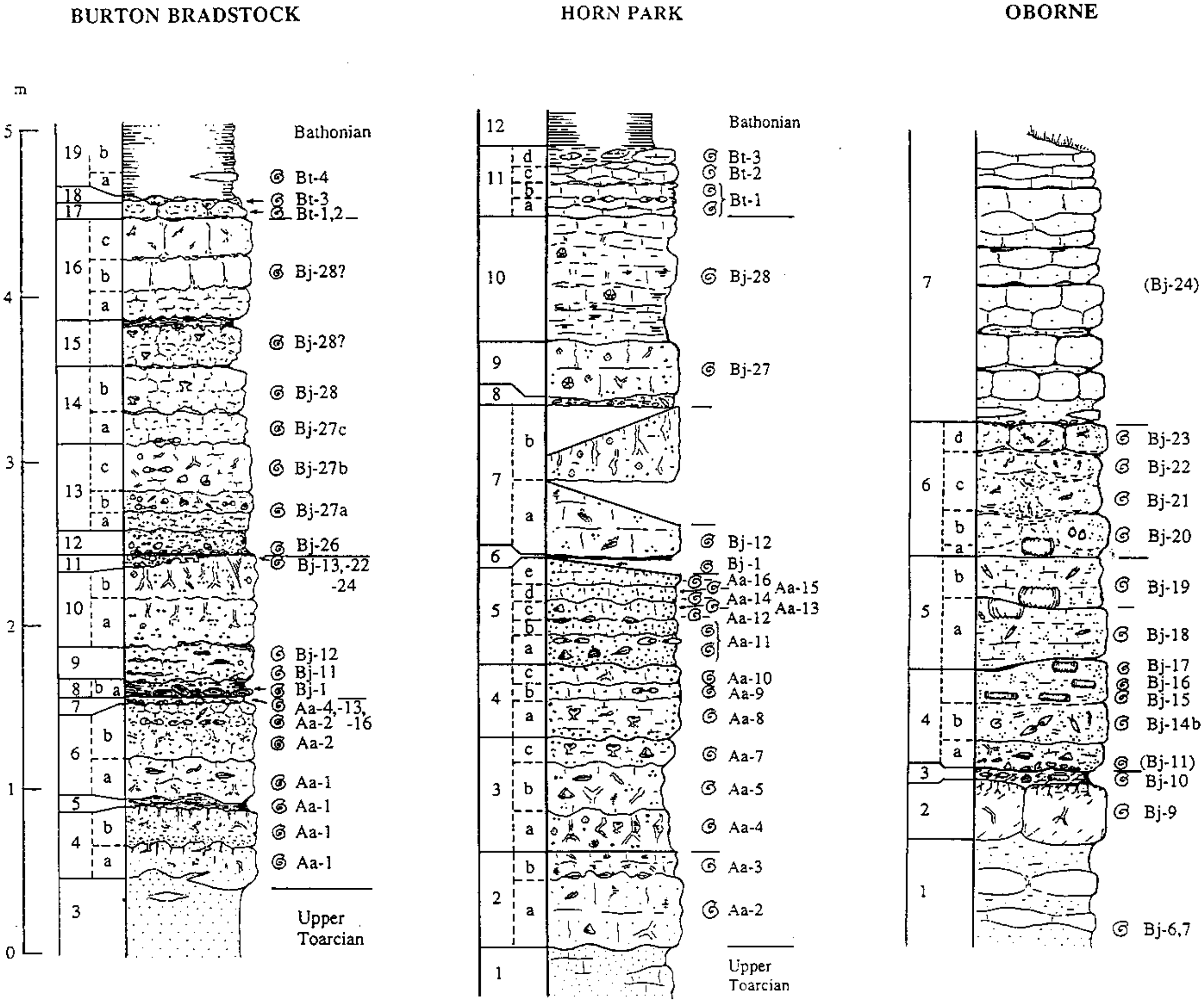


Fig. 4. Three sections in the Inferior Oolite of Dorset shown in weathering profile (nos 1, 4 and 11 in Fig. 5).

Table 3. *Ten important processes in sedimentary lithochronology*

Positive evidence	
S1	Constructive: accumulation of sediment by local chemo- or biogenesis—autochthonous
S2	Constructive: accumulation of sediment by transport—allochthonous
S3	Constructive: encrustation, chemical or epibiontic
S4	Diagenetic: compaction
S5	Diagenetic: differential concretionary cementation, e.g. of body-fossil or burrow infills
S6	Diagenetic: general induration by cementation or recrystallization
S7	Destructive: bioturbation
Negative evidence	
S8	Neutral: non-deposition, omission surfaces
S9	Destructive: differential removal of unconsolidated sediment, winnowing: lag deposits, conglomerates
S10	Destructive: erosion of consolidated sediment: erosion planes, non-sequences, pebble conglomerates

The time-duration of each process may be indicated symbolically as $\delta t(\mathrm{S1})$, $\delta t(\mathrm{S2})$, $\delta t(\mathrm{S3})$ . . . etc.

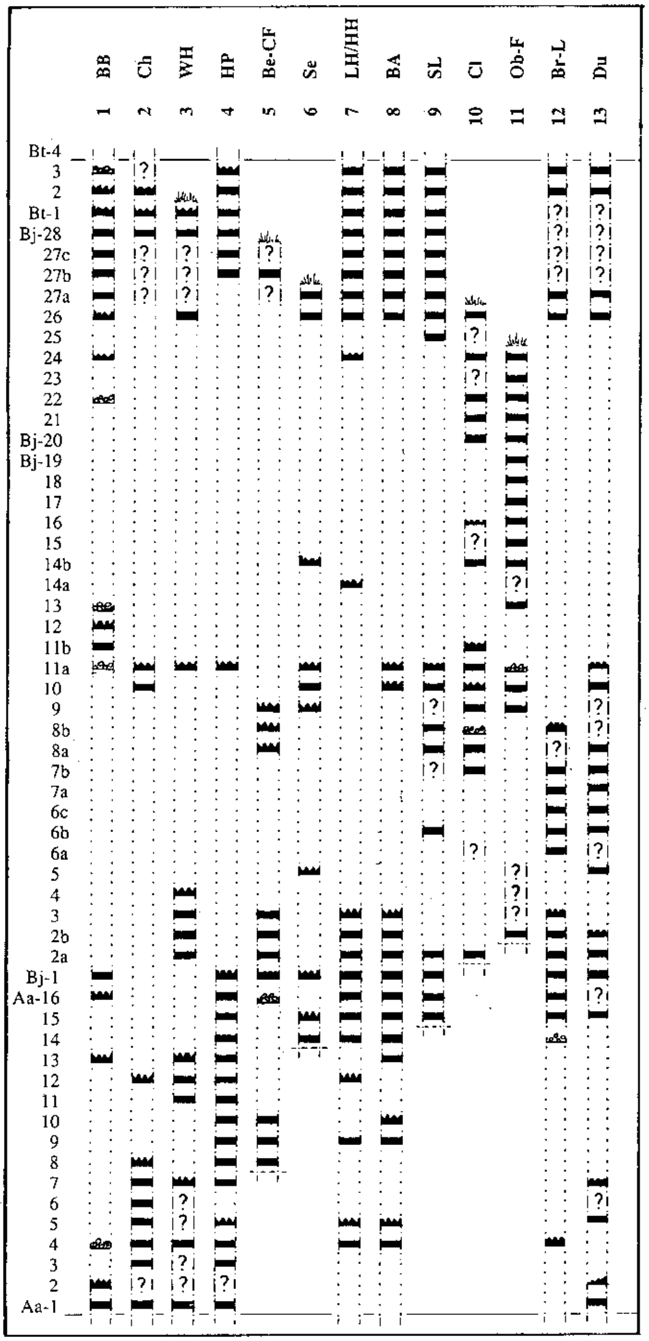


Fig. 5. The ammonite faunal horizons recognized in 13 sections of the Inferior Oolite of Dorset and Somerset. The horizons are labelled at the left as in Fig. 3. The localities, across the top, are as follows: 1 BB: Burton Bradstock (Fig. 4). 2 Ch: Chideock, Quarr Hill. 3 WH: Waddon Hill, W of Beaminster. 4 HP: Horn Park, W of Beaminster (Fig. 4). 5 Be-CF: Cockroad Farm, W of Beaminster. 6 Se: Seavington St Mary. 7 LH/HH: Louse Hill and Halfway House, W of Sherborne. 8 BA: Bradford Abbas, railway-cutting and East Hill, SW of Sherborne. 9 SL: Sandford Lane, N of Sherborne. 10 Cl: Clatcombe, Upper and Lower, N of Sherborne. 11 Ob: Oborne, Frogden Quarry, NE of Sherborne (Fig. 4). 12 Br-L: Bruton, Lusty railway-cutting. 13 Du: Dundry, SE of Bristol. Question-marks: probably present but not yet identified. Small circles: former presence indicated by pebble lags in conglomerates.

non-sequences of different ages elsewhere: such is the nature of negative evidence.

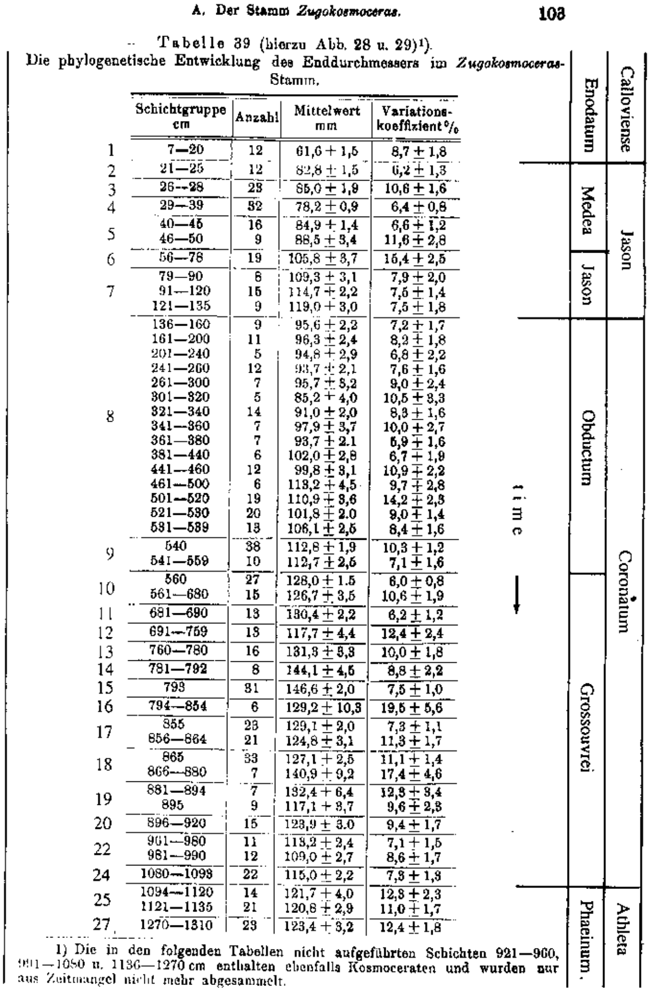
The Oxford Clay of Peterborough

Brinkmann's epic study of the Oxford Clay of Peterborough (1929) remains another of the all-time classics of stratigraphy, undiminished both in its exposition of principles and in its relevance today. It gains additionally in interest when looked at in comparison with Buckman's analysis of the Inferior Oolite. Both shared the same goals: the biochronology of ammonites at the attainable limits of time-resolution and its interpretation in terms of biological evolution. But they differ greatly in the methods used, imposed by differences of stratigraphical facies that lie at almost the opposite extremes of the range. The two studies therefore strongly complement each other in contrasting techniques but arrive at general results that turn out to be very similar.

The Lower Oxford Clay (now Peterborough Member) around Peterborough is 17 m thick. It consists at first glance of monotonous, grey, fine-grained siliclastic silts and clays (process S2 of Table 3) with subordinate carbonate and organic matter (mainly S1). Its structure ranges from fissile paper-shales to structureless mud-rock, in both of which macrofossils, notably ammonites, although crushed (S4), are still largely unbroken and horizontal. Bioturbation (S7) was thus not sufficiently vigorous to destroy the microbiostratigraphy. Looked at more closely, however, the succession is subdivided into more or less sharply bounded beds differing in colour and other details of lithology, ranging in thickness from 4 cm to 4 m. A recently revised description (Hudson & Martill 1994) lists a succession of 55 beds. The boundaries are often marked by shell-accumulations that certainly indicate sedimentary breaks, probably of omission (S8) and possibly winnowing (S9), but erosion proper (S10) does not appear to have been important. The sedimentology is therefore quite different from that of the Inferior Oolite, and the thickness of a bed may well be related to the time-duration of its formation.

Through some 13 m of these clays, Brinkmann and an assistant over a period of seven weeks collected 3000 ammonites of the genus *Kosmoceras*, recording the level of each to the nearest centimetre. (Only those who have attempted to repeat this exercise can appreciate the prodigious labour involved. Arkell, in private, did sometimes wonder whether the results were as real in the rocks as they appeared to be in print, just as others had expressed doubts about Buckman's descriptions of the Inferior Oolite. And just as in Buckman's work, re-examination has fully confirmed Brinkmann's). In 2000 of these shells, biometric characters such as dimensions and numbers of ribs were measured. The data were however not sufficiently numerous at centimetre height-intervals to be statistically significant. They were therefore combined into lots over larger stratigraphical intervals: either, in most cases, over the whole of the bed or, in a few others, over ranges of 1–40 cm within a bed. These lots were then evaluated statistically to give sets of mean values.

One of these sets is shown in Fig. 6, that of the mean maximum diameter of the adult macroconchs, *Zugokosmokeras*. The horizontal lines represent the boundaries between beds that were lithostratigraphically not further divisible. These beds have been numbered here for



A. Der Stamm *Zugokosmoceras.* 103

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	82,8 ± 1,5	6,2 ± 1,3
3	26—28	23	85,0 ± 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 ± 1,2
	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	6	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	94,8 ± 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	6,9 ± 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	38	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	7,3 ± 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	12,3 ± 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	1080—1093	22	115,0 ± 2,2	7,3 ± 1,3
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 ± 1,8

[1] Die in den folgenden Tabellen nicht aufgeführten Schichten 921—960, 991—1080 u. 1136—1270 cm enthalten ebenfalls Kosmoceraten und wurden nur aus Zeitmangel nicht mehr abgesammelt.

Fig. 6. The evolution of the adult diameter *d* of macroconch *Kosmoceras* (*Zugokosmokeras*) through the Oxford Clay of Peterborough (from Brinkmann 1929). Columns from the left: arbitrary numbering of beds as in Fig. 2; stratigraphic heights in cm; number of specimens measured; mean value of diameter, *d*; standard deviation. At the right: standard chronostratigraphic classification.

convenience (although this is not the numbering used elsewhere) and their positions in the standard zonation of the Callovian are shown in Fig. 2. Successions of such mean values were then tested for continuity and linear regression ('trends') with stratigraphical height. There were statistically quite clear examples of breaks in the former, e.g. at +135/136 cm and at +559/560 cm. But neither statistically significant breaks nor linear trends could be found within a bed, e.g. bed 8, 136–460 cm. The beds are therefore also biostratigraphically not further subdivisible within the sensitivity of digitized single-character statistical biometry. This is confirmed by the non-measurable, visual characteristics assessed by eye. The assemblage of shells from each bed has its own subtle characteristic aspect that no measurement has revealed, so that even assemblages that were biometrically unresolved can readily be distinguished by eye. The beds conform almost ideally to the definition of faunal horizons, and the ammonite biochronology of Peterborough can thus be discussed in the same terms as that of the Inferior Oolite. It is however more direct. The faunal horizons are all in immediate succession at one locality, instead of having to be assembled from many, and they are all based on the phyletic transients of only a single dimorphic lineage, that of the genus *Kosmoceras*. The question whether the morphological discontinuities at bed boundaries reflect stratigraphical gaps, or evolutionary punctuation, or both, and if the former, how large the gaps would have to be, were addressed by Brinkmann himself and revived by Raup & Crick (1981, 1982). They could not be resolved on the evidence of Peterborough alone, but the intercalation of further faunal horizons elsewhere (Callomon 1968) showed that at least in many cases, non-sequences are the major factor. The faunal horizons at Peterborough must therefore also be regarded biochronologically as a series of discrete snapshots well spaced in time.

Almost identical analyses have been applied to successions of trilobites in the Ordovician of south Wales (Sheldon 1987, 1988). Pygidial rib-counts and measurements of carapace width were made on over 3300 specimens, representing eight parallel lineages, collected in fine-grained shales from 400 stratigraphical intervals of average thickness 23 cm, totalling 90 m of sediment. Yet, as at Peterborough, the data had to be combined into lots over more extended intervals to give statistically well-defined means. These were finally presented in the form of clumped values from eight discrete, effectively instantaneous faunal horizons. Comparing the mean values from what are now effectively successive transients of the eight lineages, in some cases there are significant discontinuities, in many others not. Whether results from such a punctuated stratigraphical record can be claimed to support gradualistic evolution becomes very much a matter of the definition of 'gradualistic'.

Estimates of biostratigraphical time-resolution

We come now to the final step, the estimation of time-intervals in absolute terms, in years. There have been many attempts to date the standard geological column radiometrically and revisions appear almost annually. They differ among themselves for a variety of reasons, principally the residual uncertainties in individual age-determinations and the still sparse framework of secure anchor-points in the record. In the Phanerozoic, these differences can lie in the range of 1–5%. The scale shown at the left in Fig. 2 is chosen arbitrarily to be the Cambridge Time-Scale (CTS 89) of Harland *et al.* (1990). Radiometric age-determinations within the Jurassic are still not good enough to date with any reliability the boundaries of lower subdivisions, at Stage level (V) and below; so these are shown diagrammatically on an equal-interval approximation. In calculating durations in the Jurassic, only System boundary-ages have therefore been used. Elsewhere, estimates may be based on Series boundaries and, exceptionally, Stage boundaries as well, where their dating appears to be sufficiently reliable.

Estimates of some time-durations and time-intervals are collected in Table 4. In reading this, the distinctions between three kinds of time-estimates must be borne in mind.

The first of these is the time-duration, $\Delta t = (t_2 - t_1)$, of the largest of the units being considered (System or Series) derived from the radiometric estimates of the ages of its beginning (t_1) and end (t_2). These ages are the basic

Table 4. *Estimates of biochronological time-intervals*

Unit	Number of units n	Average duration $\overline{\Delta t_n}, \overline{\delta t_n}$	Secular resolving power $\bar{R} = \bar{t}/\overline{\Delta t}, \overline{\delta t}$ (b)
Jurassic (146–208 Ma BP)			
Standard, NW Europe			
System	1	$\Delta t = 62$ Ma	
Stages	11	$\overline{\Delta t_n} = 5.6$ Ma	
Zones: ammonites	76	820 ka	220
Subzones: ammonites	*c.* 155	400 ka	440
Horizons: ammonites	say 450	$\overline{\delta t_n} = 140$ ka	1260
Cf. S. S. Buckman (1893–1929)			
Ages: ammonites	47		
Hemerae: ammonites	375		
Other groups			
Zones: dinoflagelates (a)	16	$\overline{\Delta t_n} = 3.9$ Ma	45
nannoplankton (a)	22	2.8 Ma	63
Cretaceous (65–146 Ma BP)			
Standard, Europe, all			
System	1	$\Delta t = 81$ Ma	
Stages	12	$\overline{\Delta t_n} = 6.7$ Ma	
Zones: ammonites	*c.* 56	1.4 Ma	73
foraminifera (a)	37	2.0 Ma	52
calcareous nannoplankton (a)	25	3.0 Ma	34
Standard Valanginian–Hauterivian, N Europe			
Stages	2	$\overline{\Delta t_n} = 4.0$ Ma	
Zones: ammonites (c)	13	615 ka	220
Subzones: ammonites	21	380 ka	360
Standard Upper Cretaceous, N America			
Stages	6	$\overline{\Delta t_n} = 5.3$ Ma	
Zones/Subzones: ammonites (d)	54	590 ka	140
Triassic (208–245 Ma BP)			
Standard, Tethys–N America			
System	1	$\Delta t = 37$ Ma	
Stages	8	$\overline{\Delta t_n} = 4.6$ Ma	
Zones: ammonites (e)	32	1.2 Ma	195
Permian (245–290 Ma BP)			
Standard, Russia			
System	1	$\Delta t = 45$ Ma	
Stages	6	$\overline{\Delta t_n} = 7.5$ Ma	
Zones (o): fusulinids, Japan (a)	7	6.5 Ma	41
ammonites, Canada (a)	9	5 Ma	54
Carboniferous (290–363 Ma BP)			
Standard, all			
System	1	$\Delta t = 73$ Ma	
Stages (a)	25	$\overline{\Delta t_n} = 2.9$ Ma	
Zones: goniatites (a)	20	3.6 Ma	90
forams, Donets (a)	29	2.5 Ma	130
Regional, Namurian, England		$\Delta t =$ *c.* 15 Ma	
'Zones' (Stages)	7	$\overline{\Delta t_n} = 2.1$ Ma	
Horizons: goniatites (f)	45	$\overline{\delta t_n} = 330$ ka	975
Devonian (363–409 Ma BP)			
Standard, all			
System	1	$\Delta t = 46$ Ma	
Stages (a)	7	$\overline{\Delta t_n} = 6.6$ Ma	
Zones: conodonts (g)	28	1.6 Ma	235
Upper Devonian (a)		$\Delta t = 14$ Ma	
Zones: conodonts (h)	15	$\overline{\Delta t_n} = 930$ ka	395
Horizons: conodonts (h)	30	$\overline{\delta t_n} = 470$ ka	790
Middle–Upper Devonian		Δt 23 Ma	
Zones: ammonoids (i)	19	$\overline{\Delta t_n} = 1.2$ Ma	310
Horizons: ammonoids (j)	36	$\overline{\delta t_n} = 420$ ka	880

Table 4. (*Continued.*)

Unit	Number of units n	Average duration $\overline{\Delta t_n}$, $\overline{\delta t_n}$	Secular resolving power $\bar{R} = \bar{t}/\overline{\Delta t}, \overline{\delta t}$ (b)
Silurian (409–439 Ma BP)			
Standard, all			
System	1	$\Delta t = 30$ Ma	
Stages (a)	8	$\overline{\Delta t_n} = 3.7$ Ma	
Zones: graptolites (k)	30	1.0 Ma	425
conodonts (a)	12	2.5 Ma	170
Ordovician (439–510 Ma BP)			
Standard, all			
System	1	$\Delta t = 71$ Ma	
Stages (a)	19	$\overline{\Delta t_n} = 3.7$ Ma	
Zones: trilobites, UK (l)	*c.* 34	2.1 Ma	230
graptolites (a)	21	3.4 Ma	140
Cambrian (510–545? Ma BP)			
Middle-Upper, Standard (n)		$\Delta t = c.\ 25$ Ma	
Stages	6	$\overline{\Delta t_n} = 4.2$ Ma	
Zones: trilobites, UK (m)	35	$\overline{\Delta t_n} = 710$ ka	730
trilobites, Australia (m)	46	540 ka	970
trilobites, USSR (m)	27	930 ka	560

(a) Harland *et al.* (1990); (b) $\bar{t}$ (the average age of a System) $= (t_2 + t_1)/2$; (c) Kemper (1978) N Germany; (d) Obradovich & Cobban (1975); (e) Tozer (1984); (f) Ramsbottom (1977) and Riley (in Cope 1993); (g) cited in (a), see also Aldridge (1987), Sweet (1988); (h) Ziegler (1974), Ziegler & Sandberg (1990); (i) cited in (a), and House & Price (1985); (j) Becker (1993); (k) Rickards (1976); (l) cited in (a), and Thomas *et al.* (1984); (m) see (l) and Palmer (1977); (n) post-Tommotian trilobitiferous Cambrian only, from recent radiometric revisions by Bowring *et al.* (1993), Landing (1994), that depart significantly from the estimates in (a) and retaining the older age for the base of the Ordovician unchanged; for a recent revision of the whole of the Phanerozoic chronometric time-scale, see Odin (1994); (o) estimates of zonal durations in the Permian are still determined almost wholly by the fragmentary and highly incomplete state of the biostratigraphic record, and do not therefore say much about the intrinsic biochronological resolving-power of its guide-fossils.

numerical input to what follows. Their average gives the mean age of the unit, $\bar{t}$. The duration Δt is the homologue of what in lithochronological resolution-analysis has come to be called the *temporal scope* of an analysis (Schindel 1982, summarized e.g. by Skelton 1993).

The second, intermediate kind is the mean duration $\overline{\Delta t_{\mathrm{i}}}$ of the n finer standard chronostratigraphic units into which Δt may be subdivided ($\mathrm{i} = 1, \ldots n$): the mean duration of a Stage, Zone or Subzone within a System, etc.

The third kind is the smallest time-interval that can be resolved by fossils, the secular resolution of the biochronology, the mean time-interval $\overline{\delta t_{\mathrm{ij}}} = \Delta t/n$, where $n = n(\max)$, the maximum number of moment that can be resolved. It is the analogue of *acuity* in microstratigraphical analysis of lithochronology (Schindel 1982, or Skelton 1993). (The analogy is limited, for the microstratigraphical acuity m has the physical dimensions of a time-duration, that of the accumulation-time of an observed thickness h of sediment: $m = h/(\mathrm{d}h/\mathrm{d}t)$, where the accumulation-rate $\mathrm{d}h/\mathrm{d}t$ is assumed to be constant and continuous. In contrast, the secular resolution $\overline{\delta t_{\mathrm{ij}}}$ is a time-interval between identified instants, a time-duration of effectively negative evidence).

Lastly, it is interesting to calculate the secular resolving-power

$$R_t = \overline{t_{\mathrm{ij}}}/\overline{\delta t_{\mathrm{ij}}}$$

of the guide-fossils used to distinguish the faunal horizons i and j, of mean age $\overline{t_{\mathrm{ij}}}$, as a means of comparing them in the rocks of similar ages, or at different times during the Phanerozoic. The concept can be extended to the higher chronostratigraphical units, the Zones and Subzones, by noting that their mean durations $\overline{\Delta t_{\mathrm{i}}}$ are the same as the mean intervals of their mean ages,

$$\overline{\Delta t_{\mathrm{i}}} = (\bar{t}_{\mathrm{i}} - \bar{t}_{\mathrm{j}})$$

Finally, as t_{i}, the age of a faunal horizon, changes during the course of a System, so does R_t, even at constant resolution δt_{ij}. It suffices, therefore, also to average R_t, over the whole of the largest unit considered, of mean age t:

$$\overline{R_t} = \bar{t}/\overline{\delta t_{\mathrm{ij}}}$$

The values are given in the last column of Table 4. They show how fossils of only moderate resolving-power can achieve time-resolutions in the Cretaceous comparable to those of high-powered trilobites in the Cambrian. The resolving-power of magnetostratigraphy in the Tertiary is even less.

Fine time-resolution and time-correlation are now also being achieved in various parts of the geological column by physical methods not directly dependent on radiometric dating. They fall into two classes.

In the first class, the time-dependence of the quantity being measured is periodic and the time-resolution that of the periodicity. Best-known is magnetostratigraphy. The signal is a binary N-R bar-code whose elements vary in relative lengths that have to be determined against some other time-dependent process, assumed to be linear and continuous - in this case, sea-floor spreading (see for example Mussett & McCormack 1993). It has found greatest application in the Tertiary (reviewed in Harland *et al.* 1990). Time-resolution lies in the range of 0.1 - 1 Ma which, in rocks 50 Ma old, can give resolving-powers of 50–500. But the limitations on practical applications lie in being able to identify the chron in which the age of a particular bed lies. This requires additional evidence: either from the pattern of an extended N-R sequence, assuming it to be free of gaps or, again, from fossils (e.g. Ali *et al.* 1993). The other method in this class is the periodic chemostratigraphy of the stable isotopes of the organic metabolic elements, carbon and oxygen, reflecting climatic fluctuations that are at least in part the response to Milankovitch cycles of insolation. The time-resolution achieved in the Pleistocene is spectacular: 20 ka in rocks up to 1.6 Ma old (resolving-power 800; Weaver 1993). But the general limitations are similar to those of magnetostratigraphy—the need to locate individual levels in the sequence. Both methods are therefore best suited for use in quasi-continuous pelagic sedimentary successions, such as deep-sea sediments or polar ice-caps (Anklin *et al.* 1993; Dansgaard *et al.* 1993) Evidence of Milankovitch cyclicity is growing in pre-Pleistocene sediments (Cretaceous, Kemper 1987; Lias, Weedon & Jenkyns 1990; and see review by Schwarzacher 1993).

In the second class, the value of a measurable physical quantity varies smoothly, although not necessarily linearly, with time. The best examples are again chemostratigraphic: stable isotope compositions of elements sequestered from sea-water and subsequently preserved unchanged in the sediments, usually in calcareous fossils. ^{13}C and ^{18}O have been successfully used in the Upper Cretaceous (Jenkyns *et al.* 1994) but appear to be more useful for correlating short anomalous 'events' than for general purposes of dating and time-resolution. The most promising element so far is strontium. The marine ratio of ^{87}Sr/^{86}Sr in the reservoir of the world's oceans is expected to be least sensitive to short-term climatic fluctuations and, in such a heavy element, the ratio as then recorded in calcareous fossils to be undistorted by metabolic kinetic isotope-effects. Curves for the Late Cretaceous (McArthur *et al.* 1993, 1994) and Early Jurassic (Jones *et al.* 1994) are indeed found to be smooth. Time-resolutions attainable from their gradients are estimated to be 0.5–0.8 Ma in the former (resolving-power *c.* 100–160 in the Campanian) and 0.5–1.0 Ma in the latter (resolving-power 200–400 in the Sinemurian)—comparable to 1–2 standard ammonite Subzones.

Practical applications

The refinement of biochronology to its attainable limits, with the finesse of geological time-resolution it makes possible, continues to find three important applications, to each of which Buckman made seminal contributions.

The first is the historical one of general stratigraphical time-correlation, transcending lithostratigraphical boundaries and facies-changes. Such correlations play probably their most important role today in basin-analysis, particularly in sequence-stratigraphies, in which sharp time-controls on facies-equivalences and non-sequences are crucial. The rocks provide the primary evidence of sedimentary processes spanning an enormous dynamic range of time-scales. Their characteristic periods range from those reflected in sequence-boundaries and systems-tracts at the upper end (10^5–10^7 years), to those of cross-bedded foresets, tempestites and slumps at the lower (10^{-2}–10^{+2} years). As we saw earlier, one of the first to demonstrate how the biochronology of ammonites can descend into this regime of time-scales was Buckman himself, in the case of the Bridport-Yeovil-Midford Sands of southern England. One of the most ambitious and detailed modern sequence-stratigraphic classifications of a whole System must be the recent description of the Jurassic of the Normandy–Wessex Basin by Rioult *et al.* (1991). It rests entirely on ammonite biochronology at zonal and subzonal resolution.

The second application is to another age-old problem, that of estimating the 'completeness of the geological record'. By this is meant theoretically the fraction of the total, continuous time-duration Δt between two specified moments t_1, t_2 actually recorded in the rocks. But as we have seen, bio- and chrono-stratigraphy do not give us methods of measuring continuous time-durations: they allow us only to distinguish events at minimum time-intervals apart, δt. The operational definition of completeness has therefore to be modified (Sadler & Strauss 1990): it is the fraction of all the time-intervals δt between t_1 and t_2 that have left a recognizable record in the rocks—any record, no matter how short in itself.

In lithostratigraphy, in the special case of discontinuous but still 'complete' stratified sequences, the measure of δt is the acuity, referred to above. It is calculated assuming uniformitarian estimates of rates of sedimentation (dh/dt) taken from recent observations (Schindel 1982). The completeness is then deduced from the ratio of the observed total thickness of all the strata between time-planes t_1, t_2, to what it would have been, had sedimentation been continuous. And perhaps not surprisingly, it is found that the greater the relative acuity, $\Delta t/\delta t$, the less complete the record appears to become.

In biostratigraphy, the analogue of the acuity is the secular biochronological resolution of successive faunal horizons, δt_{ij}, or of whatever coarser unit is used. The numbers taken from the record of the Inferior Oolite shown in Fig. 5 are collected in Table 5. If by means of fossils the presence or absence only of Stages or Substages could have been recognized, the record would have appeared to be everywhere 100% complete. If standard Zones could be resolved, the record would have appeared on average to be only 73% complete. And at the resolution of the faunal horizons recognized today, the record is on average only 40% complete. But there is here an additional difficulty in that there is no independent way of estimating the maximum number of distinguishable faunal horizons ultimately to be expected between any two given time-planes t_1, t_2. The number depends on the state of knowledge: as we have seen, in the Inferior Oolite it has grown from 18 to 56. A section with the same nine faunal horizons would have changed from being biochronologically 50% complete in 1910 to only 16% complete today. As the biological record becomes more complete as a whole, so the geological record becomes more incomplete, which is precisely what Buckman said.

How do biochronological estimates of completeness based on ammonites compare with those obtained from

Table 5. *The 'completeness of the geological record' in the Inferior Oolite as indicated by ammonite biochronology*

Localities (Fig. 5)	1 BB	2 Ch	3 WH	4 HP	5 Be-CF	6 Se	7 LH/HH	8 BA	9 SL	10 Cl	11 Ob	12 Br-L	13 Du	Average
Resolution: Stages										†	†			
scope*	3	3	3	3	3	3	3	3	3	1	2	3	3	
number	3	3	3	3	3	3	3	3	3	1	2	3	3	
% completeness	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Resolution: Zones					†	†			†					
scope	14	14	14	14	11	9	14	14	10	8	7	14	14	
number	11	8	11	9	6	8	9	9	8	8	7	9	11	
% completeness	78	57	78	64	43	89	64	64	80	100	100	64	78	74
Resolution: faunal horizons														
scope	56	56	54	56	45	37	56	56	42	32	29	56	56	
number	20	18	21	23	14	10	21	22	20	22	20	22	29	
% completeness	36	32	39	41	31	27	38	39	48	69	69	39	52	43

* Only the Lower Bathonian is represented in the Inferior Oolite. But even at Substage level (Lower and Upper Aalenian, Lower and Upper Bajocian, Lower Bathonian), at which the maximum scope would be 5, the representation would be everywhere 100% complete.

† These sections have exposed only parts of the Inferior Oolite, either cut off at the tops by erosion or covered at the base.

Numbers of faunal horizons as in Fig. 5; those shown as queried taken as present.

microstratigraphical lithochronology? Both kinds of estimate can be made on the Oxford Clay of Peterborough (Figs 2 and 6). Taking the figures of average durations from Table 4, the faunal horizons of the Jason and Coronatum Zones would represent time-intervals δt_{ij} of 70 000 years. But this succession of faunal horizons is here so far the most detailed we have. At the time-resolution of faunal horizons, therefore, the Middle Oxford Clay of Peterborough appears to be biochronologically 100% complete. A microstratigraphical analysis of the same succession has been given by Schindel (1982), at time-resolutions of 10 000, 1000 and 100 years. The estimates of lithochronological completeness are 14%, 4% and 3% respectively. As Buckman would have put it, large gaps joined by exceedingly thin layers of sediment, even when the fossil record appears to be complete.

Finally, there is the third field of enquiry to which the ultimate refinement of biochronology makes an indispensable contribution. It is the mapping of patterns of biological evolution in the fossils themselves, the reconstruction of their lineages in phylogenetic classification: its use, as Buckman put it, 'in what I may call "palaeo-biology"'. But that is another story.

Conclusion

I have tried in this review to show how the refinement during the last hundred years of Jurassic geochronology by means of fossils has followed two distinct routes. In the first, going back to the founding fathers of geology, a geological column regarded to be at all times a complete representation of a continuous passage of time is subdivided successively into ever-thinner slices, the units of a standard chronostratigraphy that forms the basis of reference against which rocks are dated through correlation by means of fossils. It is therefore most widely applied to problems involving time-correlations over distances, and the precision with which this can be done at subzonal resolution is impressive. To stand on beds, never more than a few feet thick, of clays at Brora on the east coast of Scotland, or on sands at South Cave in Humberside, or shales at Peterborough and Weymouth, or limestones near Poitiers, on the Meuse or in the Ardèche, or ironstones near Hanover, or clays near Bayreuth, or ironshot oolites in the Argovian Jura, or sandstones on the Vistula, or clays in the Oka valley, east of Moscow, or marly limestones in the Caucasus or trans-Caspian Turkmenistan—knowing that in each case one is in the Enodatum Subzone of the Calloviense Zone of the Lower Callovian of the Middle Jurassic, in sediments whose age spanned perhaps only 400 ka: who could fail to be moved? Clearly, such time-control is adequate for most meso- and macrogeological problems.

The emphasis in the second route is not so much on time-correlation as on time-resolution. It was introduced by Buckman just a hundred years ago, and its results are equally impressive. To go into any quarry showing a few metres of Inferior Oolite in Dorset or Somerset, and to be able to assign any of its beds yielding ammonites to one or other of some 55 chronologically distinct levels, must also be cause for wonder. Both methods in the end imply an ability to distinguish geological events, and the finesse with which they can do so, discussed above, is comparable. The distinction between them may appear to be more a theoretical one, of principle, than one of immediate practical consequence. This is reflected in much of the stratigraphical literature, in which the distinction is rarely considered and even more rarely acted upon, with apparently little loss. Failure to bear this distinction in mind may however dictate, even if unconsciously, a choice that can fundamentally prejudice our whole approach to a geological problem. It relates to the question of completeness, discussed above, and how we deduce it (or visualize it) from graphical representations of field evidence.

When we date beds in a section, such as those shown in Fig. 4, by assigning them to standard Zones, a particular Zone is either present, shown as a bed or series of beds extending over some lithostratigraphical range, or absent, shown as a horizontal line of zero thickness. The temptation is to assume that the Zones that are recorded are tolerably complete. Looking at a graphical representation, the impression is one of long periods of sedimentation separated by brief non-sequences in the partings between beds. This is the representation that appears in chronostratigraphical compilations of regional stratigraphy, such as the Geological Society's Correlation Charts (e.g. Cope 1980*a, b* for the British Jurassic). It is the graphical representation that appears in many sequence-stratigraphical analyses, such as for instance that of the Jurassic of the Normandy–Wessex Basin by Rioult *et al.* (1991). It also surfaces widely in conventional range-charts of fossils. In contrast, the method of faunal horizons makes no *a priori* assumptions about completeness: rather the reverse, that thicknesses of rock notwithstanding, most of the time lies in the gaps, in the intervals between the brief events that are recorded (Fig. 5). The choice of interpretation bears some resemblance, therefore, to that of another classical problem. Faced with the same evidence, the optimist claims that the glass is half full, the pessimist that it is half empty. It was Buckman's achievement to have shown by means of fossils that in the Jurassic with which he was familiar, the pessimists have it. I fear his conclusions apply to Phanerozoic stratigraphy quite generally.

I am indebted to H.S. Torrens for much biographical information on the Buckman family. The details shown in Figs 3–5 incorporate many new and as yet unpublished results obtained in recent years during field-work carried out in collaboration with R.B. Chandler, A.E. England, W.E. Jones (London), J.G. Huxtable (Taunton) and D. Sole (Lyme Regis), whose help is gratefully acknowledged.

REFERENCES

Aldridge, R. J. 1987. *Palaeobiology of Conodonts.* Ellis Horwood, Chichester, for the British Micropalaeontological Society.

Ali, J. R. 1993. Magnetostratigraphic calibration of early Eocene depositional sequences in the southern North Sea basin. *In*: Hailwood, E. A. & Kidd, R. B. (eds) *High Resolution Stratigraphy.* Geological Society London, Special Publications, **70,** 99–125.

Anklin, M., and 39 other members of the Greenland Ice-core Project 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. *Nature,* **364,** 203–207.

Arkell, W. J. 1933. *The Jurassic System in Great Britain.* Oxford.

—— 1946. Standard of the European Jurassic. *Bulletin of the Geological Society of America,* **57,** 1–34.

—— 1956. *Jurassic Geology of the World.* Oliver & Boyd, Edinburgh & London.

Bather, F. A. 1927. Biological classification past and future. *Quarterly Journal of the Geological Society of London,* **83,** lxii-civ.

Becker, R. T. 1993. Anoxia, eustatic changes, and Upper Devonian to lowermost Carboniferous global ammonoid diversity. *In*: House, M. R. (ed.) *The Ammonoidea.* Systematics Association Special Volume, **47** Clarendon Press, Oxford, 115–164.

Birkelund, T., Callomon, J. H. & Fürsich, F. T. 1984. The stratigraphy of the Upper Jurassic and Lower Cretaceous sediments of Milne Land, central East Greenland. *Bulletin Grønlands Geologiske Undersøgelse,* **147,** 1–56.

Bowring, S. A., Grotzinger, J. P., Isachsen, C. E., Knoll, A. H., Pelechaty, S. M. & Kolosov, P. 1993. Calibrating rates of Early Cambrian evolution. *Science,* **261,** 1293–1298.

Brinkmann, R. 1929. Statistisch-biostratigraphische Untersuchungen an mittel-jurassischen Ammoniten über Artbegriff und Stammesentwicklung. *Abhandlungen der Gesellschaft der Wissenschaften zu Göttingen, mathematische-physikalische Klasse, Neue Folge,* **13,** 3. Teil, 1–124.

Buch, L. von 1839. Über den Jura in Deutschland. *Physikalische Abhandlungen der königlichen Akademie der Wissenschaften zu Berlin,* Jahrgang **1837,** 49–135.

Buckman, S. S. 1881. A descriptive catalogue of some species of ammonites from the Inferior Oolite of Dorset. *Quarterly Journal of the Geological Society of London,* **37,** 588–608.

—— 1887–1907. *A monograph of the 'Inferior Oolite Series'.* Monographs of the Palaeontographical Society, London.

—— 1889*a*. On the Cottewold, Midford and Yeovil Sands, and the divisions between Lias and Oolite. *Quarterly Journal of the Geological Society of London,* **45,** 440–474.

—— 1889*b*. The descent of *Sonninia* and *Hammatoceras. Quarterly Journal of the Geological Society of London,* **45,** 651–663, pl. 22.

—— 1893. The Bajocian of the Sherborne district: its relation to subjacent and superjacent strata. *Quarterly Journal of the Geological Society of London,* **49,** 479–522.

—— 1902–03. The term 'Hemera'. *Geological Magazine,* 4th series, **9,** 554–557 **10,** 95–96.

—— 1909–30. *Yorkshire Type Ammonites.* (1909–13); *Type Ammonites.* (1919–1930). Wheldon & Wesley, London.

—— 1910*a*. Certain Jurassic (Lias-Oolite) strate of south Dorset; and their correlation. *Quarterly Journal of the Geological Society of London,* **66,** 52–89.

—— 1910*b*. Certain Jurassic ('Inferior Oolite') species of ammonites and brachiopoda. *Quarterly Journal of the Geological Society of London,* **66,** 90–108, pls. 9–12.

Callomon, J. H. 1964. Notes on the Callovian and Oxfordian Stages. *In*: Maubeuge, P. L. (ed.) *Colloque du Jurassique à Luxembourg* 1962. Publications de l'Institut grand-ducal, Section des sciences naturelles, physiques et mathematiques, Luxembourg, 269–291.

—— 1965. Notes on Jurassic stratigraphical nomenclature. I. Principles of stratigraphical nomenclature. *Reports, VII Congress of the Carpatho-Balkan Geological Association, Sofia,* part ii, vol. 1, 81–85.

—— 1968. The Kellaways Beds and the Oxford Clay. *In*: Sylvester-Bradley, P. C. & Ford, T. D. (eds) *The Geology of the East Midlands.* Leicester, University Press, 264–290.

—— 1984*a*. The measurement of geological time. *Proceedings of the Royal Institution of London,* **56,** 65–99.

—— 1984*b*. A review of the biostratigraphy of the post-Lower Bajocian Jurassic ammonites of western and northern North America. *In*: Westermann, G. E. G. (ed.) *Jurassic-Cretaceous biochronology and paleogeography of North America.* Geological Association of Canada Special Papers, **27,** 143–174.

—— 1985*a*. Biostratigraphy, chronostratigraphy and all that—again *In*: Michelsen, O. & Zeiss, A. (eds) *International Symposium on Jurassic Stratigraphy, Erlangen* 1984, **3,** Geological Survey of Denmark, Copenhagen, 611–624.

—— 1985*b*. The evolution of the Jurassic ammonite family Cardioceratidae. *Special Papers in Palaeontology,* **33,** Palaeontological Association, London, 49–90.

—— 1993*a*. IV. Biochronology. 12. Ammonite Zones of the circum-Pacific region. Upper Jurassic, especially Mexico. *In*: Westermann, G. E. G. (ed.) *The Jurassic of the Circum-Pacific.* Cambridge University Press, New York, 261–269.

—— 1993*b*. The ammonite succession in the Middle Jurassic of East Greenland. *Bulletin of the Geological Society of Denmark,* **40,** 83–113.

—— 1994. Palaeontological methods of stratigraphy and biochronology: some introductory remarks. *Geobios, Mémoire Special,* **17** in press.

—— & Birkelund, T. 1980. The Jurassic transgression and the mid-late Jurassic succession in Milne Land, central East Greenland. *Geological Magazine,* **117,** 211–226.

—— & —— 1982. The ammonite Zones of the Boreal Volgian (Upper Jurassic) in East Greenland. *In*: Embry, A. F. & Balkwill, H. R. (eds) *Arctic Geology and Geophysics.* Canadian Society of Petroleum Geologists, Memoirs, **8,** 349–369.

—— & Chandler, R. B. 1990. A review of the ammonite horizons of the Aalenian-Lower Bajocian Stages in the Middle Jurassic of southern England. *Memorie descrittive della Carta geologica d'Italia,* **40,** 85–111.

——, Dietl, G. & Page, K. N. 1989. On the ammonite faunal horizons and standard zonations of the Lower Callovian Stage in Europe. *In*: Rocha, R. B. & Zeiss, A. (eds) *2nd International Symposium on Jurassic Stratigraphy, Lisboa* 1987, **1.** Universidade Nova, Lisbon, 359–376.

Caloo, B. 1971. *Caractères morphologiques non mésurables chez les Graphoceratinés (Ammonitina).* Documents du Laboratoire de Géologie de la Faculté des Sciences de Lyon, **45.**

Cariou, E. 1985. Biostratigraphic subdivision of the Callovian Stage in the Subtethyan Province of ammonites, correlation with the Subboreal zonal scheme. *In*: Michelsen, O. & Zeiss, A. (eds) *International Symposium on Jurassic Stratigraphy, Erlangen* 1984, **2.** Geological Survey of Denmark, Copenhagen, 315–326.

Contini, D. 1970. *L'Aalénien et le Bajocien du Jura franc-comtois.* Annales scientifiques de l'Université de Besançon, **3.** série, géologie, fasc. 11.

Cope, J. C. W. (ed.) 1980*a*. *A correlation of Jurassic rocks in the British Isles. Part One: Introduction and Lower Jurassic.* Geological Society of London, Special Reports, **14.**

—— 1980*b*. *A correlation of Jurassic rocks in the British Isles. Part Two: Middle and Upper Jurassic.* Geological Society of London, Special Reports, **15.**

—— 1993 High resolution biostratigraphy. *In*: Hailwood, E. A. & Kidd, R. B. (eds) *High Resolution Stratigraphy*. Geological Society, London, Special Publication, **70,** 257–265.

Cowie, J. W., Ziegler, W., Boucot, A. J., Bassett, M. G. & Remane, J. 1986. Guidelines and statutes of the International Commission on Stratigraphy. *Courier des Forschungsinstitut Senckenberg*, **83,** 1–14.

Dansgaard, W., and 10 other members of the Greenland Ice-core Project, 1993. Evidence for general instability of past climate from a 250 kyr ice-core record. *Nature*, **364,** 218–220.

Davies, A. M. 1930a. Editorial note. *In*: Buckman, S. S. *Type Armonites* **VII,** Wheldon & Wesley, London, 16–78.

—— 1930*b*. The geological life-work of Sydney Savory Buckman. *Proceedings of the Geologists' Association*, **41,** 221–240.

Dean, W. T., Donovan, D. T. & Howarth, M. K. 1961. The Liassic ammonite Zones and Subzones of the North-West European Province. *Bulletin of the British Museum (Natural History), Geology*, **4,** 437–505, pls. 63–75.

Dodgson, C. L. 1865 [1866]. *In*: Carroll, L. *Alice's Adventures in Wonderland*. Macmillan, London (1865) and Appleton, New York (1866), and later editions.

Donovan, D. T. 1973. *The influence of the theoretical ideas on ammonite classification from Hyatt to Trueman*. Paleontologica Contributions, University of Kansas, Paper **62.**

Fortey, R. A. 1985. Gradualism and punctuated equilibria as competing and complementary theories. *Special Papers in Palaeontology*, **33,** 17–28.

—— 1993. Charles Lapworth and the biostratigraphic paradigm. *Journal of the Geological Society, London*, **150,** 209–218.

Gabilly, J. 1974. Méthodes et modèles en stratigraphic du Jurassiqu *Mémoires du Bureau de Recherches Géologiques et Minières, Paris*, **75,** 5–16; reprinted in *Paleovox, Paris*, **2** (1993), 71–80.

—— 1976. *Évolution et systematique des Phymatoceratinae et des Grammoceratinae (Hildocerataceae, Ammonitina) de la région de Thouars, stratotype du Toarcien*. Mémoires de la Société Géologique de France, Nouvelle Série, **54.**

Gressly, A. 1838. Observations géologiques sur le Jura soleurois. *Nouveaux Mémoires de la Société Helvétique des Sciences Naturelles*, **2,** 1–112.

Guex, J. 1987. *Corrélations biochronologiques et associations unitaires*. Presses Polytechniques Romandes, Lausanne.

Hailwood, E. A. & Kidd, R. B. (eds) 1993. *High Resolution Stratigraphy*. Geological Society, London Special Publications, **70.**

Hantzpergue, P. 1989. *Les ammonites Kimméridgiennes du haut-fond d'Europe occidentale: biochronologie, systématique, évolution, paléogeographie*. Cahiers de Paléontologie, Paris.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. & Smith, D. G. 1990. *A geologic time scale 1989*. Cambridge University Press.

Hedberg, H. D. 1954. Procedure and terminology in stratigraphical classification. *Congres Géologique International. Comptes rendus de la XIX Session, Alger 1952*. Séction XIII, 1. partie: fasc.xiii, 205–233.

—— 1976. *International Stratigraphic Guide*. Wiley & Sons, New York.

House, M. R. & Price, J. D. 1985. New Late Devonian genera and species of Tornoceratid goniatites. *Palaeontology*, **28,** 159–188, pls. 16–20.

Howarth, M. K. 1992. *The ammonite family Hildoceratidae in the Lower Jurassic of Britain*. Monographs of the Palaeontographical Society, London.

Hudson, J. D. & Martill, D. M. 1994. The Peterborough Member (Callovian, Middle Jurassic) of the Oxford Clay Formation at Peterborough, UK. *Journal of the Geological Society, London*, **151,** 113–124.

Hyatt, A. 1889. *Genesis of the Arietidae*. Smithsonian Contributions to Knowledge, **673.**

Jenkyns, H. C., Gale, A. S. & Corfield, R. M. 1994. Carbon- and oxygen isotope stratigraphy of the English Chalk and Italian Scaglia and its palaeoclimatic significance. *Geological Magazine*, **131,** 1–34.

Jones, C. E., Jenkyns, H. C. & Hesselbo, S. P. 1994. Strontium isotopes in Early Jurassic seawater. *Geochimica et Cosmochimica Acta*, **58,** 1285–1301.

Jukes-Brown, A. J. 1903. The term 'Hemera'. *Geological Magazine, New Series*, Decade iv, **10,** 36–38.

Kemper, E. 1978. Einige neue, biostratigraphisch bedeutsame Arten der Ammoniten-Gattung Dichotomites (NW-Deutschland, Obervalangin). *Geologisches Jahrbuch, Hannover*, **A45,** 183–253.

—— 1987. Das Klima der Kreide-Zeit. *Geologisches Jahrbuch, Hannover*, **A96,** 5–185.

Landing, E. 1994. Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. *Geology*, **22,** 179–182.

Linnaeus (Linné, C. von) 1758. *Systema naturae per regna tria naturae....* Editio decima, Tom. 1, 2. Stockholm, L. Salvius.

Lyell, C. 1833. *Principles of Geology*. Vol. 3. John Murray, London.

McArthur, J. M., Thirlwall, M. F., Gale, A. S., Kennedy, W. J., Burnett, J. A., Mattey, D. & Lord, A. R. 1993. Strontium isotope stratigraphy for the Late Cretaceous: a new curve, based on the English Chalk. *In*: Hailwood, E. A. & Kidd, R. B. (eds) *High Resolution Stratigraphy*. Geological Society, London, Special Publications, **70,** 195–209.

——, Kennedy, W. J., Chen, M., Thirlwall, M. F. & Gale, A. S. 1994. Strontium isotope stratigraphy for Late Cretaceous time: direct numerical calibration of the Sr isotope curve based on the US Western Interior. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **108,** 95–119.

McKerrow, W. S. 1993. The development of Early Palaeozoic global stratigraphy. *Journal of the Geological Society, London*, **150,** 21–28.

Morlot, A. 1854 (published 1856). Notice sur le quaternaire en Suisse. *Bulletin de la Société vaudoise des Sciences naturelles*, **4,** 41–45.

Murchison, R. I. 1831. Notes on the Secondary Formations of Germany, as compared with those of England. *Proceedings of the Geological Society of London*, **1,** no. 22, 325–331.

Mussett, A. E. & McCormack, A. G. 1993. Magnetic polarity time-scales: a new test. *In*: Hailwood, E. A. & Kidd, R. B. (eds) *High Resolution Stratigraphy*. Geological Society London, Special Publications, **70,** 27–37.

Obradovich, J. D. & Cobban, W. A. 1975. A time-scale for the Late Cretaceous of the Western Interior of North America. *Geological Association of Canada, Special Papers*, **13,** 31–54.

Oechsle, E. 1958. Stratigraphie und Ammonitenfauna der Sonninienschichten des Filsgebiets, unter besondered Berücksichtigung der Sowerbyi-Zone (Mittlere Dogger, Württemberg). *Palaeontographica*, **A111,** 47–129.

Odin, G. S. 1994. Geological time scale (1994). *Comptes rendus de l'Academie des Sciences, Paris*, **318,** Ser. II, 59–71.

Oppel, A. 1856–58. *Die Juraformation Englands, Frankreichs und des südwestlichen Deutschlands*. Stuttgart, Ebner & Seubert.

Orbigny, A. d' 1850. *Paléontologie française, terrains oolitiques ou Jurassiques. Tome premier, Cephalopodes* 521–632. Paris.

Page, K. N. 1989. A stratigraphical revision for the English Lower Callovian. *Proceedings of the Geologists' Association*, **100,** 363–382.

—— 1992. The sequence of ammonite correlated horizons in the British Sinemurian (Lower Jurassic). *Newsletters on Stratigraphy*, **27,** 129–156.

Palmer, A. R. 1977. Biostratigraphy of the Cambrian System—a progress report. *Annual Reviews of Earth and Planetary Science* **5,** 13–33.

Parsons, C. F. 1974. The *sauzei* and 'so-called' *sowerbyi* Zones of the Lower Bajocian. *Newsletters on Stratigraphy*, **3,** 152–179.

—— 1976. A stratigraphical revision of the *humphriesianum-subfurcatum* Zone rocks (Bajocian Stage, Middle Jurassic) of southern England. *Newsletters on Stratigraphy*, **5,** 114–142.

—— 1980. Aalenian and Bajocian correlation chart. *In*: Cope, J. W. C. (ed), *A correlation of Jurassic rocks in the British Isles. Part two: Middle and Upper Jurassic*. Geological Society of London, Special Reports, **15,** 3–21.

Paul, C. R. C. 1985. The adequacy of the fossil record reconsidered. *Special Papers in Palaeontology*, **33,** 7–15.

Phelps, M. C. 1985. A refined ammonite biostratigraphy for the Middle and Upper Carixian (Ibex and Davoei Zones, Lower Jurassic) in north-west Europe and stratigraphical details of the Carixian-Domerian boundary. *Geobios*, **18,** 321–362.

Ramsbottom, W. H. C. 1977. Major cycles of transgression and regression (mesothems) in the Namurian. *Proceedings of the Yorkshire Geological Society*, **41,** 261–291.

Raup, D. M. & Crick, R. E. 1981. Evolution of single characters in the Jurassic ammonite *Kosmoceras*. *Paleobiology*, **7,** 200–215.

—— & —— 1982. *Kosmoceras*: evolutionary jumps and sedimentary breaks. *Paleobiology*, **8,** 90–100.

Rickards, R. B. 1976. The sequence of the Silurian graptolite zones in the British Isles. *Geological Journal, Liverpool*, **11,** 153–188.

Rioult, M., Dugué, O., Jan du Chene, R., Ponsot, C., Fily, G., Moron, J.-M. & Vail, P. R. 1991. Outcrop sequence stratigraphy of the Anglo-Paris Basin, Middle to Upper Jurassic (Normandy, Maine, Dorset). *Bulletin des Centres de Recherche, Exploration Production, d'Elf-Aquitaine*, **15,** 101–194, pls. 1–9.

Sadler, P. M. & Strauss, D. J. 1990. Estimation of completeness of stratigraphical sections using empirical data and theoretical models. *Journal of the Geological Society, London*, **147,** 471–485.

Schindel, D. E. 1980. Microstratigraphic sampling and limits of paleontologic resolution. *Paleobiology*, **6,** 407–426.

—— 1982. Resolution analysis: a new approach to the gap in the fossil record. *Paleobiology*, **8,** 340–353.

Schwarzacher, W. 1993. Milankovitch cycles in the pre-Pleistocene stratigraphic record: a review. *In*: Hailwood, E. A. & Kidd, R. B. (eds) *High Resolution Stratigraphy*. Geological Society London, Special Publications, **70,** 187–194.

SHELDON, P. R. 1987. Parallel gradualistic evolution of Ordovician trilobites. *Nature,* **330,** 561–563.

—— 1988. Trilobite size-frequency distribution, recognition of instars, and phyletic size changes. *Lethaia,* **21,** 293–306.

SKELTON, P. 1993 The fossil record of evolution in species. *In*: SKELTON, P. (ed.) *Evolution: a biological and palaeontological approach.* Open University and Addison-Wesley, 445–508.

SMITH, W. 1816. *Strata identified by organized fossils.* W. Aarding. London.

STENO, N. 1669. *De solido intra solidum naturaliter contento dissertationis prodromus.* Florence.

STURANI, C. 1971. *Ammonites and stratigraphy of the* "Posidonia alpina" *beds of the Venetian Alps.* Memorie degli Istituti de Geologia e Mineralogia dell'Universita di Padova, **28.**

SWEET, W. C. 1988. *The Conodonts.* Oxford Monographs on Geology & Geophysics, **10.** Clarendon Press, Oxford.

THOMAS, A. T., OWENS, R. M. & RUSHTON, A. W. A. 1984. *Trilobites in British stratigraphy.* Geological Society of London, Special Reports, **16**

TORRENS, H. S. 1978. The Sherborne School Museum and the early collections and publications of the Dorset Natural History and Antiquarian Field Club. *Proceedings of the Dorset Natural History and Archaeological Society,* **98,** 32–42.

—— 1988. What price the advancement of science? British Association for the Advancement of Science, Oxford, 5–9 September 1988, no. **C17.**

TOZER, E. T. 1984. *The Trias and its ammonoids: the evolution of a time scale.* Geological Survey of Canada Miscellaneous Reports, **35.**

TRUEMAN, A. E. 1923. Some theoretical aspects of correlation. *Proceedings of the Geologists' Association,* **34,** 193–203.

WAAGEN, W. 1867. Über die Zone des *Ammonites sowerbyi. Benecke's geognostisch-paläontologische Beiträge,* **1,** 507–668.

—— 1869. Die Formenreihe des *Ammonites subradiatus. Benecke's geognostisch-paläontologische Beiträge,* **2,** Heft 2, 181–256.

WEAVER, P. P. E. 1993. High resolution stratigraphy of marine Quarternary sequences. *In*: HAILWOOD, E. A. & KID, R. B. (eds) *High Resolution Stratigraphy.* Geological Society, London, Special Publication **70,** 137–153.

WEEDON, G. P. & JENKYNS, H. C. 1990. Regular and irregular climatic cycles and the Belemnite Marls (Pliensbachian, Lower Jurassic Wessex Basin). *Journal of the Geological Society, London,* **147,** 915–918.

WENDT, J. 1971. Genese und Fauna submariner sedimentärer Spaltenfüllungen im mediterranen Jura. *Palaeontographica,* **A136,** 121–192.

WESTERMANN, G. E. G. & CALLOMON, J. H. 1988. The Macrocephalitinae and associated Bathonian and Early Callovian (Jurassic) ammonoids of the Sula Islands and New Guinea. *Palaeontographica,* **A203,** 1–90.

WILLIAMS, H. S. 1901. The discrimination of time values in geology. *Journal of Geology,* **9,** 579–80.

WOODWARD, H. B. 1892. On geological zones. *Proceedings of the Geologists' Association,* **12,** 295–315.

ZIEGLER, W. 1974. Conodont stratigraphy of the European Devonian. *Memoirs of the Geological Society of America,* **127,** 227–284.

—— & SANDBERG, C. A. 1990. *The Late Devonian standard conodont zonation.* Courier Forschungsinstitut Senckenberg, **121.**