

TIME IN STRATIGRAPHY

by T. G. MILLER

ABSTRACT. Recent publication of several formalized systems of stratigraphic classification and nomenclature provides an opportunity for the re-assessment of certain stratigraphic concepts.

The scope and categories of stratigraphic studies are examined and related to the nature of the chronological record available in extant rocks. Lithostratigraphic data are identified as the matrix of a body of biostratigraphic evidence which serves as the basis for construction of a model time-scale using biochronological divisions. The notion of a separate 'time-stratigraphy' with 'time-stratigraphic' units is considered to be invalid.

The nature of stratigraphic boundaries in relation to diastrophic processes, the general nature of stratigraphic divisions, and the special status of the biochronologic zone are discussed, together with problems of correlation.

THE papers presented at a recent Symposium on Harmony in Stratigraphic Classification (*American Journal of Science*, 1959) formed an important exposition of current North American ideas and practice. It has been followed by an equally important summary of the corresponding Russian views (Rotay 1960), which has been criticized by Hedberg (1961). A more complete and formal statement of the American position is contained in the Code of Stratigraphic Nomenclature (referred to below as the *Code*) presented by the American Commission on Stratigraphic Nomenclature (1961) and further developed in the Statement of Principles of the International Subcommittee on Stratigraphic Terminology (1961).

There is, in addition, a formidable literature of 'theoretical stratigraphy', the development and elaboration of which has rested, for the greater part of this century, mainly in the hands of American workers. This is hardly surprising in view of the enormous programme of successful stratigraphic investigation carried out during this period, and the great range and diversity of the problems involved. At the same time a programme of similar scope has been undertaken by Russian stratigraphers, working on similar problems and in areas approximately comparable with those of their American counterparts. Because of language and other difficulties of intercommunication much of the Russian work seems to have proceeded in isolation. Jeletzky (1956) has already drawn attention to some currently accepted over-refinements and complications in stratigraphic theory, and to some defects and fallacies. Certain aspects of the subject have also been briefly dealt with by Henson (1944).

It is possible that confusion in the interchange of ideas has arisen through a tendency to allow the formulation of generalized concepts to be too closely influenced by practical, and especially economically important, requirements. In the discussion that follows, reference is made, wherever possible, to examples of contemporary usage.

THE STRATIGRAPHIC RECORD

It will perhaps be generally agreed that in all kinds of stratigraphic study the rocks, whether already formed or in the course of formation, are the only source of evidence. This body of evidence, and indeed stratigraphy as a scientific discipline, may be apprehended in either a chronological or a physico-geometrical sense. The first of these categories is concerned with the establishment of a true time-order of the actual events and

processes leading to the formation of rock masses, and requires a consideration of time both as *age* and *duration* of events and causal processes. The second category requires the empirical description of rock masses in purely material, i.e. physical or geometrical, essentially non-temporal, terms. It is a paradox that while the chronological aspect of stratigraphy is interpretative or derivative, and hence strictly secondary to the visible physico-geometrical aspect which is the actual matrix of the evidence, it must nevertheless be considered actiologically primary, since the processes involved are causally anterior to their material product.

If this dual nature of stratigraphic studies is accepted, it becomes necessary to consider how 'time-evidence', whether of age (date), i.e. temporal location, or of duration, i.e. elapsed time, is contained in or represented by the available documentary records, namely the rocks.

The *Code* states (Article 2): 'Categories of stratigraphic units are multiple. According to different concepts and criteria, they comprise mutually overlapping but distinct types of stratigraphic units. This Code provides regulations and recommendations relating to (i) rock-stratigraphic units, (ii) soil-stratigraphic units, (iii) biostratigraphic units, and (iv) time-stratigraphic units. The Code also treats two categories of units that are not in themselves stratigraphic units but are closely related. These are (v) geologic-time units, which are fundamentally related in concept to time-stratigraphic units, and (vi) geologic-climate units, which are based on Quaternary stratigraphic units.'

The categories with which the present discussion is concerned are (i), (iii), (iv), and (v). It is immediately clear that among these a difference of kind exists between, on the one hand, notions of rock- and bio-stratigraphy—(i) and (iii)—dealing with material objects; and, on the other, time-stratigraphy and geologic time—(iv) and (v). Time itself cannot be said to accumulate, and can only be said, rather naïvely, to 'exist' as an instantaneous dimensionless present, which 'is' a continuous transition from the observer's past to his future. However, since time as a phenomenon, is, so far as stratigraphy is concerned, 'given', omnipresent, continuous, rectilinear, and irreversible, so that the metaphor 'the passage of time' is continually in use, there can be no advantage in trying to codify 'geologic time' differently from 'ordinary' time, with its artificial minute-hour-day-year organization based on the behaviour of the earth as a planet. As more radiometric evidence of age is collected, so the importance of 'ordinary time' fixed points in stratigraphic analysis will increase. Neither does there seem to be any justification for setting up a scale of 'time-stratigraphic' units purporting to be independent of others. The *Code*, indeed, states (Article 26a) that the time-stratigraphic units proposed '... are usually made to coincide with ... some other kind of stratigraphic unit ... which thus serves as an objective reference'. It may be asked in this connexion whether any 'time-stratigraphic' unit—a system or a stage, for example, could be recognized with any certainty (except by analogy) in the absence of fossil—i.e. biostratigraphic—evidence? Or whether, supposing such a unit to have been recognized either by analogy or on radiometric grounds, its boundaries could be satisfactorily determined in the absence of fossils?

Time and geological events

In a 'normal' sedimentation-denudation situation, various states or conditions of the earth's surface, whether subaerially exposed or concealed by water, in the instant of

observation are *isochronous* or *synchronous*, considered stratigraphically. Records of the surface form and composition made at arbitrarily chosen intervals would catalogue and describe successive surfaces of identical age marking a temporal progression analogous to the successive frames of a cinematograph film. However, in the denudation sector there is systematic retrogressive destruction of surfaces that were once continuous with preserved surfaces in the sedimentation sector, taking this to be undisturbed and 'normal'. The record of isochronous surfaces is, therefore, potentially complete only in the sedimentation sector. In that such a preserved pile of separate, complete, isochronous surfaces would in effect 'represent' or 'record' the passage of time,* it may be taken as an imaginary model of potentially complete elapsed time. This stratal pile, or ideal succession, is the primary model or reference-frame in geochronological stratigraphy. If the ocean basins are considered to be permanent features of the earth's surface, it is conceivable that such a complete succession might actually exist. But if it does exist it remains at present inaccessible, while the visible successions are demonstrably incomplete. However, since it is currently thought unlikely that the ocean basins are permanent, it follows that a complete stratal record is also unlikely to exist.

In this connexion it should be noted that some kinds of igneous rock may become effectively part of the sedimentational or accumulative record, while others will not. The emergence at the earth's surface (whether subaerial or subaqueous) of extensive masses of lava or pyroclastic material causes immediate modification of the surface. Such newly formed igneous or para-igneous rocks then take their place as parts of successive isochronous surfaces. On the other hand, intrusive bodies emplaced below the surface cannot at the same time form part of that surface, although they may deform it. Such bodies are, nevertheless, the result of finite and, theoretically, identifiable event-sequences. It is a paradox that these bodies, whose position in a stratigraphic-age scale is often difficult to fix closely, are commonly used radiometrically to provide ages-in-years (the so-called 'absolute ages' of many stratigraphers) for their emplacement, and hence an 'age-bracket' for their sedimentary envelope and cover. Similar limitations on precision in stratigraphic-age fixing apply also to metamorphic and other deformation-processes or event-sequences, although, as in many igneous complexes, internal relative histories may often be derived from physico-geometric considerations such as metamorphic grade, crystal condition, petrofabric, tectonic style, and so on.

Thus it emerges that only a limited part of the total geological record, namely the sedimentary part *sensu lato*, can be used in attempting to provide a step-ladder or scale having a general use as the main fabric of a stratigraphic model of elapsed time. The primary task of the stratigrapher who wishes to establish a valid geochronology is therefore to isolate from the multiplicity of the sedimentary record the significant base-data for a time-scale. Chronologically significant details must be extracted from the mass of chronologically irrelevant material, much or even all of which may, nevertheless, be utilizable in physico-geometrical analysis, or even, in some cases, in providing support for a relative local 'time-order'. Thus electric-log character, inorganic lithology, mineralogy, and other purely physical attributes may provide circumstantial evidence of local temporal order, but cannot refer directly to a real age-scale or general chronology.

* The problems connected with the notion of the 'passage of time' are not discussed here, and the notion is accepted uncritically for the present purpose as a convenient fiction (cf. Smart 1956).

Lithostratigraphic evidence as 'primary matrix'

It is clear that among the many characteristics of the sedimentary rocks, those having special relevance to time-order are the ones which retain a link with, or are a direct manifestation of, the original causal processes of deposition and erosion. However, deposition in the sense of simple inorganic accumulation in itself alone cannot provide a systematically arranged series of identifiable steps capable of being used as an age-scale model, since there is no way at present either of 'signalling' a unique age or of telling how much elapsed time is 'represented by' a particular body of sediment or rock, or what segments of elapsed time are not represented at all. Refined long-range correlational analysis of the inorganic accumulative lithostratigraphic record is therefore difficult or even impossible. How could the Karroo succession, for example, be fitted to the British stratigraphic column without fossil evidence? Nevertheless virtually all pre-Phanerozoic and many other successions have to be analysed, *faute de mieux*, and tentatively correlated, by reference to some non-systematic or historically 'coarse' scheme based on the pure lithostratigraphic record, i.e. on (1) simple before-and-after relations ('simple' here in the sense of primitive: the considerations actually involved, for example, in the elucidation of a polyphase metamorphic complex, may be extremely sophisticated); and (2) radiometric age-in-years determinations of contained minerals. An example of this state of affairs is the gradual unravelling of the relations of the Moinian and Dalradian rocks of Scotland and their tentative and partial correlation with the Torridonian and certain Lower Palaeozoic formations.

Biostratigraphic evidence

Since the inorganic element in the available evidence is not yet able to supply geochronological data adequate for refined and extended analysis, we are left with the originally organic or biostratigraphic element as the main chronologically significant body of evidence contained within the primary lithostratigraphic matrix.

The relevant principle in this connexion has been concisely set out by Teichert (1958, p. 99): 'The only natural processes that are of a unidirectional and non-reversible nature and that leave universally occurring testimony in the rocks are radioactive decay and organic evolution. The study of past life-forms and their distribution in the rocks (palaeontology and biostratigraphy) provides a reference-system for determining the order of succession of geological events from the Cambrian onwards. Radioactive decay supplies an approximate (skeleton) reference-grid of dates in absolute [*sic*] terms.'

This admirably unequivocal proposition can be taken as the foundation upon which to build a systematic frame of reference related to the passage of time and divisible into more or less discrete parts, i.e. a true but still internally relative (and, at present, rather loose) geochronology (cf. Jeletzky 1956). It is explicitly supported in the *Code*, Article 19f: '... Commonly, biostratigraphic evidence is the most useful means for determining time-stratigraphic boundaries, but criteria for defining biostratigraphic and time-stratigraphic units differ fundamentally.' Hedberg (1959, p. 680) also takes this position, but with an important addition, when he writes: 'The evolutionary sequence of fossils may always be superior to any other means for geochronological dating of fossiliferous sediments, but we already know that other means can contribute greatly to dating and to time-stratigraphic correlation even in fossiliferous rocks. . . .' Earlier in the same paper

Hedberg states (p. 676): '... some workers have proposed that the same set of units should be used for biostratigraphic divisions as for time-stratigraphic divisions, inferring that fossil zones are the only time-stratigraphic units. ...'

It will be noticed that in these extracts—as in the *Code*—reference is made to a category of *time-stratigraphic* divisions, although this is not a feature of Teichert's fundamental proposition, which deals only in biostratigraphic and radiometric terms. The question therefore arises as to the place of this 'time-stratigraphy' in geochronological analysis, and its relation (if any) to biostratigraphy.

THE 'TIME-STRATIGRAPHY' CONCEPT

The *Code* states, in Article 26: 'A time-stratigraphic [chronostratigraphic] unit is a subdivision of rocks considered solely as the record of a specific interval of geologic time.' This is somewhat extended in Remark (a): '... They are material units. Each is the record of an interval of time that extended from the beginning to the ending of its deposition. ... In actual practice, the scope of a time-stratigraphic unit in its type-section or type-area is usually made to coincide with that of some other kind of stratigraphic unit, such as a biostratigraphic or a rock-stratigraphic unit, which thus serves as an objective reference. As time-stratigraphic units depend for definition on actual sections of rock, care should be taken to define geologic-time units in terms of time-stratigraphic units and not vice-versa.'

Time-stratigraphy has been discussed at some length by Wheeler and Beasley (1948), Hedberg (1948), and Wheeler (1958*b*); lithostratigraphy by Wheeler and Mallory (1956); and biostratigraphy by Wheeler (1958*a*) and Young (1960). Reservations have been expressed by Rodgers (1959) and Story and Patterson (1959). It will be convenient to take specific examples from some of these accounts:

- (i) Hedberg (1948, p. 456): 'The time-value of stratigraphic units based on fossils will fluctuate from place to place with faunal-facies variation in much the same manner as the time values of a lithologic formation may vary.'
- (ii) Hedberg (1959, pp. 681–2): 'The boundaries of biostratigraphic zones may cut across time-horizons, across formation-units, and across the boundaries of any other kind of stratigraphic unit.'
- (iii) Wheeler (1958*b*, p. 1048): 'Analysis of time-stratigraphy ... has led to the observation that not all time-stratigraphic units are entities of constant temporal value. Some regarded as most useful for regional synthesis and thus as bases for historical interpretation occur as space-time variables.'
- (iv) Wheeler (1959, p. 700): '... the criteria involved in delineating biostratigraphical units ... may not serve directly to delineate time-stratigraphical units.'

These examples exhibit certain inconsistencies in the understanding of the regions of applicability and validity of the various stratigraphic categories under discussion, in particular the ability of the undifferentiated stratigraphic record to signal identifiable temporal location and specific duration.

One of the fundamental aspects used by Wheeler in developing the idea of 'time-stratigraphy' as a discrete concept is the 'complexly variable three-dimensional relationship' encountered in litho- and bio-stratigraphy, and the difficulty that only two of these

can be represented on a two-dimensional surface (Wheeler 1958*b*, p. 1047; cf. also Bell *et al.* 1961). Time, in the sense of comparative duration, must in Wheeler's view be shared with, and to a greater or lesser extent correspond to or be involved in, stratal thickness, as a 'vertical' dimension. Now it is clear that thickness in sedimentary successions does not *systematically* represent temporal duration, although its origin in the familiar 'law' of superposition is fundamentally valid in a highly generalized way. It is also true that there generally *seems* to be a relation between thickness and elapsed time, since the only visible sign of duration is stratal thickness. This is the case, for example, in a regularly and delicately laminated mudstone, where the observer feels intuitively that sedimentary thickness, signifying accumulation at a definite rate, is a direct function of duration. In the same way complete cyclothemic sequences may convey an even stronger impression of 'pure'—i.e. continuous—recorded duration. But the presence of well-marked bedding-planes, erosion surfaces, nodule beds, condensed deposits, even abnormally well-sorted accumulations, must all indicate *subtractions* from the stratal record. The need to account for these gaps in the record has led to the introduction of a whole series of technical terms, e.g. lacuna, hiatus, erosional vacuity, &c. (cf. Bell *et al.* 1961, Sanders 1957). However, none of these inorganic phenomena is able to contribute anything more than strictly local and circumstantial, and non-comparative, chronologic information. The establishment of a chronologic *scale* depends upon the availability for investigation and analysis of progressive and irreversible change in relatively easily identifiable entities either independent of the processes under direct examination—as in the case of 'ordinary' time, with numerically ordered points and intervals counted from a conventionally agreed initial datum point—or only secondarily associated with them. The temporal arrangement of such associated or secondary phenomena is capable of furnishing a relative time-scale whenever direct methods fail, or whenever the primary events are transient (as they usually are), and incapable of providing permanent evidence. Recourse to this 'coarse' assessment of the passage of time is the familiar standard method of the archaeologist and pre-historian, now, like non-human stratigraphy, supplemented by radiometric techniques which can provide scattered 'age-in-years' reference points.

The important point for emphasis here, in relation to stratigraphy, is the clear distinction that needs to be made between (a) the age of events, (b) time as duration of conditions or processes, and (c) the recording of the passage of time. A time-scale is an artefact for representing systematically and rationally (i.e. ordering) a succession of events (themselves, it should be noted, also no more than hypothetical constructs) within a temporal reference frame. Ideally such a time-scale would be independent of events, in the way that our everyday conventional time-scale seems to us to be, but of course is not, independent. A way out of this confusion is to regard events as simultaneous not because they appear to occupy the same 'moment of time', but simply because they happen together. 'They correlate themselves because they co-exist. . . . [The] moment is not a temporal entity existent in its own right, it is simply the class of co-existent events themselves. *We derive time from events, not vice-versa*' (Gunn 1929, p. 323, quoted in Whitrow 1961, p. 36: my italics). Thus the stratigrapher's time-scale has to be constructed from a selection of traces of progressive and irreversible events or processes (secondary organic) contained within a matrix of products of events which are effectively non-progressive and potentially reversible, but whose temporal location it is intended to

systematize. The primary events are the preserved relics of the 'transfer process' of Wilson (1959)—removal+transport+deposition—now represented by the whole body of lithostratigraphic evidence, *and they are without strict chronological significance*. The secondary events whose traces are retained within the primary matrix constitute the body of biostratigraphic evidence, and these, since they are the results of identifiable progressive change, have positive chronological significance. There is an additional body of evidence within the primary matrix, namely the products of diagenetic effects. These are in their turn capable of conveying some chronological significance, but this will normally be crude (simple before/after) and local; and, which is more important, it will refer to a portion of elapsed time subsequent by an unknown amount to the original depositional events.

The only meaningful time signals are therefore contained in the biostratigraphic body of evidence. However, because of limitations in the discriminatory power of palaeontological analysis, not all of the organic content of a rock mass can be put to a chronological use. For example, the much-quoted 'repetition' of facies-controlled organic assemblages is a repetition only in the sense that the evolutionary changes involved are below the level of palaeontological detection. The effect of this limitation is important in that it necessitates the separation of two kinds of biostratigraphic evidence according to chronological significance. A zonal assemblage which 'repeats' in a facies-controlled situation is of little or no chronological value. The assemblage which invariably appears in the same sequential relation to precedent and following assemblages is the only source of chronologically significant 'signals'. The strata containing it should be distinguished as a biochronologic zone.

Thus it appears that the only presently available rational geochronological indices are biostratigraphically based—i.e. *biochronologic*. However, if these biochronologic indices are to be realized as rock-divisions, this realization must be in terms of identifiable parts of their lithostratigraphic matrix, in order to make description and comparison possible. The question therefore arises whether, and to what extent, biochronologic divisions can be said to have meaningful and determinable lithostratigraphic expression.

THE NATURE OF STRATIGRAPHIC BOUNDARIES

It is true that very occasionally a stratal surface, or vertically limited band, can be safely taken to represent an original sedimentation surface of short-term duration for a comparatively large fraction of the total former sedimentation area. In other words, it is a real 'horizon', and is really synchronous or isochronous. Examples are some lava flows, bentonite seams (cf. Adams and Rogers 1961), possibly tonstein seams (cf. Scheere 1954), thin, widespread evaporite sequences, and thin unique fossil bands like, for example, the *Saccocoma* and *Uintacrinus* bands in the upper Jurassic and upper Cretaceous respectively. Widespread glaciogene 'horizons' may fall into the same category, and, in non-fossiliferous or pre-Cambrian successions, these, together with such other distinctive divisions as thin limestone bands of wide lateral extent, may be taken as effectively synchronous within a rather 'coarse' geochronological context.

Such stratigraphically 'two-dimensional' horizons may with some confidence be regarded as chronologically 'instantaneous' surfaces, and may be represented in tabulations

or on maps as lines. They probably represent the highest level of geochronological precision at present available to the stratigrapher. However, most of the boundary lines placed in stratigraphic tabulations, or drawn on geological maps, are of a much lower level of precision, in that they are not virtually two-dimensional, but represent a more or less extended transition from one lithological condition to another, i.e. involve a temporal duration, or interval.

Inter-formational intervals can either be positive or negative in terms of sedimentation. If sedimentation was continuous through the interval (the positive case), a separation into neighbouring formations is seen only if a change of régime occurred such as to produce a change in lithology which is usually gradual. There is thus no dividing-line (surface) between the two, but a transition which 'represents' at a given locality a certain amount of elapsed time. It cannot legitimately be represented graphically by a line, although of course it normally is. If, on the other hand, sedimentation was interrupted, the interval will have a negative significance in terms of the accumulative potential, and will normally be expressed visibly as a surface of non-depositional or erosional significance, i.e. as the familiar 'break in the sequence', lacuna, hiatus, &c. Such surfaces may legitimately be taken to be more or less satisfactory approximately two-dimensional physico-geometric entities, and may be represented graphically by a line.

Nevertheless, an interval of this negative kind must still resemble its positive counterpart in having a durational significance. The erosional interval has in reality two 'sides', one the preserved residual upper limiting surface of the originally older sedimentary régime; the other the initial depositional surface of the younger sedimentary régime. Thus, while in the positive case the interval represents duration extending from the initiation to the termination of change from lithology A to lithology B in continuous sedimentary sequence, in the negative case the interval represents the duration of the erosional (or non-depositional) episode sandwiched between the sedimentation-states now represented by lithologies A and B. Furthermore, in both cases, if a considerable area is involved, the interval must be interpreted as the expression of more or less deep-seated diastrophic processes, and thus may have varied systematically in age from place to place, so that the actual durations involved may have been of similar length but different mean age, or ages of starting and finishing. The geochronological significance of such intervals thus requires investigation, since it is the 'temporal origin' of many, indeed most, graphical boundary lines. It is clearly of the first importance to establish the precise nature of these intervals, since practical utility and the necessity for communication both demand the continual creation and recognition of boundary lines as reference signs or markers in stratigraphic analysis realized as maps or tabulations, and especially wherever economic considerations are involved.

Breaks in the succession

'Breaks' in the sedimentary stratal sequence indicate subtraction from the steady supply of stratigraphic data, whether produced by the neutral condition of non-deposition, or the true negative of erosion. At the present time the only mechanism known to be capable of producing virtually simultaneous (synchronous) sedimentation changes in widely separated parts of the world is a eustatic sea-level alteration caused by relatively rapid variation in oceanic water volume or distribution. For this the controlling factor is the expansion or contraction of the polar ice-caps. This would account for only

a comparatively small change in sea-level, and probably, in the long run, only a small interruption of major sedimentary régimes. Furthermore, since glacial events on a large scale, although well known, appear to be rather rare in the stratigraphic record, these glaciogene eustatic changes must be considered of minor importance as break-producing mechanisms.

However, a far more powerful mechanism, but capable of producing only non-synchronous, or temporally progressive, sedimentation-changes, is available in the processes of *diastrophism* or crustal deformation. Such deformation is expressed at the earth's surface as major or minor form alterations (depth) of the ocean basins and their margins, and similar form alterations (relief) of continental interiors and their margins. These form alterations involve resultant radial changes of position of the surface relative to the geoid, but are unlikely, except in the special cases of rifts, diapirs, cauldron subsidences, &c., to be truly radial, and in consequence must be expressed as tilts or warps, or tangential translations on various scales (cf. Hallam 1963). Tilts or warps are unlikely to be produced instantaneously on a large scale, and their formation may therefore be expected to have secular duration. Consequently, there will follow changes in the sedimentary régime of the regions affected, and these may be severe enough to cause shifts through the neutral state of non-deposition to the negative state of erosion, or vice versa. But whatever may be the actual end-state of tilt-induced régiminal changes, inter-regional temporal variation of their initiation, duration, and termination will normally be present, and must lead ultimately to an expression as rock surfaces (whether depositional or erosional) having systematically variable age. Thus both sedimentation-limiting changes, and non-depositional or erosional situations, will come to have variable ages. This geologically familiar state of affairs ('facies crossing time-lines' *auctt.*) has for long been known to British stratigraphers as *diachronism* (after Wright 1926), and continuous age-variable surface, or even whole lithostratigraphic units, formed in diastrophically controlled circumstances are called *diachronous*. Since diastrophic control is ubiquitous, it seems likely that most positive lithostratal transitions, and negative surfaces or intervals, both of which may be used in one way or another as stratigraphic boundaries, must be to some extent diachronous.

However, it is fortunate that normal stratigraphic successions do contain these intervals or transitions, even though diachronous, since they allow fragmentation, albeit quite arbitrary, of the local section into more or less compact lithostratigraphic divisions (members, formations, groups, &c.). Moreover, where visible erosion surfaces, unconformities, re-work levels, condensed deposits, and so on are numerous, it is clear that considerable subtraction from the stratigraphic record within divisions has also occurred. But since diastrophic processes as the root cause of sedimentation changes must, as we have seen, have temporal duration, and since variations in local and regional surface configuration will produce varying reaction-times to structural changes, there is no *a priori* reason to expect detailed sequential similarities at widely separated localities. On the contrary, it is the observed detailed non-coincidence of such episodes that allows the gradual filling in of stratigraphic gaps in successions by the collection of new evidence not present in primary or type areas, but discovered by extension of investigation to regions of complementarity in the alternation of deposition and erosion. For example: '... Possibly the explanation of the occurrence, in Central Arabia, of *Ermo-ceras* and *Magherina* without *Strenoceras*, *Garantiana*, and *Parkinsonia*, infallible indices

of the Bajocian stage all over the world, is that the *Ermoceras* fauna lived in the interval between the Middle and Upper Bajocian, which in many parts of Europe was a time of earth-movement and erosion, and is always indicated by a break (non-sequence). This was the period of the Bajocian denudation of Buckman' (Arkell 1952, p. 296). Thus the lithostratigraphic divisions of the stratigraphic column in one part of the world need not, and in general will not, correspond to those in another, distant, part.

By contrast, general organic event-sequences, or the pattern of evolutionary change as displayed in fossil assemblages, when expressed in terms of the available geochronological scale, in which the smallest operational division, the biochronological zone, represents a duration in the order of 500,000 years, may reasonably be expected to show a high level of coincidence in widely separated areas. When observed on this scale many local and regional variations in rate of change of assemblages will be smoothed out and cease to be significant as anomalies. Such a smoothed record accounts for the observed high level of coincidence in the sequential order of geochronological divisions based on globally distributed fossil groups such as many graptolites, ammonoids, fusulinids, and agnostids. It is this coincidence which makes world-wide stratal correlation a practical possibility. However, for refined regional analysis, which may use benthonic, even sessile, rather than pelagic forms, contained within the limits of a single stage or sub-stage, considerations of homotaxial rather than synchronous correspondence, migration rates, arrival and extinction levels (cf. Bancroft 1945), and, pre-eminently, facies control, will almost certainly be involved. Nevertheless, strictly correlative rock-units are still only identifiable in biostratigraphic terms, however much circumstantial or supporting evidence may be supplied by the lithologic matrix. It is probable that the tendency uncritically to identify as 'time-lines' geochronologically non-significant physico-geometrical horizons or surfaces has been a cause of confusion in stratigraphic thinking. It must be kept clearly in mind that the only valid 'time-lines' are the real transitions or intervals between divisions of the biochronologic scale, together with the rare synchronous horizons already mentioned (*supra*, p. 120).

PERIODS, ZONES, AND STAGES

The view expressed by Bell and others (1961, p. 668) in a 'Note for General Consideration' relating to the *Code*, that the *period* is the fundamental geochronologic unit, is open to criticism, on the grounds that not only are they (the periods) no more than conceptual units, but that they are based on lithostratal records (systems, &c.) which, being terminated in most cases by physical breaks, are, *ex hypothesi*, incomplete. Moreover, the boundaries between the periods are normally without real chronologic significance, just as the 'boundary' between the eighteenth and nineteenth centuries is without real significance in human history.

Historically, stratigraphic studies have gone forward by a progressive refinement, in the form of multiple subdivision, of the whole stratal reference system or stratigraphic column. Lyell, in the definitive third edition of his *Principles of Geology* (1834), shows (vol. iv, appendix, pp. 305-14) the once-familiar division of the stratigraphic column into Primary, Secondary, and Tertiary periods. These, in turn, are broken down into, for example, Jura limestone group, Lias group, New red sandstone group, Carboniferous

group (including Old red sandstone), and Greywacke group; and these again are shown as consisting of 'Principal members' (p. 309) at a variety of named localities.

By 1886, Jukes-Browne was able to put forward, in his *Students' Handbook of Historical Geology*, almost the modern sequence of systems, but continued to show, now as 'stages', Lyell's 'formations', although of course in a greatly increased number. But Jukes-Browne was already making the fallacious assumption that systems could be *subdivided* into stages or groups, these into sub-groups, and the sub-groups into zones. That this was, in fact, a fallacious procedure could have been deduced from the experience of Sedgwick and Murchison, who, in the middle quarters of the nineteenth century, had been *building up*, respectively, the Cambrian and Silurian system, from the central overlapping portion of which Lapworth (1879) eventually carved the Ordovician.

Further, the non-primacy of the classical systems, and hence of the periods, in actual practice, can be seen in the large number of cases of disagreement on the assignment of certain formations, or parts of formations, or stages, to adjoining systems. Thus the Tremadocian stage is, in Britain, conventionally placed in the Cambrian, because its upper limit is commonly a surface of unconformity, while in Scandinavia it is placed in the Ordovician (Stubblefield 1958*b*, p. 4); the British Rhaetic (so-called, it may be noted, in the absence of ammonite evidence) is placed in the Jurassic, whereas in southern Europe it is placed in the Triassic; the British Downtonian was for long regarded as the top division of the Silurian but is now made the lowest of the Devonian, and so on. In fact, as stratigraphy developed, two different methods of chronological 'labelling' seem to have become super-imposed: (i) an older, rather crude arrangement based partly on local formational limits, frequently coincident with important local structural breaks, and partly on a general assessment and understanding of the organic content; and (ii) a newer, more refined, appreciation of the biostratigraphic sequence ideally independent of structural interruptions, and concerned to produce a succession of biochronologic zones, independent of lithology, complete for any given region, and by interdigitation, overlap, or lateral replacement, eventually envisaged as complete, or potentially complete, for the whole earth. For convenience of everyday reference, and more particularly for inter-regional correlation, which may be forced to use fairly broad divisions, since only these are recognizable at long range, the old period and system names have been retained, even although they are capable of causing positive confusion by the disordering of stratigraphic, and particularly biostratigraphic, observations (cf. Eames *et al.* 1962). But as soon as more refined analyses and correlations are undertaken, the value, in terms of both accuracy and precision, of the old labels decreases, and first the zone and then the stage become the more useful and significant.

Status of the 'biostratigraphic' zone

The notion of the geochronologically significant biostratigraphic zone is fairly generally established in the minds of stratigraphic palaeontologists, especially in Europe, almost to the extent of uncritical acceptance as something 'given'. The definition of Marr (1898), or a variant of it, is often quoted: 'Zones are belts of strata, each of which is characterized by an assemblage of organic remains, of which one abundant and characteristic form is chosen as index.' However, this definition is not sufficiently close, and its potential ambiguity may be illustrated by reference to a paper already

mentioned (Young 1959, p. 755): '... to me, if the fauna is recurrent, the zone is recurrent.' The possibility of a properly defined (i.e. unique) *biochronologic* zone recurring in a vertical succession of rocks is directly opposed to the basic principles of correct geochronological analysis.

Article 23 of the *Code* defines a *concurrent range zone* as '... the overlapping ranges of specified taxa, from one or more of which it takes its name'. Remark (6) states: 'This ... is the zone generally recognized by stratigraphers when they use fossils in attempting time-correlation of strata. Such zones are formal zones. Historically this usage derives from Oppel.' It is interesting to compare the Russian position as it is given by Rotay (1960, p. 47): 'The compass and boundaries of the zone are defined by the limits of the extent of a definite grouping of widely distributed and preferably rapidly changing organisms, constituting the zonal faunal (or floral) assemblage, which is not repeated either in the overlying or underlying deposits. Into the content of each zonal assemblage ought to enter as far as possible all the stratigraphically most important groups of fauna (flora) represented in the given deposits. The extent of a zone embraces generally a whole biogeographic region or province, less often a significant part of the latter; sometimes a zone can be extended also through two or even several regions or provinces. To a zone, distinguished in the deposits of this or that facial content, may be added also deposits contemporaneous with it but of different facies, which are interbedded with palaeontologically characterized deposits of the zone or directly replace it in its range.

'... When necessary, one may introduce into the name of the zone the two or three most typical species, distinctive in the whole region of the extent of the zone or characteristic in various combinations in the different parts of that region. ... For deposits that are more or less contemporaneous but belong to sharply different biogeographic provinces (especially if these are developed in geographically widely separated regions) or for successions that are sharply different in facies and stratigraphically not directly connected (especially for subdivisions of synchronous marine and continental deposits), separate schemes of zonal division can be applied.'

This Russian exposition is worthy of note in that it refers clearly and without ambiguity to the 'mutually exclusive' situations in which possibly equivalent zonal schemes contain few or no shared indicator elements in their organic assemblages.

Kinds of biochronologic zone

It is a convention to take sections in rocks of marine origin as major standards for systematization and reference in the Phanerozoic Eon. In these standard successions there are considerable advantages in making a distinction between those zones that are defined in terms of benthonic assemblages and those defined in terms of pelagic assemblages. The former may be expected to have a more restricted lateral geographic application, being more closely facies-controlled, than the latter. The two kinds may be distinguished as *b*-zones and *p*-zones respectively. In all stratigraphic analyses of inter-regional scope, and ideally in all such analyses, the chronological status of the *p*-zones will be higher in terms of inter-regional utility, whereas the *b*-zones will usually allow greater local refinement. An example of this contrast is provided by a comparison of the standard graptolite-based *p*-zones of the British Ordovician Caradoc Series with the approximately corresponding *b*-zones based on brachiopod-trilobite assemblages proposed by Bancroft (1945). Two, and part of a third, *p*-zones are considered by Dean (1958, 1960) to

be equivalent to *fourteen b-zones*. Similarly, in the British Jurassic Cornbrash formation two ammonite *p-zones* correspond to four brachiopod *b-zones* (Arkell 1956), and the thin (less than 35 ft.) formation contains an inter-stage boundary.

Delimitation of zones

Stratigraphers have little direct evidence of the ways in which faunal assemblages actually change and replace each other over long periods of time. In fossil assemblages it is generally difficult to distinguish cases of real evolutionary acceleration from cases of simple non-representation in the lithostratigraphic record. In a seemingly fairly uniform and homogeneous formation like the English Chalk, morphological change in some animal groups, such as the echinoids, may appear as a smooth sequence, while in others it may be jerky and show discontinuities. Brinkmann's (1929) work on the (mainly) Callovian Oxford Clay, and its fauna of kosmoceratid ammonites, revealed in an apparently unbroken clay succession a series of discontinuities, some of which ('ammonitenschlachtfelder') were marked by concentrations of ammonite shells. The time 'represented by' these diastems appears to exceed the 'rock-recorded' time. Despite the occurrence of such diastems, and in view of the difficulty of interpreting their 'time-significance', it is often impossible to decide exactly when one zone has 'finished' and another has 'begun', in lithologically homogeneous successions. Conversely, the presence of strongly developed and almost certainly diachronous discontinuities makes it impossible in many cases to be sure of the geochronological significance of the physico-geometrical boundary actually observable.

An example of the difficulties commonly encountered is provided by Young (1959, p. 753): '... the remaining zones are transitional from one to the next. The top of the *Monopleura-Toucasia* zone is drawn at that horizon at which *Caprinuloidea* becomes a more dominant fossil than the combination of *Monopleura* and *Toucasia*. This is a subjective choice and the margin of error is probably plus or minus one and a half feet.'

The correct approach to the general difficulties of the manipulation and ordering of observational data used in determining zones and stages has been set out by McLaren (1959, p. 736): '... the presence of one or two species among the whole fauna indicates that the palaeontologist is dealing with a zone previously recognized some distance away. His knowledge of the evolution or time-range of these species may lead him to suggest their age-equivalence to the previously-recognized zone. This procedure involves the application of hypothesis (an "act of faith") ... and ... is ... dominantly subjective. ... Finally ... he may state that in his opinion the rocks are of Palaeozoic, or Devonian, or late Cretaceous, or early late Norian age. This is purely subjective and depends on application of a series of hypotheses. ... Palaeontologic correlation is a difficult and skilled discipline, requiring a high order of experience and judgment. ...'

It cannot be too strongly emphasized that biochronologic zones are not entities capable of determination by means of real boundary surfaces to which real 'time value' can be ascribed. Nor can zonal boundaries be said to exist, except in odd and very exceptional surfaces, *by themselves*. Nevertheless, the orderly procession of zones has real significance in geochronological analysis. The criterion for the validity of a zone must be its regular and universal position in space above a precedent zone and below a following one in a 'sandwich' pattern. The construction of the refined stratigraphic column as we now understand and use it has depended on a leap-frog advance from one

sandwich relationship to another, progressively, from zones of the Lower Cambrian to those of the Pliocene and Pleistocene. The recognition of the presence of a zone by means of the fossils contained in rock strata precedes conceptually, and is more important than the pragmatic need to specify zonal boundary surfaces intended to delimit the zone for purposes of reference or reproduction. The fossil evidence can only signal the presence of 'rock-record' indicating a *general age*, i.e. a non-limited sector of elapsed time, in the way that the sound of a human voice indicates the presence of a person without being capable of indicating the shape or position of that person. It therefore follows that the zonal sequence should almost always be in a state of incipient refinement, as unsuspected gaps are filled in by the discovery of more complete successions. It must also be borne in mind that the more completely the rock record seems to 'account for' elapsed time the more difficult it must become to draw inter-zonal transitions. It remains true of most stratal sequences that physico-geometrical surfaces are without geochronological significance. Only where extremely sharp biochronological breaks occur, or where several zonal assemblages follow each other in a much reduced thickness of strata, can physico-geometrical surfaces be said to approximate fairly closely to the condition of chronological significance, and even this must be regarded as strictly local.

The important principle to establish is the conceptual precedence and validity of the biochronologic zone as an entity without rigidly determinable boundaries, as against the artificial pragmatic requirement of dividing-lines on a geochronologic scale on maps and descriptive tabulations.

Status of the Stage

In most Phanerozoic regional stratigraphic analyses the stage is now the basic division for correlation and interpretation. It is necessary, therefore, to investigate the current status and usage of the stage as a concept. Some recent examples of such usage are set out below.

- (i) Young (1960, p. 347): 'Albert Oppel . . . gave the zone its present stratigraphic concept [*sic*] by making it a subdivision of a stage.'
- (ii) Storey and Patterson (1959):
 - (a) p. 709: 'D'Orbigny's stratigraphic zone is more familiar from its adoption and refinement by Oppel as a subdivision of a stage.'
 - (b) p. 719: 'It is serious violation of stratigraphic principles to consider that a regional unconformity occurs within a stage.'
 - (c) p. 715: 'Zone, stage, series, system and group are not palaeontological units and should not be confused with geological time units. The latter are bounded arbitrarily by abstract time-planes which should not be confused with real stratigraphic boundaries.'
- (iii) Wheeler (1959, pp. 697-8): ' . . . boundaries between units of constant time-value must be established arbitrarily, and those between time-variable units occurring within maximum time-limits (such as system, series, and stage) are in part arbitrary and in part natural. Configuration of all other space-time units is controlled by natural phenomena such as deposition, non-deposition and erosion.'

From these examples it is immediately clear that the biochronologic zone is considered to be a subdivision of a stage. However, this was not the intention of Oppel,

rightly regarded as the architect of the modern systematic zonal scheme, following, as Jeletzky points out (1956, p. 703), the pioneer work of D'Orbigny (1842-9). Oppel (1856-8), tabulating the zonal sequence in the European Jurassic rocks, set out three columns, headed *Formationsabteilungen*, *Etagen oder Zonengruppen*, *Zonen*. The use of the word *étage* is derived from D'Orbigny, who had recognized in the Jurassic rocks of France a regular succession of ten distinct faunal assemblages. Oppel's work, in effect, resulted in an increase in the number of faunal assemblages that could be distinguished in the Jurassic rocks, from ten to thirty-three. At the same time Oppel rearranged D'Orbigny's terminology, so that the stages now became groups of zones, *the zone being the primary unit*.

It is from this historical base that Arkell (1956, p. 7) derived his formulation of the relation between stage and zone: 'Just as it is convenient to group together formations into series,* so it is convenient to group like zones together and reduce the numbers for practical purposes, and above all to have a grouping which enables several zones to be correlated in a general way over long distances when the zones individually are too precise. Such groupings of zones are stages.' Later (p. 9) Arkell elaborates this definition: 'As units of the single world scale of classification Stages must be based on zones. As now used they are essentially groupings of zones, but they transcend zones both vertically and horizontally. . . .' Again (p. 11): 'The possibility of describing and analysing a geological system as a whole, all over the world, depends primarily on availability of a single universal language for use in classification. This language the stages provide. . . .' Finally (p. 9): 'When a new fauna is found . . . not present or not detected at the type locality, it falls readily into place if it comes between two zones already in the stage, but if it falls at the boundary between two stages it has to be classed according to its nearest palaeontological affinities.'

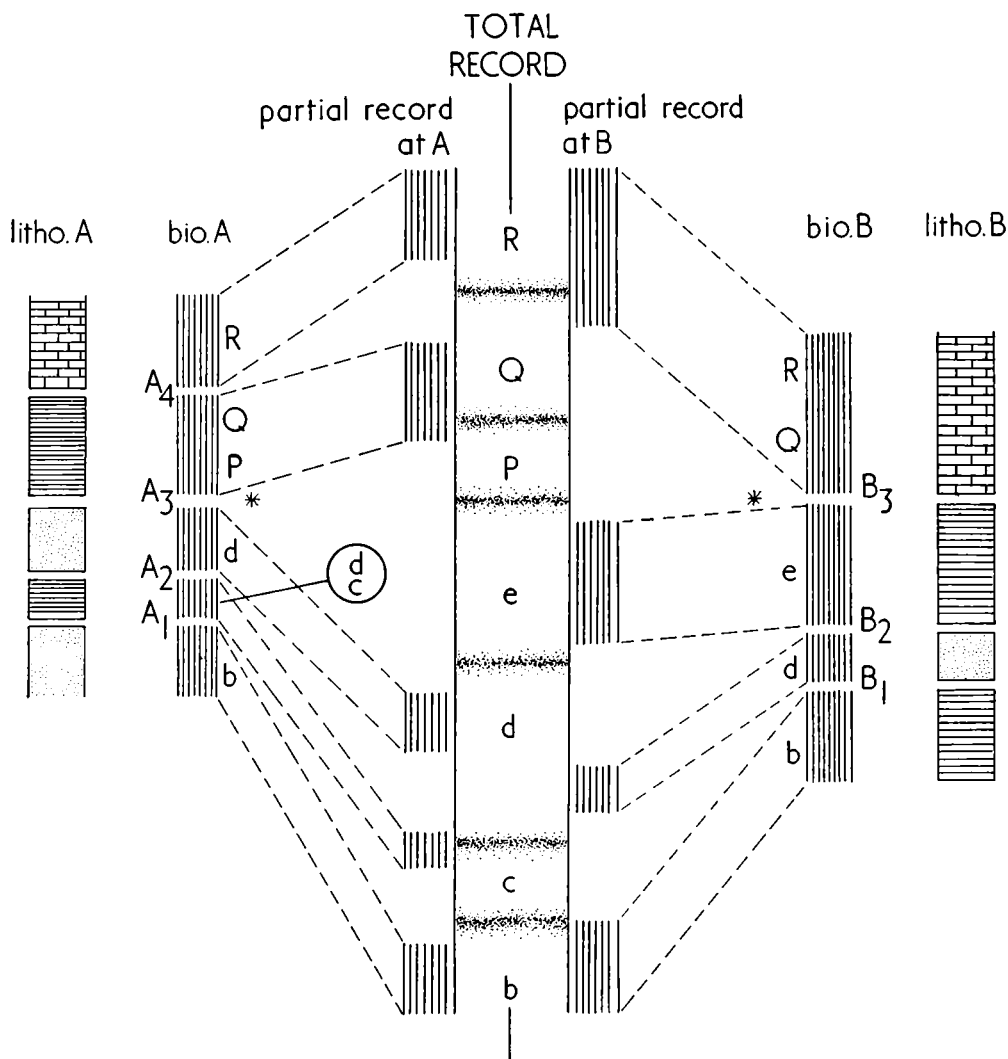
We may thus conclude that although the stage must be regarded as the most convenient unit for long-range correlation and, therefore, as the basic unit in inter-regional stratigraphic analysis, it is not itself the primary biochronologic unit. This primary quality clearly resides, as we have seen, in the biochronologic *zone*. It is possible that confusion has arisen in the minds of many stratigraphers from the appearance, in the usual setting-out of hierarchical geochronological organizational systems, of the stage as 'superior' to the zone. But in fact this 'superiority' does not imply primacy. Just as, in military terms, a battle-group or division may be (erroneously) considered as *divided* into brigades, battalions, and squadrons, in fact such a group is *made up* of the subordinate units, whose existence is anterior to the larger category, itself more arbitrary and abstract than its components. Similarly, the biochronologic zone is anterior to the stage, but, in Arkell's words, is transcended by the more abstract conception of the stage. 'Whereas the individual zone cannot be recognized beyond the area of occurrence of its index species or typical fauna, a stage can be followed all over the world by a series of overlapping correlations, and by the general grade of evolution of its critical fauna' (Arkell 1956, p. 7).

* This use of *series* is, of course, wrong. The lithostratigraphic term used to unite a number of formations is *group*.

CONCLUSIONS

From the several aspects of stratigraphic analysis discussed above it emerges that geochronologically significant conclusions can only be reached by means of radiometric

or biological data. Physico-geometrical data (apart from radiometric) can do no more than provide a crude local relative chronology, or circumstantial evidence in support of a biochronologic framework. The historical development of stratigraphic studies has led to the adoption of a set of time-indices which have acquired an appearance



TEXT-FIG. 1. Diagrammatic model to illustrate the geological time problem.

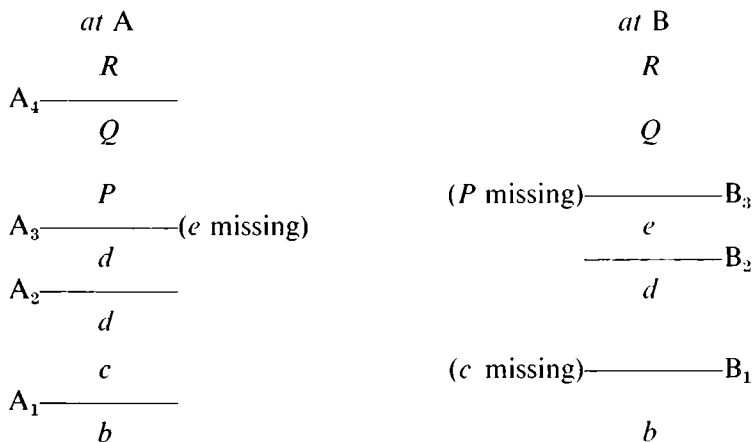
of independence, but which are, in reality, biochronological. The notion of theoretically identifiable 'time-stratigraphic' indices is considered invalid and is rejected.

In order to provide a visible illustration, and if possible a clarification of the geological time problem, a diagrammatic model is set out in text-fig. 1, of which the centre column represents an 'ideal' of separate, individually synchronous surfaces, in a sedimentation-situation of unbroken, steady-rate accumulation. The fossils contained within such an

uninterrupted succession are assumed to be reducible to zonal assemblages grading into each other. Index letters are attached to successively distinguishable assemblages, and it is further assumed that an upper and lower grouping on biological grounds, stemming from a real developmental progression, permits the recognition of two stages, one with zones *b*, *c*, *d*, and *e*; the other with zones *P*, *Q*, and *R*.

The two narrow columns immediately flanking the central one represent *actual* sedimentation records at two separate localities A and B. The vertically ruled sectors show positive episodes of preserved sedimentation, while the intervening blanks record neutral (non-depositional) or negative (deposition-with-erosion) intervals. In each case the appropriate fossils are assumed present in the preserved sectors, which are correctly placed in relation to the central complete record.

The two outermost columns on each side show the actual lithostratigraphic and biostratigraphic successions available to observers at A and B, i.e. they reproduce the inner records, but closed up into a contiguous sequence, with diastems numbered A_1 —, B_1 — respectively, and lithologies indicated by conventional ornament. In terms of biochronologic zones and diastems the two successions are



It will be noticed that the two lithostratigraphic successions are superficially similar, but in terms of the unknown ideal succession of the centre column, only at the extreme top and bottom (i.e. in the *R* and *b* zones) was sedimentation in fact proceeding at the same time at the two places. Moreover, only three cases of 'real' inter-zonal transitions are to be found, namely, *c/d* and *P/Q* at A, and *Q/R* at B. No boundary line can, of course, be drawn for these. Where physical breaks (diastems) occur, and appear to coincide with inter-zonal boundaries, as at *b/c* and *Q/R* at A; and at *b/d*, *d/e*, and *e/Q* at B, the missing sectors cannot be estimated unless sub-zonal discrimination is possible. It is therefore not permissible to regard such boundaries, identified at different localities, as isochronous, unless the amount of interval is precisely measurable in biochronologic terms. It will also be noticed that the inter-stage boundary (at A₃ and B₃) is clearly identifiable at the two localities, but has different duration-significance in the two cases.

Considered in terms of the crude lithological successions, apart from the misleading similarity of the two columns, there would be a strong temptation to draw an important boundary line at the base of the uppermost lithological type, i.e. at diastems A₁ and B₃.

While at B this 'contains' a true inter-stage boundary, at A it is chronologically considerably above the base of the upper stage.

This model brings out the primacy of the biological evidence in geochronological analysis, and shows that sequential division must be in terms of *intervals*, which represent more or less temporal duration, rather than synchronous surfaces, which, although imaginable, and ideally present, cannot at present be detected in sufficient number to be practically useful.

Acknowledgements. I am indebted for valuable discussion of some of the problems of stratigraphic analysis to Dr. B. K. Holdsworth, Dr. J. M. L. Lambert, and Mr. J. E. Thomas.

REFERENCES

- ADAMS, J. A. S. and ROGERS, J. J. W. 1961. Bentonites as absolute time-scale calibration-points. *Ann. N.Y. Acad. Sci.* **91**, 390-6.
- AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE. 1961. Code of Stratigraphic Nomenclature. *Bull. Amer. Assoc. Petr. Geol.* **45**, 645-65.
- ARKELL, W. J. 1952. Jurassic ammonites from Jebel Tuwaig, Central Arabia. *Phil. Trans. Roy. Soc. B* **633**, 236, 241-313.
- 1956. *Jurassic Geology of the World*. Edinburgh: Oliver & Boyd, xiv+806.
- BANCROFT, B. B. 1945. The brachiopod zonal indices of the stages Costonian to Onnian in Britain. *J. Palaeont.* **19**, 181-252.
- BELL, W. C., KAY, M., MURRAY, G. E., WHEELER, H. E., and WILSON, J. A. 1961. Report of Sub-Committee of American Commission on Stratigraphic Nomenclature: Note 25—Geochronological and Chronostratigraphic units. *Bull. Amer. Assoc. Petr. Geol.* **45**, 666-73.
- BRINKMANN, R. 1929. Statistische-biostratigraphische Untersuchungen an mittel-jurassischen Ammoniten über Artbegriff und Stammesentwicklung. *Abh. Gesell. Wissensch. zu Göttingen, M.-Ph. Klasse N. F.* **13**, 1-250.
- DEAN, W. T. 1958. The faunal succession in the Caradoc Series of South Shropshire. *Bull. Brit. Mus. (Nat. Hist.) Geology*, **3**, 193-231.
- 1960. The Ordovician trilobite faunas of South Shropshire. I. *Ibid.* **4**, 73-143.
- D'ORBIGNY, A. 1849-52. *Cours élémentaire de paléontologie et de géologie stratigraphique*, 2. Paris.
- FAMES, F. E., BANNER, F. T., BLOW, W. H., and CLARKE, W. J. 1962. *Fundamentals of Mid-Tertiary Stratigraphic Correlation*. Cambridge: University Press, viii+151.
- HALLAM, A. 1963. Major epeirogenic and eustatic changes since the Cretaceous, and their possible relation to crustal structure. *Amer. J. Sci.* **261**, 397-423.
- HEDBERG, H. D. 1948. Time-stratigraphic classification of sedimentary rocks. *Bull. Geol. Soc. Amer.* **59**, 447-62.
- 1958. Stratigraphic classification and terminology. *Bull. Amer. Assoc. Petr. Geol.* **42**, 1881-96.
- 1959. Towards harmony in stratigraphic classification. *Amer. J. Sci.* **257**, 674-83.
- 1961. The stratigraphic panorama. *Bull. Geol. Soc. Amer.* **72**, 499-518.
- HENSON, F. R. S. 1944. Stratigraphic classification and nomenclature. *Geol. Mag.* **81**, 166-9.
- INTERNATIONAL SUBCOMMISSION ON STRATIGRAPHIC TERMINOLOGY. 1961. Statement of Principles of Stratigraphic Classification and Terminology (H. D. Hedberg, ed.) *Rep. XXI Int. Geol. Cong.* pt. 25, 1-38.
- JELETZKY, J. A. 1956. Palaeontology the basis of practical geochronology. *Bull. Amer. Assoc. Petr. Geol.* **40**, 679-706.
- JUKES-BROWNE, A. J. 1886. *Handbook of Historical Geology*. London: Bell, xi+597.
- LAPWORTH, C. 1879. On the Ordovician system. *Geol. Mag.* **16**, 13-14.
- MCLAREN, D. J. 1959. Role of fossils in dating rock units. *Amer. J. Sci.* **257**, 734-51.
- MARR, J. E. 1898. *Principles of Stratigraphical Geology*. Cambridge: University Press, 304.
- OPPEL, A. 1856-8. *Die Juraformation Englands, Frankreichs, und des südwestlichen Deutschlands*. Stuttgart.

- RODGERS, J. 1959. The meaning of correlation. *Amer. J. Sci.* **257**, 684–91.
- ROTAY, A. P. (ed.) 1960. Stratigraphic Classification and Terminology (Second edition). *Nat. Comm. Geol. U.S.S.R.* Moscow: State Publishing Office, 59.
- SANDERS, J. E. 1957. Discontinuities in the stratal record. *Trans. N.Y. Acad. Sci. Ser. II*, **19**, 287–97.
- SCHEERE, J. 1955. Contribution à l'étude des tonstein du terrain houiller belge. *Publ. Assoc. pour l'étude de la paléontologie et de la stratigraphie houillère*, **19**,
- SMART, J. J. C. 1956. In FLEW, A. G. N. (ed.) *Essays in Conceptual Analysis*. London: Macmillan, xi+265.
- STOREY, T. P. and PATTERSON, J. R. 1959. Stratigraphy—traditional and modern concepts. *Amer. J. Sci.* **257**, 707–21.
- STUBBLEFIELD, C. J. 1958. In WHEELER, H. E. 1958 (discussion). *Colloques internationaux du Centre national de la recherche scientifique*, **76**, 15–23.
- TEICHERT, C. 1958. Biostratigraphic concepts. *Bull. Geol. Soc. Amer.* **69**, 99–119.
- WHEELER, H. E. 1958a. Primary factors in biostratigraphy. *Bull. Amer. Assoc. Petr. Geol.* **42**, 640–55.
- 1958b. Time-stratigraphy. *Ibid.* **42**, 1047–63.
- 1959. Stratigraphic units in space and time. *Amer. J. Sci.* **257**, 692–705.
- and BEASLEY, E. M. 1948. Critique of the time-stratigraphic concept. *Bull. Geol. Soc. Amer.* **59**, 75–86.
- and MALLORY, V. S. 1956. Factors in lithostratigraphy. *Bull. Amer. Assoc. Petr. Geol.* **40**, 2711–23.
- WHITROW, G. J. 1961. *The Natural Philosophy of Time*. Edinburgh: Nelson, xi+324.
- WILSON, J. A. 1959. Transfer, a synthesis of stratigraphic processes. *Bull. Amer. Assoc. Petr. Geol.* **43**, 2861–2.
- WRIGHT, W. B. 1926. Stratigraphic diachronism in the Millstone Grit of Yorkshire. *Rep. Brit. Assoc. Adv. Sci.* 354.
- YOUNG, K. 1959. Technique of mollusc zonation in Texas Cretaceous. *Amer. J. Sci.* **257**, 752–69.
- 1960. Biostratigraphy and the new palaeontology. *J. Palaeont.* **34**, 347–58.

T. G. MILLER
Department of Geology,
Keele University,
Staffordshire

Manuscript received 10 February 1964