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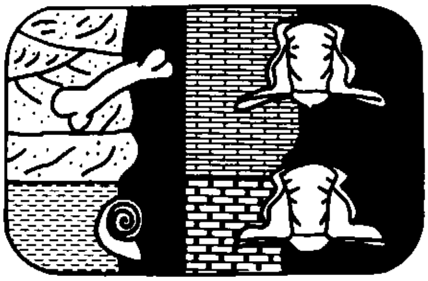

PALEOSCENE #3. Dual Biostratigraphy: Zones and biofacies

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Introduction

The passage of time can be determined according to various dating techniques and ordering criteria in geology. Of these, biostratigraphic study of fossils in rock is the most practical, most economical, and arguably the most accurate means of measuring geologic time. The fossil record extends back to the early Archean (Schopf, 1983), but biostratigraphy is effectively applicable only to Phanerozoic strata where abundant skeletonized fossils permit a finely divided relative time scale (Harland *et al.*, 1982).

Biostratigraphy has its roots in the classic empirical work of Smith, Cuvier, and Brongniart in the first decade of the 19th century (Rudwick, 1972) which demonstrated that units of strata could be characterized and correlated on the basis of fossils (Berry, 1968). Recognition that a well-differentiated and non-repeating fossil record was the product of, and indeed confirmation of, organic evolution followed half a century later as stratigraphic paleontology was re-interpreted in light of Charles Darwin's revolutionary theory (Bretsky, 1979).

Every geologist involved in correlating and mapping Phanerozoic rocks has had to assess biostratigraphic information provided by a paleontologist. Such data are most commonly in the form of age determinations of fossil collections — Early Ordovician, Arenigian, or *Tetragraptus fruticosus* Zone — the precision depending on the size, nature, and preservation of the collections. Naturally, most geologists have assumed that biostratigraphy is concerned only with the temporal significance of fossils in rocks; that is, with the *age* of rock units, with the drawing of *time lines* in strata, and with the establishment of relative *time scales*. The spatial significance of fossils in rocks has seldom been satisfactorily integrated into biostratigraphic analyses, but this aspect is potentially as significant as the traditional temporal aspect (Kleinpell, 1938, p. 32).

The concept of facies is fundamental to both biostratigraphy and lithostratigraphy and forms a strong unifying theme. Biostratigraphic units (zones, biofacies), like lithostratigraphic units (formations, lithofacies), are three-dimensional mappable units whose distribution in strata is influenced by environmental factors. Both biofacies and lithofacies were clearly identified in Gressly's (1838) original formulation of the facies concept and in Walther's seminal *Principle of Correlation of Facies* (see Hancock, 1977; Middleton, 1973). Lithofacies studies have been central to the recent resurgence of interest in stratigraphic models and syntheses — for example, in the development of facies models (Walker, 1984) and for basin analysis (Miall, 1984) — but biofacies have rarely been fully utilized in stratigraphic contexts. Indeed, techniques such as "index fossil" biostratigraphy, graphic correlation, and chronostratigraphy, attempt nothing less than to expurgate facies from biostratigraphy.

Here, we emphasize biostratigraphy as a dual stratigraphic discipline that is equivalent to lithostratigraphy in both scope and application. Biostratigraphy may be defined as that branch of stratigraphy that is concerned with recognition and mapping of fossil units in rock, and with their temporal and spatial significance. From this perspective, a major task of biostratigraphy is to separate, as clearly as possible, the temporal and spatial controls on the distribution of fossils in rock. This is best done with separate units — zones and biofacies, respectively.

Zones are best defined by species range data, simply because species have the short temporal durations necessary for the establishment of fine divisions. For biostratigraphy, biofacies should be defined at generic or higher levels in order to produce units with significant stratigraphic ranges which may, in turn, be used to gauge the degree of environmental association of biotas. Thus, segregation of the spatial and temporal components is based on analyses of fossil collections at different taxonomic levels — genera for biofacies and species for zones.

Walther's Principle emerges as an essential key to biostratigraphic analysis — a sequence of biofacies is set up within a lithofacies framework and successions of zones are established for the biofacies belts (Figure 1).

Our examples are drawn largely from trilobites in Lower Paleozoic rocks, but the dual biostratigraphic method we propose is equally applicable to other benthic or nekto-benthic organisms in Phanerozoic rocks.

"Index Fossil" Biostratigraphy

The "index fossil" concept represents the traditional approach to isolation of the temporal component of biostratigraphy. Text books of historical geology invariably make a distinction between two kinds of fossils — those with short vertical ranges occurring in a variety of lithofacies are given the accolade "excellent index fossils", whereas those with long vertical ranges occurring only in single lithofacies are denigrated as "poor index fossils" or, worse, as "facies fossils" (Dott and Batten, 1981, p. 57-58; Stanley, 1985, p. 115-116). The "index fossil" approach implies that some groups of organisms are immune to environmental influences, so that time is the only important control on their distribution. Such "index fossils" are supposedly infallible guides to the age of strata. Groups whose distribution indicates control by environmental factors are regarded as poor sources of biostratigraphic data and, accordingly, they tend to be avoided. "Index fossil" biostratigraphy misses a vast source of fossil distributional data by emphasizing temporal ranges at the expense of spatial ranges.

The approach to earth history inherent in "index fossil" biostratigraphy bears a curious similarity to that shown by Abraham Werner's global lithostratigraphic system of the late 18th century (see Berry, 1968). In both systems, the historical products (fossils and rock types) are arranged, like layers of an onion, in a single, world-wide, non-repeating temporal sequence such that the identification of a unique element of either sequence provides an age determination. Werner's global lithostratigraphic system collapsed when it was demonstrated that his lithologic units are not world-wide in extent, but instead are the products of local environmental conditions (that is, facies). "Index fossil" biostratigraphy is compromised for the same reason, as is any other biostratigraphic technique based on the premise that time alone governs the vertical order of fossils (for example, Shaw's, 1964, graphic correlation method).

By calling for the demise of "index fossil" biostratigraphy, we are not denying that some fossil species have very wide distributions that encompass many continents; merely that such species are rare. Evidence from fossil and recent marine invertebrates indicates an inverse relationship between geographic and environmental ranges and rates of speciation and extinction (Jackson, 1977; Hansen, 1980). Geographically widespread species usually have long stratigraphic ranges whereas those of geographically restricted species are invariably short — the "biostratigrapher's paradox" of Scheltema (1977, p. 106). Moreover, many of the time-honoured groups of "excellent index fossils" have now been shown to be influenced by facies — graptolites (Finney, 1984; Lenz and Chen, 1985), ammonites (Ziegler, 1981; Bayer and McGhee, 1985) and conodonts (Clark, 1984).

Biostratigraphic Units

A scientific discipline is, in large measure, defined by the nature and classification of its units. Thus, the concept of biostratigrahy as a dual discipline is exemplified by a nested classification of two types of units. Temporal and spatial units serve to partition, to measure, and to name different aspects of biotic patterns in rock. Both are necessary for full biostratigraphic analysis.

The relationship of temporal biostratigrahy and evolutionary paleobiology on one hand, and spatial biostratigraphy and paleoecology on the other, requires explanation. Eldredge and Gould (1977) noted that the establishment of a zonal scheme (temporal biostratigraphy) is a purely empirical procedure that does not depend on an understanding of the processes of species origin. Similarly, the establishment of a sequence of biofacies (spatial biostratigraphy) is a procedure which demands no prior knowledge of the various physical and biological factors responsible for limiting the distribution of taxa. In other words, there exists a pattern-process linkage between the pairs of disciplines; with temporal and spatial biostratigraphy defining the vertical and lateral distributional patterns, and evolutionary paleobiology and paleoecology dealing with the underlying processes.

Temporal biostratigraphic units. The zone, the traditional unit of biostratigraphy, was first conceived by Albert Oppel (1856) for a sequence of strata characterized by a unique association of species. Oppel's

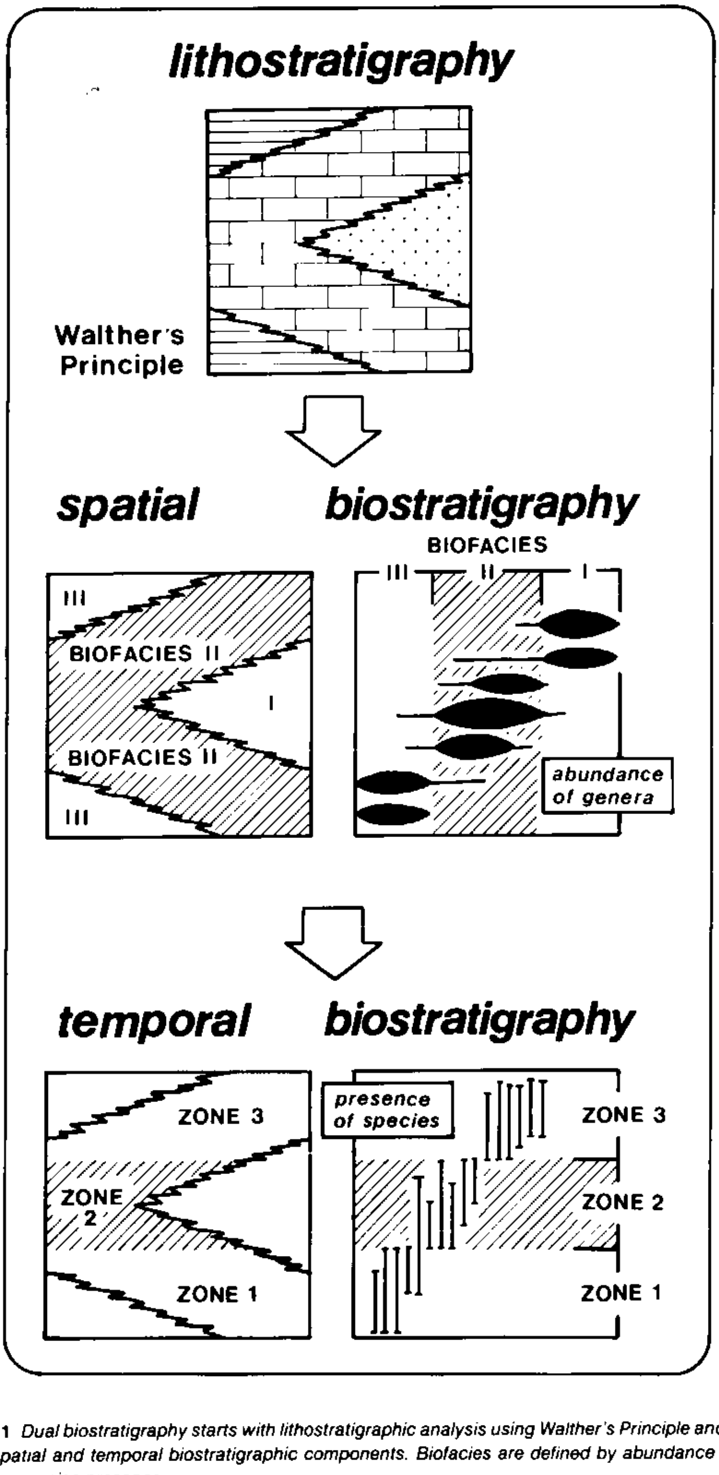

Figure 1 *Dual biostratigraphy starts with lithostratigraphic analysis using Walther's Principle and proceeds to the spatial and temporal biostratigraphic components. Biofacies are defined by abundance of genera; zones by species presence.*

biostratigraphic method was remarkably modern and involved documentation of the vertical ranges of all species in a number of sections. Zones were defined to include persistent and exclusive co-occurrence of the same species in different sections. Oppel set up 33 Jurassic zones in western Europe and claimed that each was the same age at all localities. As Hancock (1977) noted, Oppel's definition and analysis of zones marked the birth of the *discipline* of biostratigraphy as opposed to the *practice* of biostratigraphy which dates back to William Smith in the early years of the 19th century (Smith, 1817). Oppel grouped his zones in the stages that had been introduced a few years before by Alcide d'Orbigny (1849-52) as large-scale biostratigraphic units which were defined as bodies of strata characterized by fossil associations and developed independently from lithofacies (Monty, 1968). Oppel's zones were named for important species, commonly ammonites, whereas d'Orbigny's stages were named for geographic localities.

Thus, by the latter part of the last century, a nested classification of biostratigraphic units existed — a stack of zones making up a stage. These units were defined on the basis of fossils in rock and, therefore, were obviously biostratigraphic in nature. In this century, the simple and straightforward arrangement has been augmented, refined, redefined, and undermined to such an extent that now, one hundred years after the deaths of Oppel and d'Orbigny, there exists no generally accepted understanding of the meaning of the terms zone and stage. A plethora of names obscures the true nature of a zone and a stage is no longer considered to be a biostratigraphic unit by many investigators.

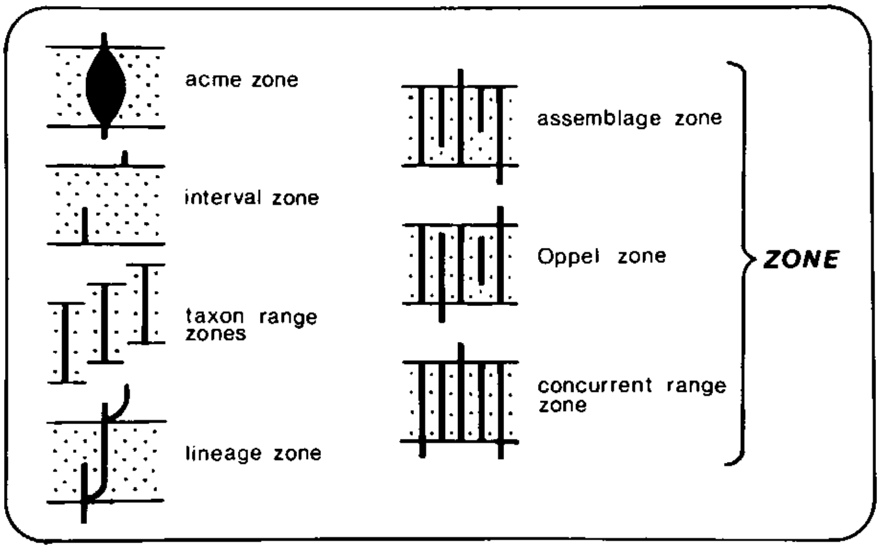

Figure 2 *The plethora of different zonal types is unnecessary. The four types in the first column are superfluous. The three types in the second are here lumped under the plain name zone.*

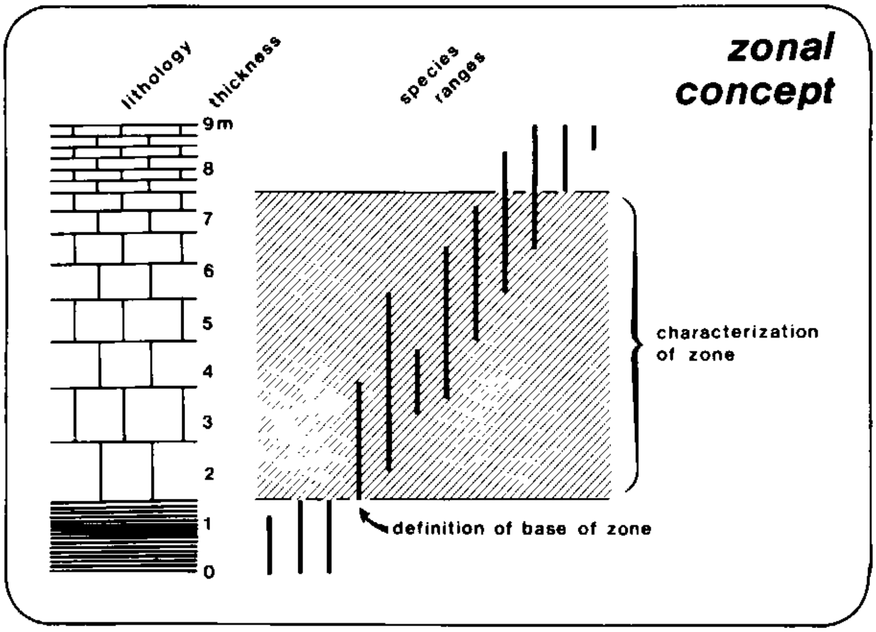

Figure 3 *A zone is characterized by the presence of an assemblage of species in a body of strata; its base is defined by the first occurrence of a single species; its top by the base of the succeeding zone.*

In general, taxonomists of paleontologic or stratigraphic items fall into two camps — *splitters* who seek to subdivide entities on the basis of minute differences and *lumpers* who attempt to unite entities on the basis of shared characters. The current terminology of zones reflects one hundred years of rampant splitting. The major kinds of commonly recognized zones include assemblage zones, taxon range zones, lineage zones, concurrent range zones, Oppel zones, acme zones and interval zones (for example, Hedberg, 1971, p. 10-21).

This list of differently-named zones is largely superfluous. Most types may be eliminated with little loss. Taxon range zones or teilzones are merely overlapping ranges of different species at one locality and therefore contribute little to the definition of intervals of strata. The establishment of lineage zones amounts to a restatement of species range data as ancestor-descendant scenarios; at best, a questionable procedure (see Forey, 1982, for an incisive critique of such "paleontological stories"). We concur with Eldredge and Gould (1977, p. 38) that, "there seems to be no way to use ancestor-descendant relationships in biostratigraphic research". Acme zones deal with taxon abundance through stratal intervals and, as such, belong with biofacies in spatial biostratigraphy. Interval zones have no internal characteristics — they are merely the stratal thickness between unrelated biostratigraphic horizons. Differences between an Oppel zone, a concurrent range zone, and an assemblage zone are obscure or trivial; they are lumped under the plain name *zone* (Figure 2; see also Johnson, 1979, p. 936).

We advocate a return to biostratigraphic roots by considering a zone to be simply an interval of strata that is *characterized* by an association of a number of species, the base of which is *defined* by the first occurrence of a single species at a stratotype, and which can be *correlated* beyond the stratotype (Figure 3; see also Murphy, 1977). Its top is the base of the succeeding zone and it takes its name from a single species.

Sequences of zones define stages in the temporal biostratigraphic hierarchy and stages define series which, in turn, define systems (Figure 4). The base of each unit indicates the base of the next unit in the hierarchy; therefore, each stage, series, and system is effectively defined by the first occurrence of a single species at the base of a zone. For example, the base of the

Monograptus uniformis Zone at a boundary stratotype at Klonk, Czechoslovakia now defines the bases of both the Lochkovian Stage and the Devonian System (Martinsson, 1977) and indicates the top of the underlying zone, stage, and system at this locality.

Recognition of any biostratigraphic unit rests upon identification of a characteristic association of fossils and, because all biotic associations are subject to geographic and facies restriction, it follows that no temporal unit can possibly be applied to all rocks of the same age on all continents. Zonal sequences are typically defined on the basis of species of one biotic group, and may well be restricted to single bio- and lithofacies belts on a part of a continent. Stages often encompass a number of zonal sequences defined for different biotic groups and for different areas of a single continent or province. Series may embrace different stadial sequences for the distinct biotas of, for example, marine and lacustrine environments, and ideally they incorporate different regional stadial sequences of an entire continent. Systems differ from other biostratigraphic units because convention has dictated that they are to be applied to all facies and provinces on all continents.

Spatial biostratigraphic units. Spatial biostratigraphy uses units that have previously been restricted to paleoecology and paleobiogeography. The biofacies, the basic unit of spatial biostratigraphy, has been a central component of the facies concept since the days of Gressly and Walther. Indeed, Walther's Principle was formulated as the "Law of Correlation of Biotopes" before it was applied to lithofacies (Middleton, 1973).

The term biofacies, like lithofacies (Walker, 1984), has been used in many different ways (either abstract or concrete, descriptive or interpretive). We retain the traditional meaning of biofacies as a biotic stratigraphic unit of environmental signifance but, for biostratigraphic purposes, restrict its application to stratal intervals characterized by associations of genera or higher taxa. Of course, biofacies could also be established for associations of species, but in such cases, the spatial signal cannot easily be separated from the temporal signal. We prefer to define biofacies with relative abundance data, but presence-absence data could also be used. Definition of biofacies may be made by visual inspection of relative abundance data shown, for example, by simple pie diagrams, but quantitative techniques such as cluster analysis produce more rigorously defined units and displays the degree of linkage between biofacies (see Macdonald, 1975; Ludvigsen and Westrop, 1983; Ward, 1985).

The distribution of many biofacies (or communities or associations) established on the basis of generic relative abundance of benthic or nekto-benthic organisms displays close correspondence to substrate type or lithofacies (for example, McGhee and Sutton, 1981, p. 40; Brenchley and Cocks, 1982, p. 806; Kaljo, 1982, p. 13), but this need not always be the case (see Ludvigsen, 1978; Noble, 1979).

Some investigators have dealt with spatial biostratigraphy under different names. The discipline termed ecostratigraphy by Martinsson (1973) shares some similarities with dual biostratigraphy as outlined here. Ecostratigraphy attempts to define and correlate fossil ecosystems in strata by the explicit use of biostratigraphic techniques (see Kaljo and Klaamann, 1982). Ecosystems are defined as "fossil communities" developed within distinct lithofacies belts (in effect, spatial biostratigraphic units) which are then allocated to a zonal framework. Despite repeated attempts to justify a unique position for ecostratigraphy within stratigraphy (Waterhouse, 1976; Hoffman, 1981), this discipline remains, in theory as well as in practice, biostratigraphy in a facies context. A different name is not required.

In the hierarchy of spatial biostratigraphic units proposed here (Figure 4), biofacies define provinces which, in turn, define realms; that is, closely paralleling Valentine's (1973) hierarchy of ecologic units. If faunal differentiation is particularly strong, an intermediate level, the subprovince, might be inserted between the biofacies and the province.

Correlation of biostratigraphic units. Biostratigraphy concerns both classification and correlation of strata on the basis of fossil content — two goals that are operationally distinct. Classification is inherently a regional endeavour through which the fossils and strata of one area are arranged into hierarchies of spatial and temporal biostratigraphic units. Correlation is an extra-regional procedure by which the sequence of biostratigraphic units of one area are temporally aligned with those of another area. Different characteristics of strata can be exploited for correlation between regions (Dunbar and Rodgers, 1957, p. 272-283), but detailed correlation should be based on shared species.

The ability to correlate two different zonal sequences does not require that one of these sequences becomes redundant, any more than correlation of two formations means that one name should be applied to both lithologic units.

Biostratigraphy and Time

Techniques and methods that measure the duration of elapsed time between recorded events are essential to all historical sciences. Therefore, the seemingly rational stratigraphic triad championed by Hollis Hedberg, long-time chairman of the International Subcommission of Stratigraphic Classification, has been accepted widely. Hedberg (1976; see also North American Stratigraphic Code, 1983) proposed that stratigraphy should consist of litho-, bio-, and chronostratigraphy as formal disciplines concerned with rocks, fossils, and time. Units of the first two may be defined and characterized objectively on the basis of rock and fossil records. But what about chronostratigraphy?

Hedberg claimed that the basic unit of chronostratigraphy is the chronozone, a tabular entity bounded by imaginary time planes which project from the base and top of a biostratigraphic zone into all facies to encircle the globe. Chronozones are grouped together into stages. Chronostratigraphic boundaries are, by Hedbergian fiat, isochronous and therefore superior to biostratigraphic boundaries which tend to be

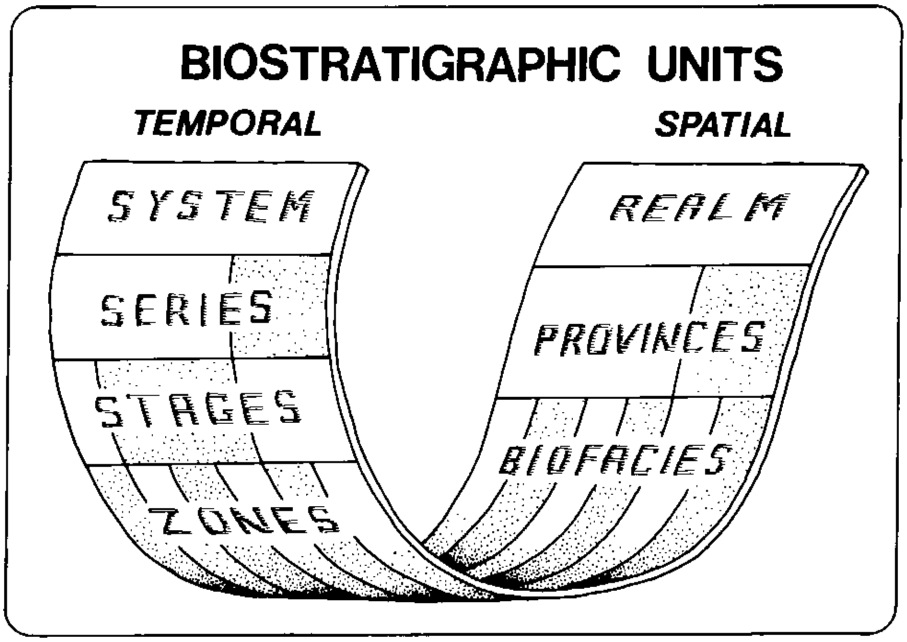

Figure 4 *The two classes of biostratigraphic units are interdependent and hierarchic in nature.*

diachronous. However, an isochronous boundary is of little use if it cannot be recognized by objective criteria. The fact remains that the boundary of a chronozone is fixed and determinable in strata *only* where it coincides with the boundary of a biostratigraphic zone (see also Jeletzky, 1956, p. 699; Dunbar and Rodgers, 1957, p. 293; Donovan, 1966, p. 158). In other words, "what chronozones attempt to be is impossible in the real world" (Johnson, 1979, p. 940). It follows that a chronozone is either an illusion or else identical to a biostratigraphic zone. Therefore, the foundations of chronostratigraphy as a separate discipline crumble (Wiedmann, 1970, p. 42). Time cannot be used as a primary diagnostic criterion of a stratigraphic unit because all time information in stratigraphy is derived from rocks and fossils (Watson, 1983). The stage and higher units, appropriated for chronostratigraphy by Hedberg, should be restored to biostratigraphy.

Some paleontologists have claimed that the biostratigraphic distribution of certain fossil groups is so good that it is, in effect, chronostratigraphic — for example, ammonites (Woodford, 1963, p. 96), conodonts (Sweet, 1984, p. 33), and graptolites (Berry and Boucot, 1970, p. 26). Hancock (1977, p. 19) responded appropriately to such claims,

> "The fact is that chronostratigraphic units are an imaginary entity of no value, and to claim an ammonite zone to be chronostratigraphic is to debase a practical stratigraphic unit, as well as to deny the biological characteristics of the origin, dispersal, and extinction of species populations — none of which is likely to be isochronous."

So, how does one achieve isochroneity in stratigraphy? Hedberg's approach was simple, but illusory - he legislated isochronous boundaries between chronostratigraphic units. In the real world of stratigraphy, matters are more complex. Isochroneity can probably never be attained, but it can be approached through detailed biostratigraphic analysis of one or more biotic group which leads to a reduction of the degree of diachroneity of biostratigraphic boundaries (see also Scott, 1985).

A zonal succession based on one biotic group can often be used to evaluate the completeness and correlation of a zonal succession based on another group with a different distributional pattern. For example, Bergström (1978) was able to show with conodont biostratigraphy that the North American Ordovician graptolite zonal reference standard in Texas contains a significant hiatus of measurable duration.

Temporal biostratigraphic units provide the only practical scale for measuring and naming intervals of Phanerozoic time. A distinction has often been made between the name of a *stratigraphic* interval (zone, stage, series, system) and the name of the corresponding *time* interval (secule, moment, chron, age, epoch, period). Not only is such nomenclature confusing, it is also unnecessary and, moreover, tautologic ("the *T. fruticosus* Zone was deposited during the *T. fruticosus* Chron"). The hierarchy of temporal biostratigraphic units established here obviates the requirement of a separate set of time terms. These units incorporate the best time information possible by stratigraphic means. Reference to the time interval defined by the *T. fruticosus* Zone, Maastrichtian Stage, Wenlock Series, or Devonian System is simple, clear, and unequivocal (see also Jeletzky, 1956, p. 700-701).

Geologic time information is being supplied by radiometric or fission-track dating techniques at an increasing rate. Such dates are very important in a variety of geologic and paleontologic contexts, but they are not stratigraphic in nature and they have never been used as the basis of a separate chronometric classification of Phanerozoic time, such as those devised by Goldich (1968) and James (1972) for Cryptozoic time. A numerical scale in years as a source of time data is distinct and separate from that provided by the sequence of temporal biostratigraphic units. Even though detailed equivalence cannot be drawn between the two scales, it is clearly important to determine approximate durations of biostratigrahic units by numerical dating of minerals or shells from fossiliferous sequences.

A Recipe for Dual Biostratigraphy

Perhaps the clearest statement of dual biostratigraphy comes from a demonstration of how its units are defined and applied in a realistic example; here, one based on benthic fossils in carbonate rocks.

Two measured sections, X and Y, through a single formation comprise three carbonate lithofacies (Figure 5). Fossils occur in all lithofacies and 33 large collections include representatives of eight genera (A-H).

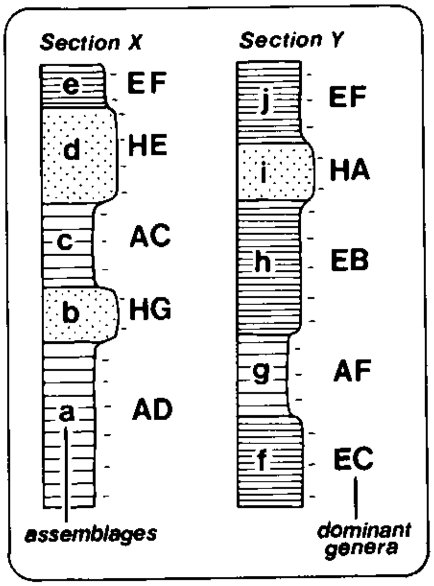

Figure 5 *Biostratigraphic example. Two sections showing three lithofacies (patterns), fossil collections (dashes), and preliminary assemblages (a-j) of genera (A-H).*

Generic relative abundances vary considerably and, for ease of presentation in this example, the collections have been amalgamated into ten assemblages (a-j) according to dominance of different pairs of genera (in an actual study, the analysis would be conducted with individual collections). In this example, the extent of the generic assemblages corresponds to the lithofacies; a reasonable but not an essential postulate.

How many biofacies occur in these strata? How robust are they? And what is their distribution? Answers to these questions of spatial biostratigraphy proceed from generic relative abundance data of specimens in each assemblage (or collection) which are entered as an original data matrix (Figure 6) and then subjected to statistical analysis. We have used cluster analysis in our example, but other techniques, such as factor analysis or ordination, may be equally appropriate. Different coefficients of association can be used in cluster analysis; we prefer Pearson's product-moment correlation coefficient (Ludvigsen and Westrop, 1983). A re-ordered data matrix is then plotted with the genera in R-mode clustering order and the assemblages in Q-mode clustering order. Intersections of the R- and Q-mode clusters define three biofacies in terms of stratal occurrence, generic composition, and relative abundance. biofacies are named for the most abundant genus (Figure 6).

Temporal biostratigraphy starts with identification of all species, in this case 28 (A1 to H4), followed by documentation of the distribution of at least one specimen of each species in both sections, and finally by definition or recognition of zonal units (Figure 7). Ideally, zones should be based on such species that occur abundantly and frequently in every collection. Here, those taxa have already been identified as the name bearers of the three biofacies, and species of genera A, E, and H should logically form the basis for zonal sequences. In this example, zones will be restricted to single biofacies and lithofacies. Figure 7 shows the stratigraphic distribution of ten zones, each named for the species that defines its base, and their distribution within three biofacies.

The information gained by dual biostratigraphic analysis of fossils in sections X and Y can now be used to solve a number of stratigraphic problems.

(1) The two sections may be linked in a stratigraphic cross-section as an example of the traditional application of biostratigraphic data (Figure 8). According to this procedure, the presence of the same temporal biostratigraphic units in the two sections indicates time equivalence. But because the zonal boundaries coincide with the biofacies boundaries (with one exception — base of Zone A2 in Section X), the boundaries of Zone E3 and Zone A2 are undoubtedly diachronous.

(2) A correlation chart of the three biofacies-specific zonal sequences may be assembled.

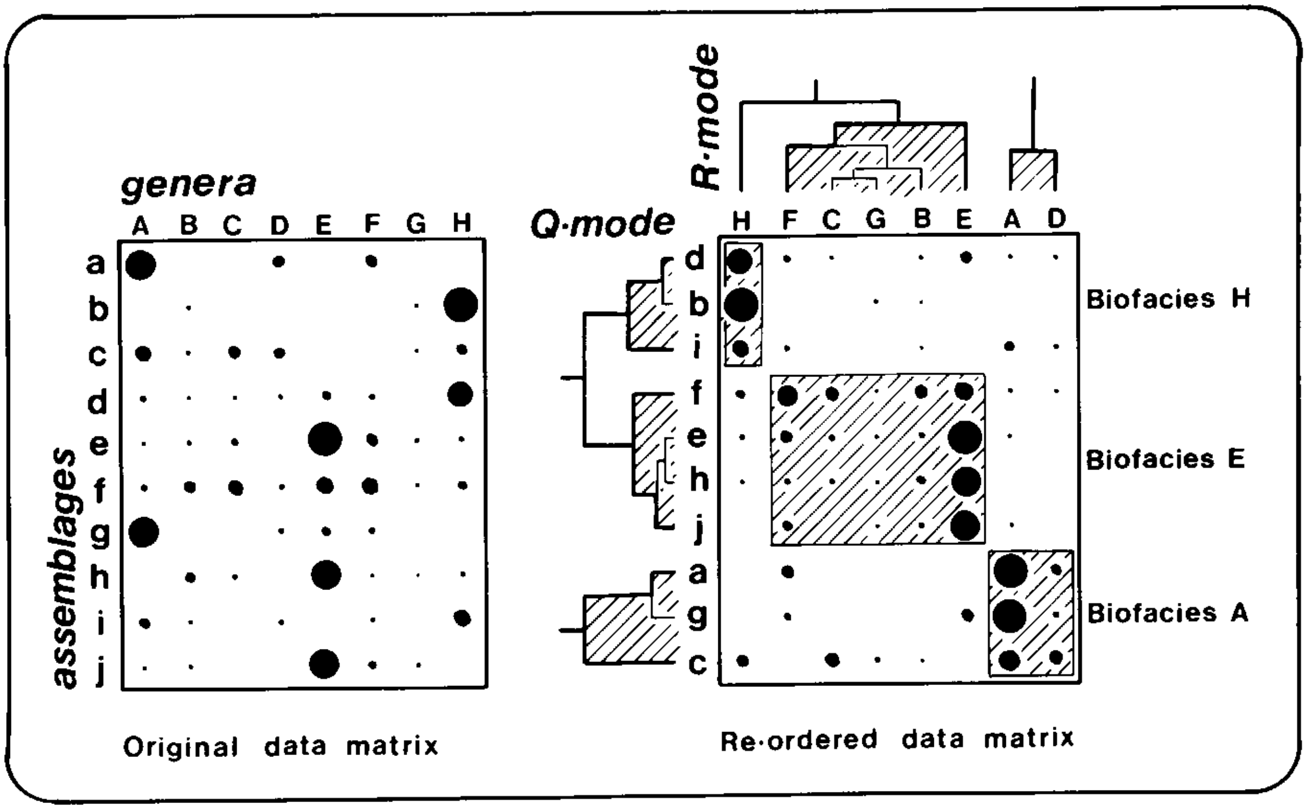

Figure 6 *Biostratigraphic example. Original data matrix of generic relative abundance of specimens is re-ordered by cluster analysis. Intersections of Q- and R-mode clusters define three biofacies (spatial biostratigraphic units).*

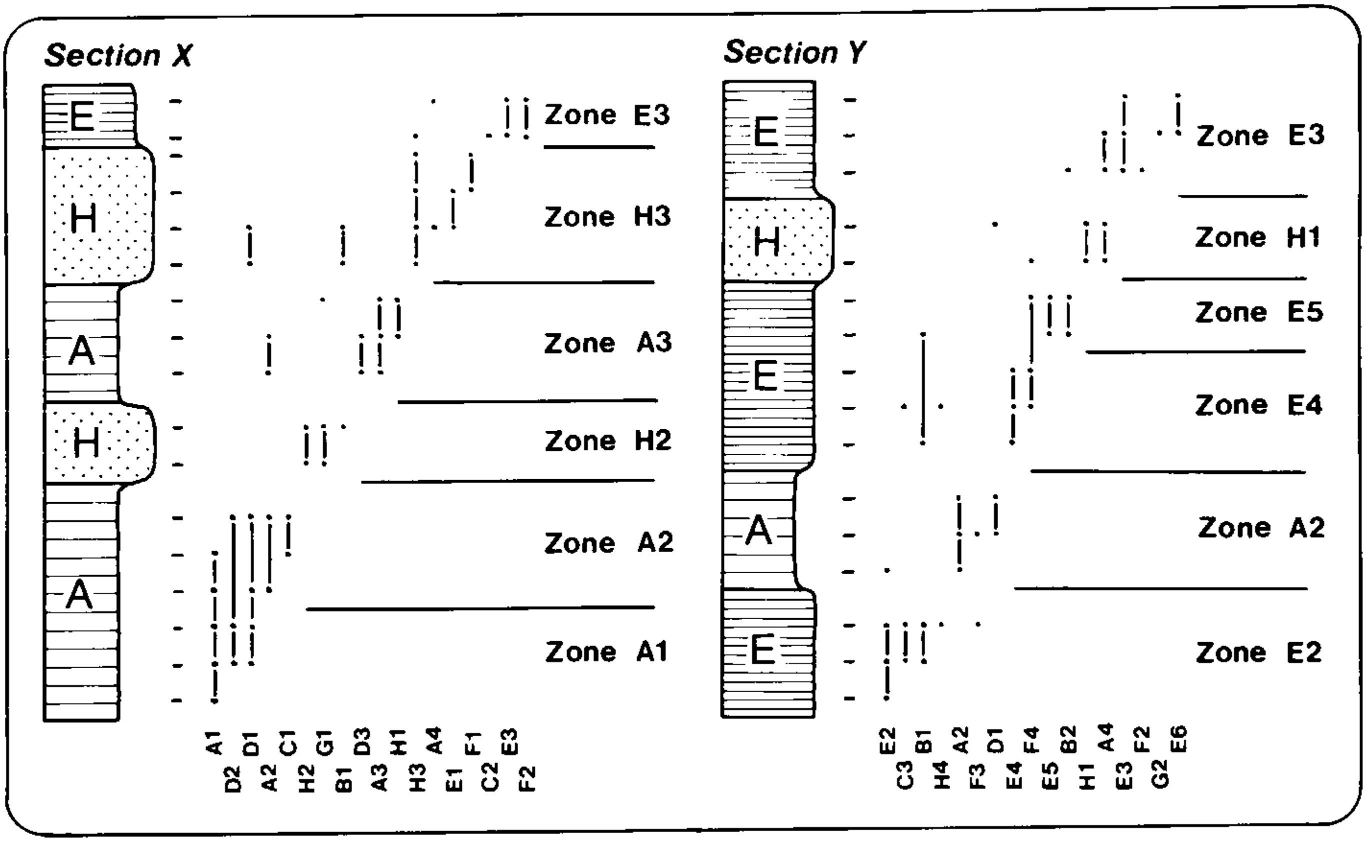

Figure 7 *Biostratigraphic example. Vertical distribution of species in the two sections permit definition of biofacies-specific zones (temporal biostratigraphic units)*

Although each biofacies consists largely of a unique association of genera (Figure 8), some species extend across biofacies boundaries (Figure 7) such that correlation of the zonally-defined segments of the biofacies is possible (Figure 9). The correlation chart reveals the incomplete nature of the biostratigraphic record for the two sections. Only about half of all possible zone/biofacies combinations are represented by fossiliferous rock. Additional sections are required to improve the coverage.

(3) Finally, the spatial and temporal biostratigraphy (and lithostratigraphy) may be integrated. The biostratigraphic landscape shown in Figure 10 incorporates all spatial and temporal units from sections X and Y, but the degree of characterization shown requires additional data from other sections. Displays such as this give full expression to the three-dimensional nature of both classes of biostratigraphic units. With the addition of lithofacies data, it come close to capturing the pattern of shifting environments through time that is the framework for both basin analysis and for the investigation of macro-evolutionary phenomena such as mass extinction and adaptive radiation.

Implications of Dual Biostratigraphy

The concept of biostratigraphy outlined here permits segregation of the temporal and spatial components of a single fossil record. This has certain inevitable implications for stratigraphy, some of which are dealt with below.

Many zones are lithofacies-specific. Albert Oppel's (1856) zonal studies emphasized the vertical ranges of species through sections and ignored the lithologic aspect of the strata. The obvious consequence of his stratigraphic philosophy is not merely that fossils are better guides to stratigraphic history than is lithology (which had already been demonstrated by William Smith many years before) but, more importantly, that the factors that govern the succession of fossils in a region are not those that control the succession of rocks. If fossils and rocks march to different drummers, then biostratigraphy may legitimately be divorced entirely from lithostratigraphy.

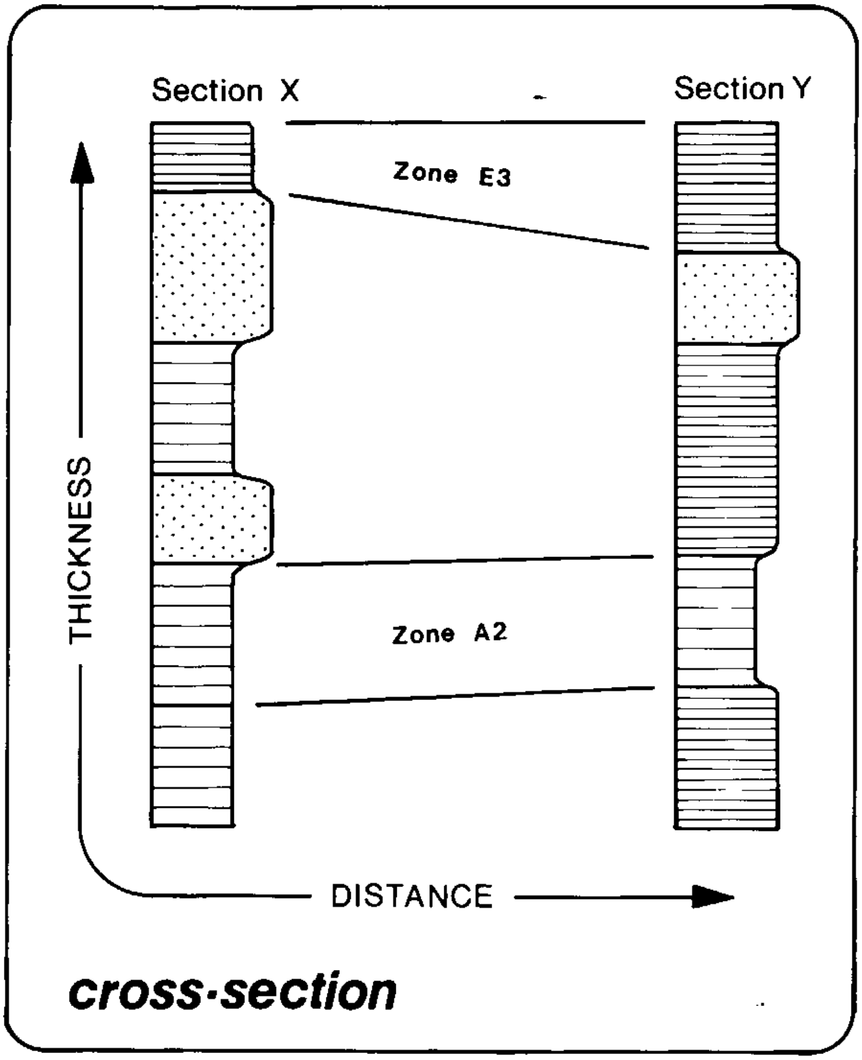

Figure 8 *Biostratigraphic example. Joint occurrences of zones in the two sections permit construction of a stratigraphic cross-section.*

By contrast, a dual biostratigraphic approach emphasizes that zones are temporal manifestations of biofacies which, in turn, are often firmly rooted in lithofacies. Therefore, a biostratigraphic study should naturally start with analysis of lithofacies before proceeding on to fossil distributions.

Figure 11 shows some of the factors that are critical for biostratigraphic analysis of Upper Sunwaptan (Upper Cambrian) strata of North America. Five trilobite biofacies are linked to five major carbonate lithofacies which extend from platform subtidal settings to moderately deep slope settings on Laurentia. Each of these biofacies, defined on the basis of generic abundance, is strongly dominated by a different family (Ludvigsen and Westrop, 1983). It is clear that a single sequence of zones based on species of one family of trilobites only cannot be applied to all strata and to all trilobites. As many as five separate zonal successions, each based on species of a different dominant family, are necessary to incorporate the full spatial differentiation of these trilobites. Each zonal succession is tied closely to separate lithofacies and biofacies, and the successions must then be assembled into a correlation chart (see Figure 9).

In the example above, fossils and rocks do march to the same environmental drummer, but in other examples they may not be in such perfect step. However, many biostratigraphers have arrived at similar conclusions about the necessary interrelationship of zones, biofacies, and lithofacies. For example, Robison (1976) established separate sets of coeval trilobite zones for different mid-Cambrian lithofacies and biofacies in the Great Basin of Nevada and Utah. Von Bitter *et al.* (1986) recognized a *Mestognathus* biofacies for conodonts in Lower Carboniferous hypersaline lagoonal-sabkha carbonate lithofacies and established a succession of zones based on species of *Mestognathus* applicable only to this biofacies and lithofacies.

Soviet paleontologists have practised a comparable regionally based biostratigraphy for many years. Repina's (1981) summary of Lower Cambrian biostratigraphy of Siberia, for example, established that different trilobite families in three major lithofacies are classified in three separate zonal successions assigned to different stages which then are correlated.

Biostratigraphic units are regional units. A biostratigraphic unit, be it temporal or spatial, requires a characteristic fossil assemblage to permit its recognition. Even though a few individual taxa (and zones) may have very widespread distributions, no known living or fossil assemblage is distributed world-wide and in all facies; it follows that all biostratigraphic units must be restricted geographically (Valentine, 1977).

Figure 9 *Biostratigraphic example. The three biofacies-specific zonal sequences may be assembled into a correlation chart.*

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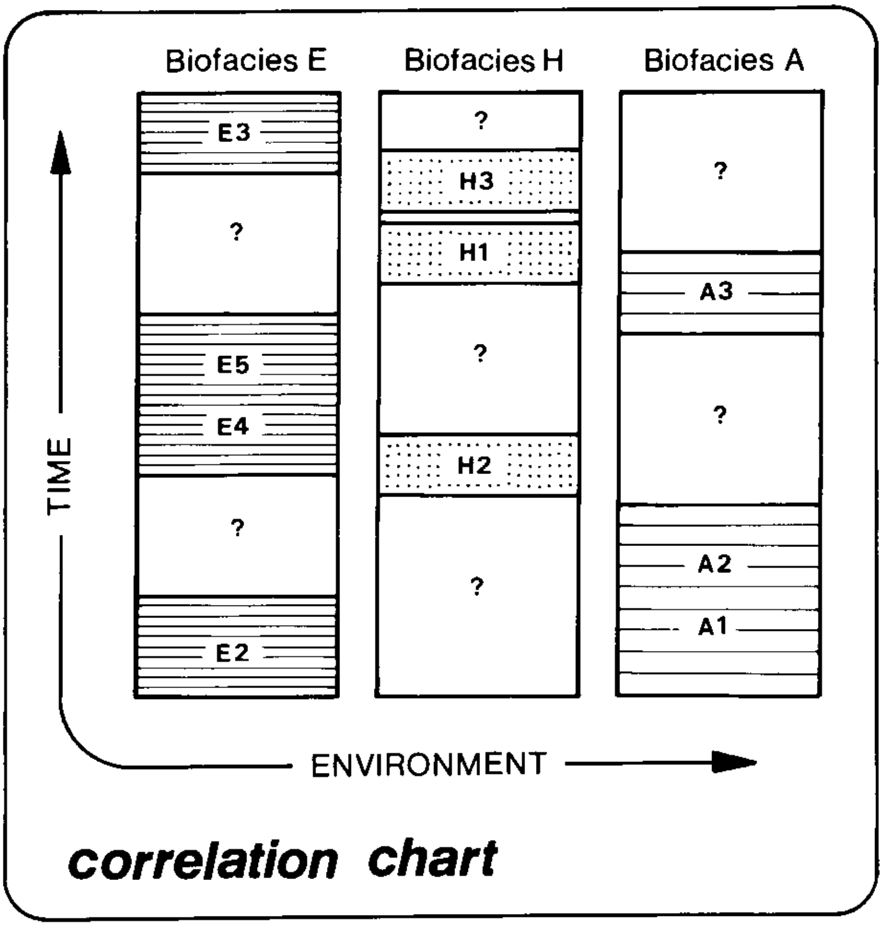

Figure 10 *Biostratigraphic example. Integration of spatial and temporal biostratigraphic units into a three-dimensional biostratigraphic landscape. The degree of differentiation shown requires data from sections additional to X and Y.*

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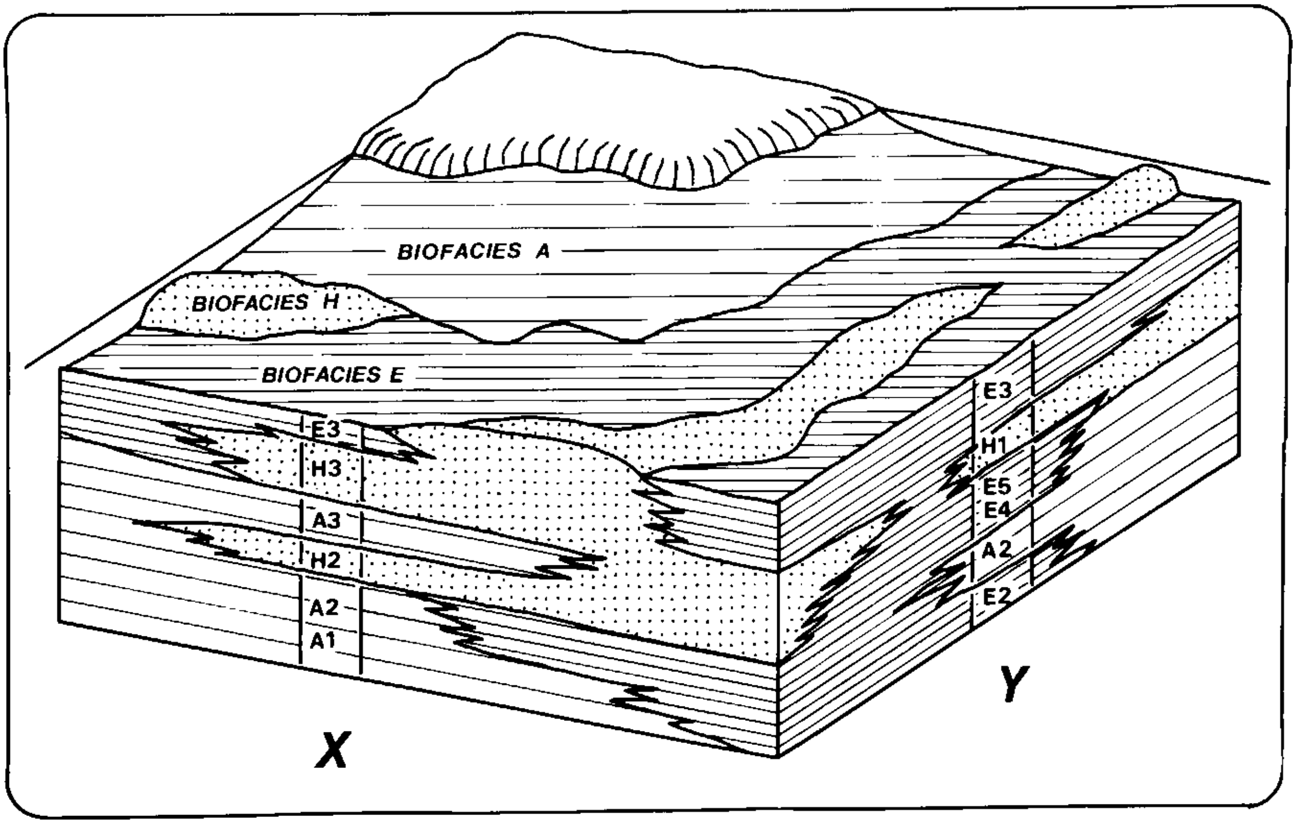

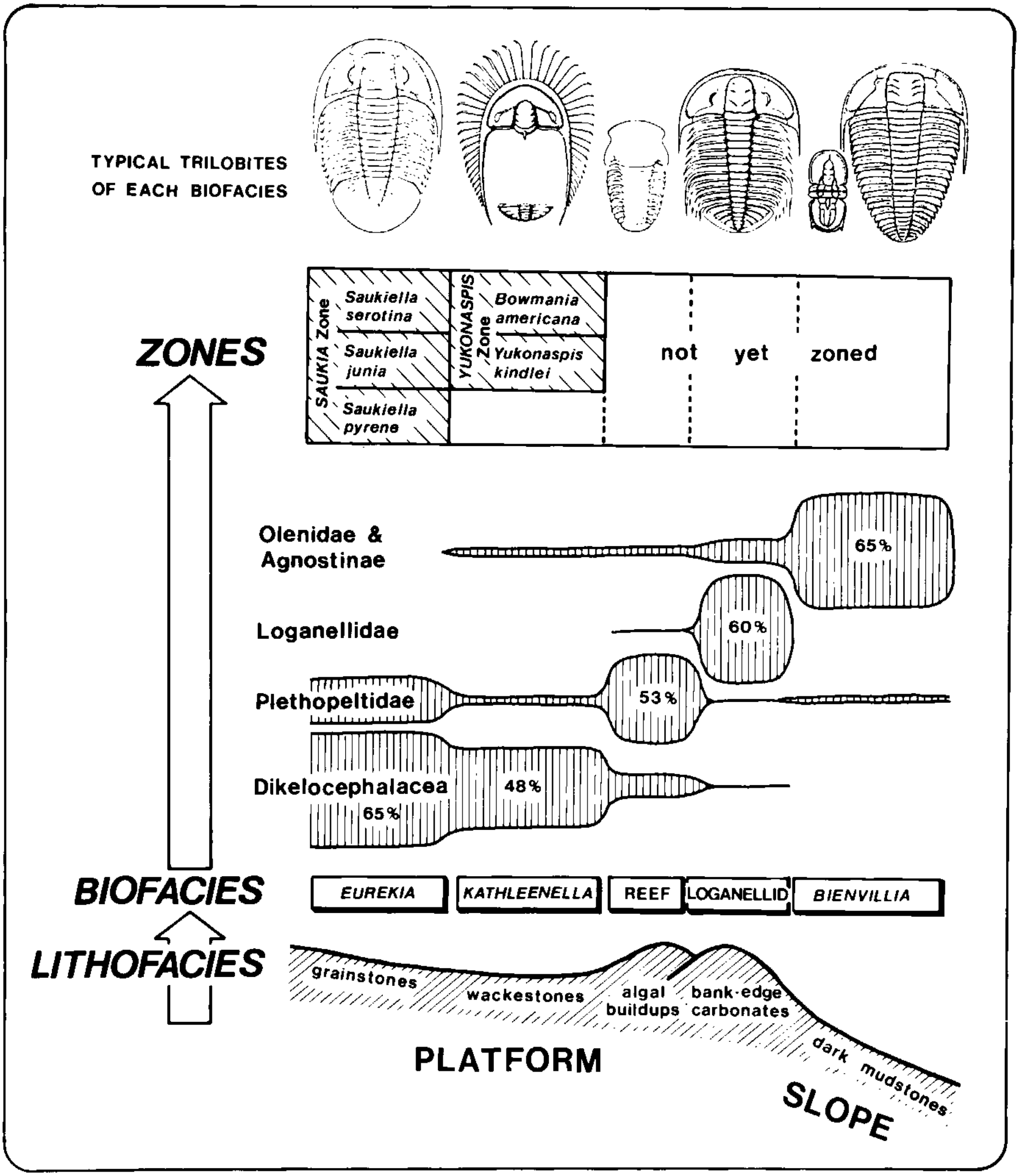

Figure 11 *Many zones are lithofacies-specific. Five carbonate lithofacies in Sunwaptan (Upper Cambrian) strata of Laurentia support five different trilobite biofacies. The distribution of individuals belonging to different families indicates that a number of zonal successions are required to capture the spatial differentiation of these trilobites, and that each zonal succession will be linked to a separate lithofacies. (Data from Ludvigsen and Westrop, 1983).*

Most zones and biofacies are established for, and are applicable within, one or, at most, a few lithofacies on a portion of a biotic province. A stage is typically applicable only to a single province, subprovince, or continent where it may incorporate different zonal successions for separate regions and for various fossil groups.

Figure 12 is a correlation chart of regional Upper Cambrian stages established on five separate continents. Each of these trilobite-based stages comprises a different stack of zones as an expression of the unique stratigraphic succession and faunas of each of these Cambrian provinces (Ludvigsen and Westrop, 1985). Blackwelder's (1981, Text-fig. 3) correlation chart of regional Upper Cenozoic molluscan-based stages for different provinces provides a comparable example.

The International Commission on Stratigraphy has been dealing much differently with global biostratigraphic nomenclature. With the laudable intent of improving communication between geologists, it is now promoting a "common language" in stratigraphy (Bassett, 1985) — that is, the development of a single global chronostratigraphic scale of stages and series to replace all provincial nomenclatures. Decisions are coming down at an impressive rate. For the Silurian System, boundary definitions and stratotypes of four global series and seven global stages have already been ratified (Holland, 1985) and, for the Devonian, seven global stage names have been agreed upon and are now awaiting ratification of boundary stratotypes (Ziegler and Klapper, 1985). Other portions of the Phanerozoic are currently being prepared for similar "chronostratigraphic" attention.

Such nomenclature cannot be applied realistically on a global scale and to all facies. Zones and stages are temporal biostratigraphic units naturally limited in their application by the finite distribution of their characteristic fossils. Nomenclature becomes artificial and misleading if these units are extended beyond the range of the fossils into different facies and provinces (Watson and Wright, 1980, p. 159). Two examples will suffice.

The Llandovery Series (Lower Silurian) is divided into three global stages on the basis of graptolite zonal biostratigraphy at boundary stratotypes in Wales (Holland, 1985). These stage names are clearly applicable to many successions in Europe, Asia, and even to basinal shales flanking Laurentia in which the definitive graptolite zones are developed (Lenz, 1982). They have no relevance, however, for Lower Silurian carbonate rocks of, for example, Anticosti Island (Lespérance, 1981) that lack characteristic graptolites and which should be classified biostratigraphically into regional stages of the Anticosti Series (Barnes and McCracken, 1981) according to prevalent biotic elements such as conodonts, trilobites, brachiopods, or ostracodes.

Almost all biostratigraphers have treated the dozen stages of the Cretaceous System as if they were global units. However, examination of the stadial boundary criteria recently proposed by a group of Cretaceous specialists (Birkelund *et al.*, 1984) reveals that, of the eleven stages above the Berriasian, nine are defined basally by zones established for species of cephalopods that are found in either the Boreal Realm or the Tethyan Realm; not in both. Thus, the Albian Stage of Boreal North America, for example, cannot be considered the same unit as the Albian Stage of Tethyan France, regardless of how their boundaries are thought to correlate, because they are defined by different boundary criteria and characterized by different fossils in wholly different zones (see Kauffman, 1979, fig. 3). Not all Cretaceous biostratigraphers have accepted these global stages as applicable to all facies. For some years, vertebrate paleontologists have used appropriately a sequence of regional stages based on mammalian faunas in western North America (Russell, 1975; Fox, 1978).

The stages of the Llandovery Series and of the Cretaceous System are acceptable regional biostratigraphic units but, contrary to the International Commission on Stratigraphy, they are neither global units nor chronostratigraphic units. We do not need an artificial "common language" in order to communicate with other stratigraphers. What is needed are accurate two-way "interpreters" of biostratigraphic data from different regions — that is, correlation charts of zones and stages. Such charts provide detailed information on composition and sequence of different sets of regional biostratigraphic units and indicate levels of confidence of correlations. A single chronostratigraphic nomenclature shows neither.

Biostratigraphic units form a hierarchy. The temporal biostratigraphic units of a single province comprise a hierarchic arrangement that rests upon the first occurrence of a single species at the base of a zone. This zone then defines the base of a stage. Both units are best standardized by objective

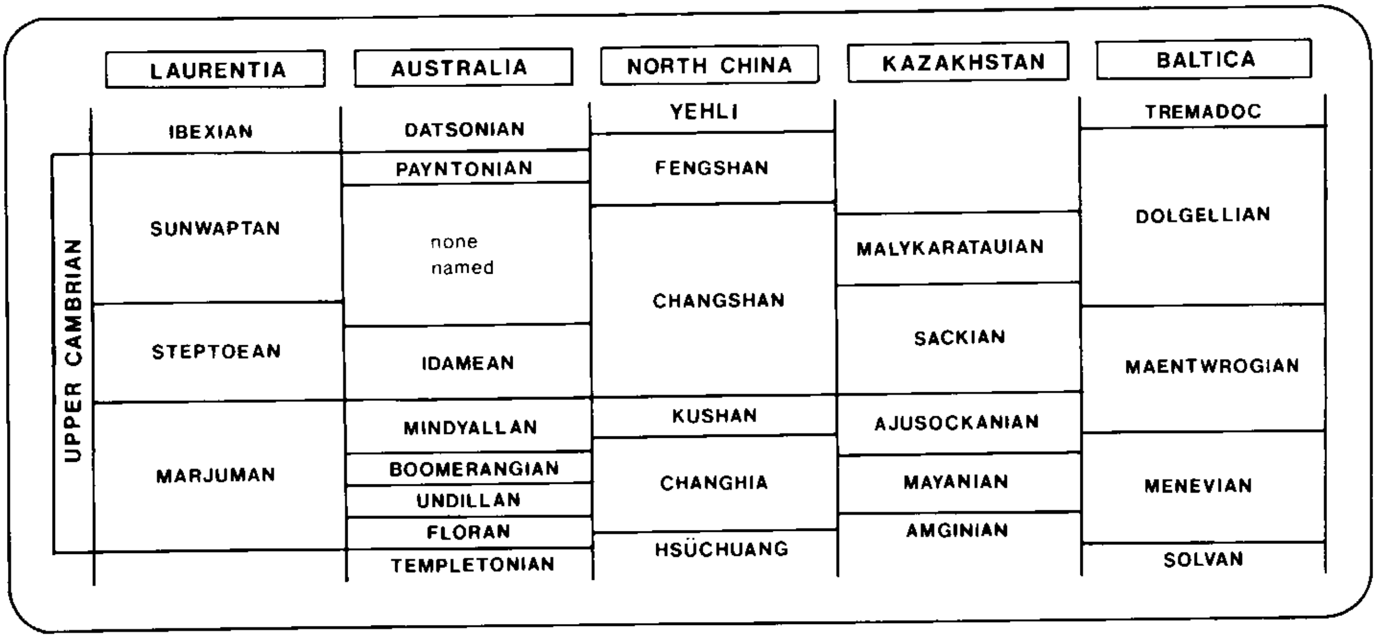

Figure 12 *Biostratigraphic units are regional units. A stadial name is typically applicable to the fossils and strata of a single province. The different names and boundaries of Upper Cambrian stages of five separate continents and provinces reflect the unique stratigraphic history and the distinct faunas of each area. (From Ludvigsen and Westrop, 1985).*

boundary and unit stratotypes. In the Lower Paleozoic, for example, each of about half a dozen provinces are best characterized by a separate hierarchy of zones, stages, and perhaps series.

Figure 13 shows a hierarchic classification of Cambrian temporal biostratigraphic units for Laurentia. Neither the base of the Cambrian nor the base of the Ordovician has yet been formally defined.

Systems are global biostratigraphic units of convenience. Zones, stages, and biofacies comprise objectively defined stratal intervals which, like formations, are regionally mappable stratigraphic units limited by the distribution of diagnostic fossils. Systems, however, are stratigraphic units with a difference. They are tied to occurrences of specific fossils and, as such, are clearly biostratigraphic in nature; but unlike other stratigraphic units, they are not regional units. Since the 1840's, systems have been accepted as being global in extent (see Rudwick, 1985). We acknowledge that a set of large-scale global biostratigraphic units is useful in many geologic studies, but the artificial nature of systemic nomenclature presents special problems in areas distant from the boundary stratotype.

In the hypothetical example shown in Figure 14, a boundary stratotype of System A in Area 1 defines a common basal boundary for a biostratigraphic hierarchy of Stage H and Zone S. In other areas where this stage and zone are not present, System A must be defined operationally by different boundary criteria; that is, with reference to Zone W in Area 2, or according to a different hierarchy of Stage L and Zone T in Area 3.

The Silurian System on Anticosti Island, for example, is a unit of convenience defined basally by the Anticosti Series and not, as at the boundary stratotype in Britain, by the Llandovery Series. The base of the Anticosti Series of Barnes and McCracken (1981) is somewhat older than the base of the Llandovery Series (Lespérance, 1985).

The dozen Phanerozoic systems (that is, Vendian to Neogene) are unquestionably useful as global units in spite of problems of correlation and of information content. Such problems increase at progressively lower hierarchic levels and, therefore, the hundreds of Phanerozoic stages (or, indeed, thousands of zones) would serve as meaningless or deceptive global biostratigraphic units of convenience.

Diachroneity of biofacies can be resolved. Turnover of species of component genera provides the basis for a temporal biostratigraphy within biofacies. The sequence of zones generated from species ranges acts as a scale against which diachroneity of biofacies in different sections may be measured. For example in the Lower Sunwaptan, diachroneity of the outer shelf *Ellipsocephaloides* Biofacies between Alberta and Texas is clearly expressed by correlation of subzones based on different species of *Ellipsocephaloides* (Figure 15). Similarly, diachroneity in the appearance of Upper Sunwaptan Reef Biofacies in Oklahoma, Texas and Alberta (Figure 16) is resolvable by correlation of subzones of the *Saukia* Zone. In both of these Upper Cambrian examples, diachroneity is related to the spread of biofacies in response to lithofacies shifts. It is worth noting that many established zones that are based on generic ranges, such as the *Ellipsocephaloides* Zone, are likely to display comparable diachroneity.

Zones tend to track biofacies. The sequence of zones in any stratigraphic section will reflect the stacking order of biofacies which, in turn, is often influenced by the order of lithofacies. For example, in the Upper Sunwaptan of North America, different subzones of the *Saukia* Zone have been established for the Reef and *Eurekia* Biofacies (Figure 16). Shifts of biofacies through each geographic region account for changes in both zonal and subzonal nomenclature.

Provinces can be correlated. Provinces are best characterized by their biofacies and, therefore, provinciality is expressed on generic and higher taxonomic levels. This means that detailed correlations across provincial boundaries are at best difficult and sometimes impossible. A provincial spectrum of shallow water to deep water biofacies, however, may coincide with an endemic-pandemic trend and this spatial pattern can be exploited for temporal biostratigraphy.

Figure 17 shows a hypothetical spatial biostratigraphic hierarchy in which Biofacies I to IV define low-latitude Province A and Biofacies 1 to 4 high-latitude Province B. The two provinces are separated by a wide ocean. Provincial endemicity is expressed as family level differences between warm-water

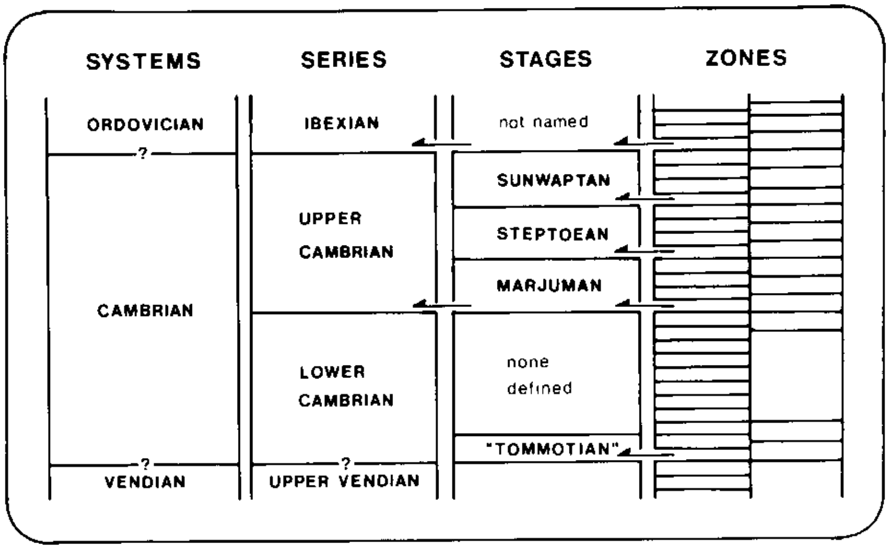

Figure 13 *Biostratigraphic units are largely hierarchic. In a nested classification of Cambrian temporal biostratigraphic units of Laurentia, the base of a zone (shown diagrammatically) defines the base of a stage which defines the base of a series. The base of the Cambrian System and the Ordovician System have not yet been defined. Upper Cambrian stages were established recently by Ludvigsen and Westrop (1985).*

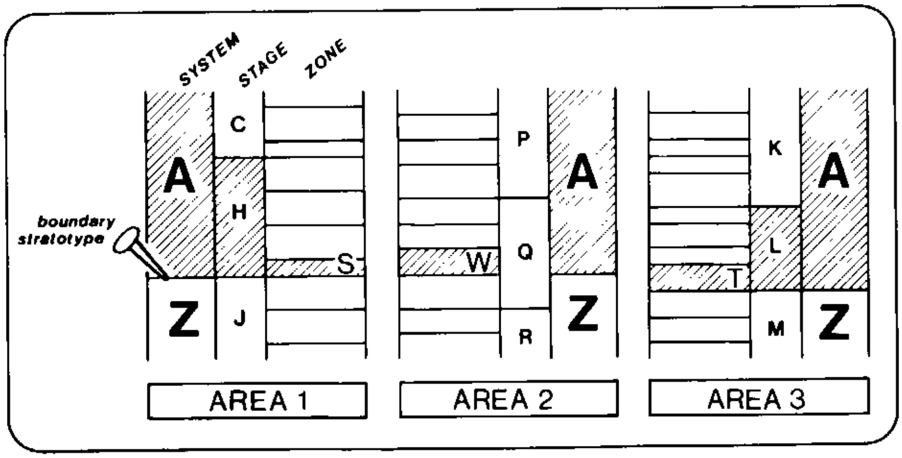

Figure 14 *Systems are global units of convenience. A boundary stratotype defines System A with reference to Stage H and Zone S in one area. In different areas, System A has to be recognized operationally by reference to other zones and stages.*

Biofacies I and II and cool-water Biofacies 1 and 2. Correlations, which must be based on shared species, cannot be made between the interior portions of the two provinces, but they may be possible between Biofacies IV and Biofacies 4 which occupy comparable slope environments and which comprise portions of a pandemic cold-water assemblage. Sea-level changes would interleave endemic and pandemic biofacies along the margins of both provinces; or debris from the continental margin would introduce exotic blocks containing endemic biofacies into a sequence of pandemic biofacies. The temporal aspect of the biofacies will allow lines of correlation to be carried to the endemic interiors of both provinces via the pandemic fringing biofacies (see also Cocks and Fortey, 1982).

Biostratigraphy and environmental spectra. A dual approach to the study of fossils in rock permits segregation and classification of the temporal and spatial components of biostratigraphy. These two components can then be integrated as a space-time spectrum of environments which may serve as a framework within which biotic patterns such as extinction, radiation, and migration could be studied. This kind of analysis emphasizes, for example, that extinction does not occur primarily at specific horizons in a section; rather, it occurs within an environment during a certain time span.

Figure 18 shows a series of environmental spectra across the Cambrian-Ordovician boundary beds in western North America. Temporal biostratigraphy is contributed by two different sets of zonal successions; spatial biostratigraphy by adjoining biofacies in different lithofacies (see also Figure 11). These spectra could serve as a backdrop for a number of biotic patterns. Here, we show the diachronous invasion of the trilobite *Missisquoia* into North America, presumably from Australasia. The genus first appeared as a rare element in deep platform lime mudstones, then increased in abundance during its migration into the shallow carbonate belt, and eventually it became a dominant element in the shallow carbonate belt at the same time as it vacated the deep platform environment. Some investigators have suggested that this trilobite should define the base of an Ordovician System in North America. However, dual biostratigraphic analysis shows that the diachronous migration of *Missisquoia* occurs through four biofacies and across five subzones and three zones. Such dynamic environmental analysis is possible only through application of two-component biostratigraphy.

Species and spatial biostratigraphy. The dual approach is based on the premise that a biostratigraphic signal can be split into its spatial and temporal components by manipulation of the fossil record at different taxonomic levels. In brief, abundance of genera records biofacies whereas presence of species records zones. This generalization is a practical solution that works in a majority of the cases we have studied. But not in all! Species are not immune to environmental influences and, with an exceptional record, it is possible to document subtle biofacies patterns expressed on species levels.

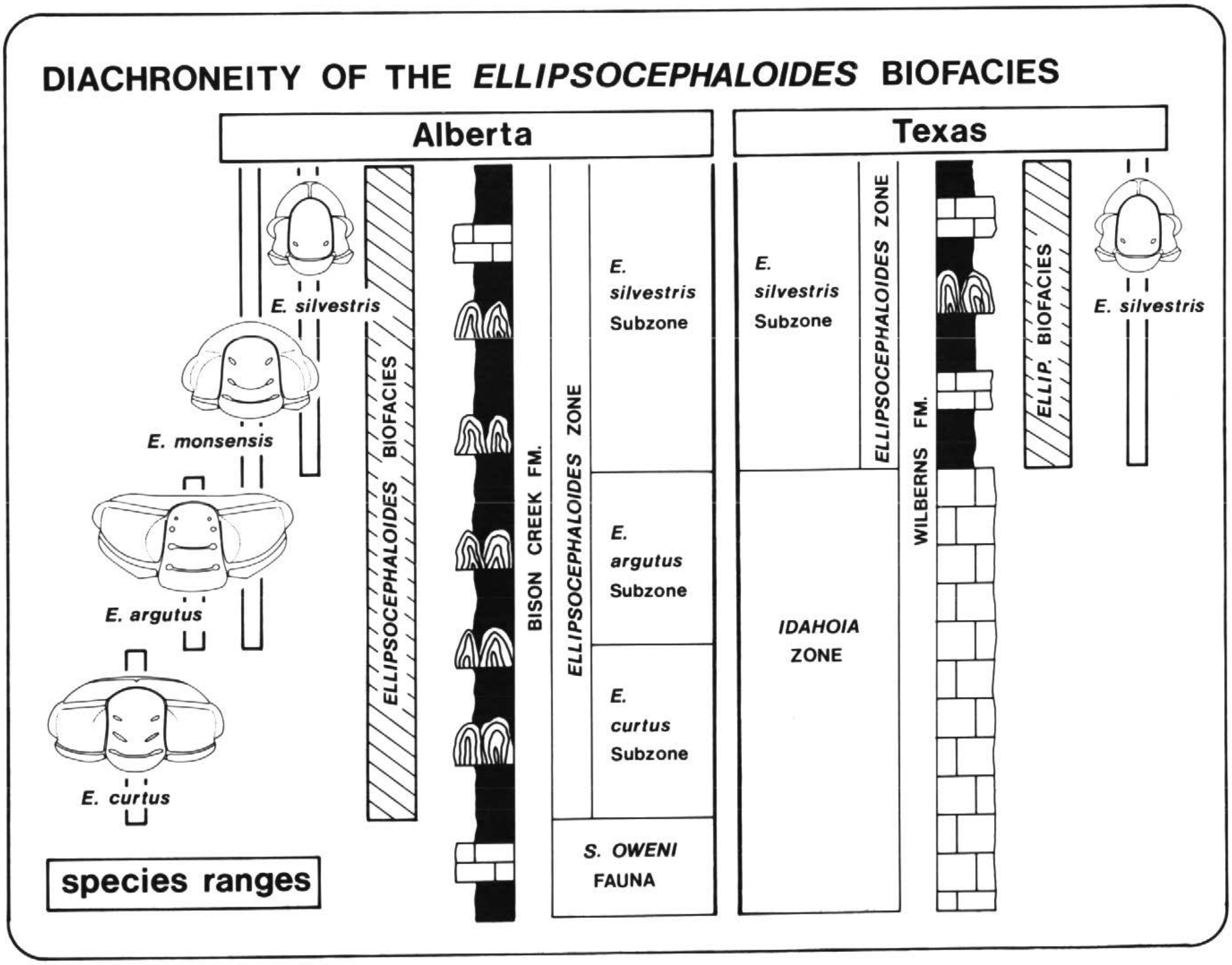

Figure 15 *Many biofacies are resolvably diachronous. The base of the* Ellipsocephaloides *Biofacies (and Zone) is measurably younger in Texas than in Alberta. Such diachroneity is resolved by decoupling the spatial and temporal biostratigraphic components of fossil sequences.*

The olenid trilobite *Triarthrus* which is represented by five species in Upper Ordovician grey shales of Ontario and Quebec provides a rare documented record of spatial biostratigraphy expressed on the species level (see Jones and Narbonne, 1984, for a similar example with brachiopods). This genus is common to abundant in the Whitby Formation and equivalent shale units where it defines a *Triarthrus* Biofacies, some 50-100 m thick (Figure 19). Within this biofacies, abundance peaks of different species replace each other up-section in a regular order: *T. eatoni* (and *T. spinosus*), then *T. canadensis* (or *T. glaber*), and finally *T. rougensis*. This sequence, however, is almost certainly *not* controlled by temporal factors because dominance patterns of the three species groups follow exactly appearances of different shale colours in each of the four areas. It is clear that these species cannot form the basis for a temporal sequence of zones; rather they appear to be expressions of a spatial pattern of three sub-biofacies within the *Triarthrus* Biofacies that is governed by shale colour. The colour is, in turn, apparently influenced by variation in disseminated organic material that appears to be related to oxygen levels on the sea bottom.

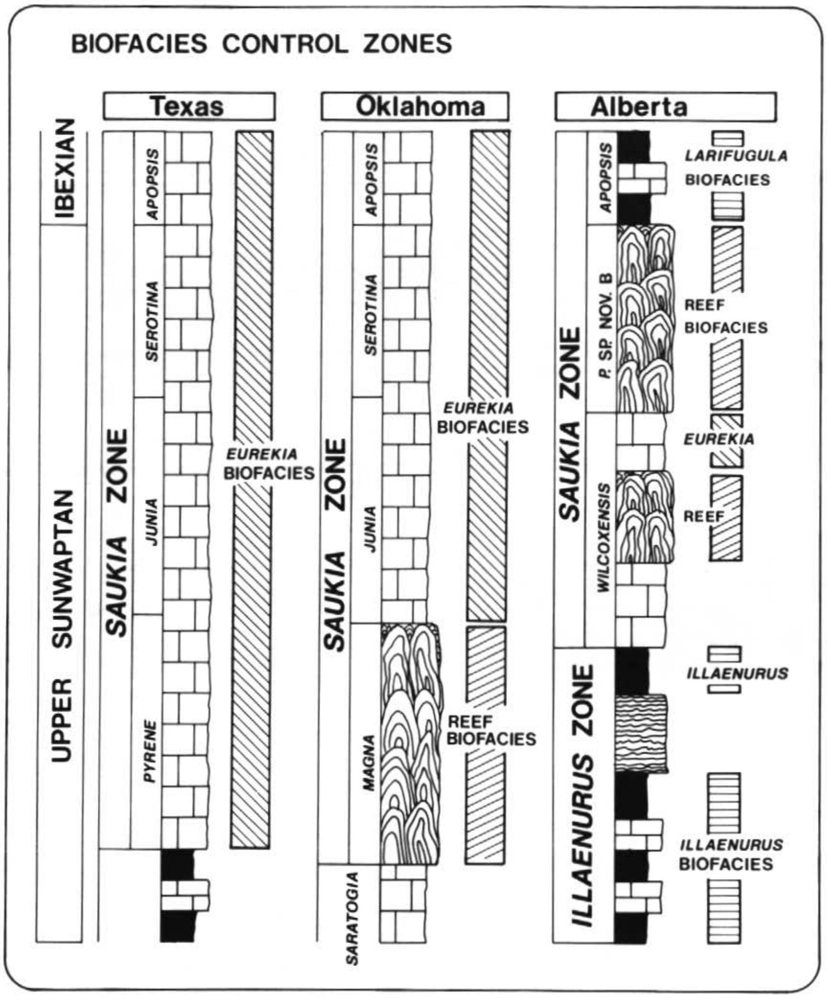

Figure 16 *Zones tend to track biofacies. The stacking order of biofacies influences the zonal nomenclature. Subzonal nomenclature of the* Saukia *Zone (Upper Cambrian) is controlled by appearance of either the Reef Biofacies or the* Eurekia *Biofacies.*

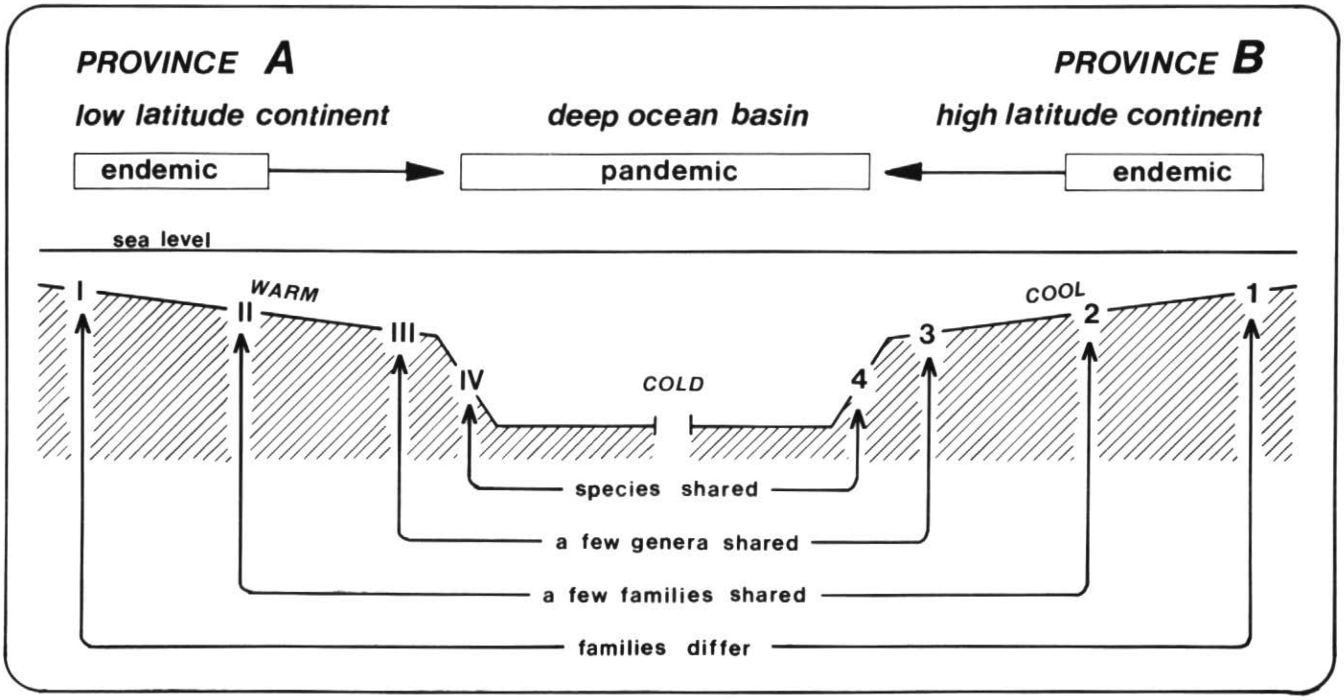

Figure 17 *Provinces may be correlated. Provinces A and B are defined by faunas which differ on family levels. A temporal biostratigraphic signal can be carried from one province to another via the pandemic fringing biofacies which share genera and species. (Based on figure by Fortey and Owens, 1978).*

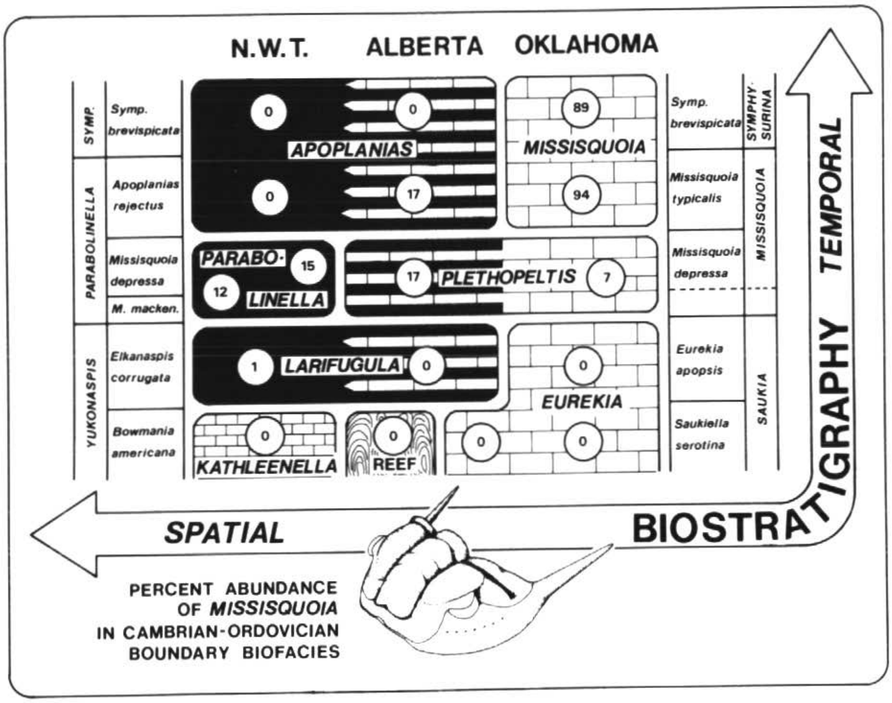

Figure 18 *Biostratigraphy and environmental spectra. Spatial and temporal biostratigraphic components define a sequence of environmental spectra in the Cambrian-Ordovician boundary interval of western North America. The diachronous migration of the trilobite* Missisquoia *is documented. (Data from Ludvigsen and Westrop, 1983).*

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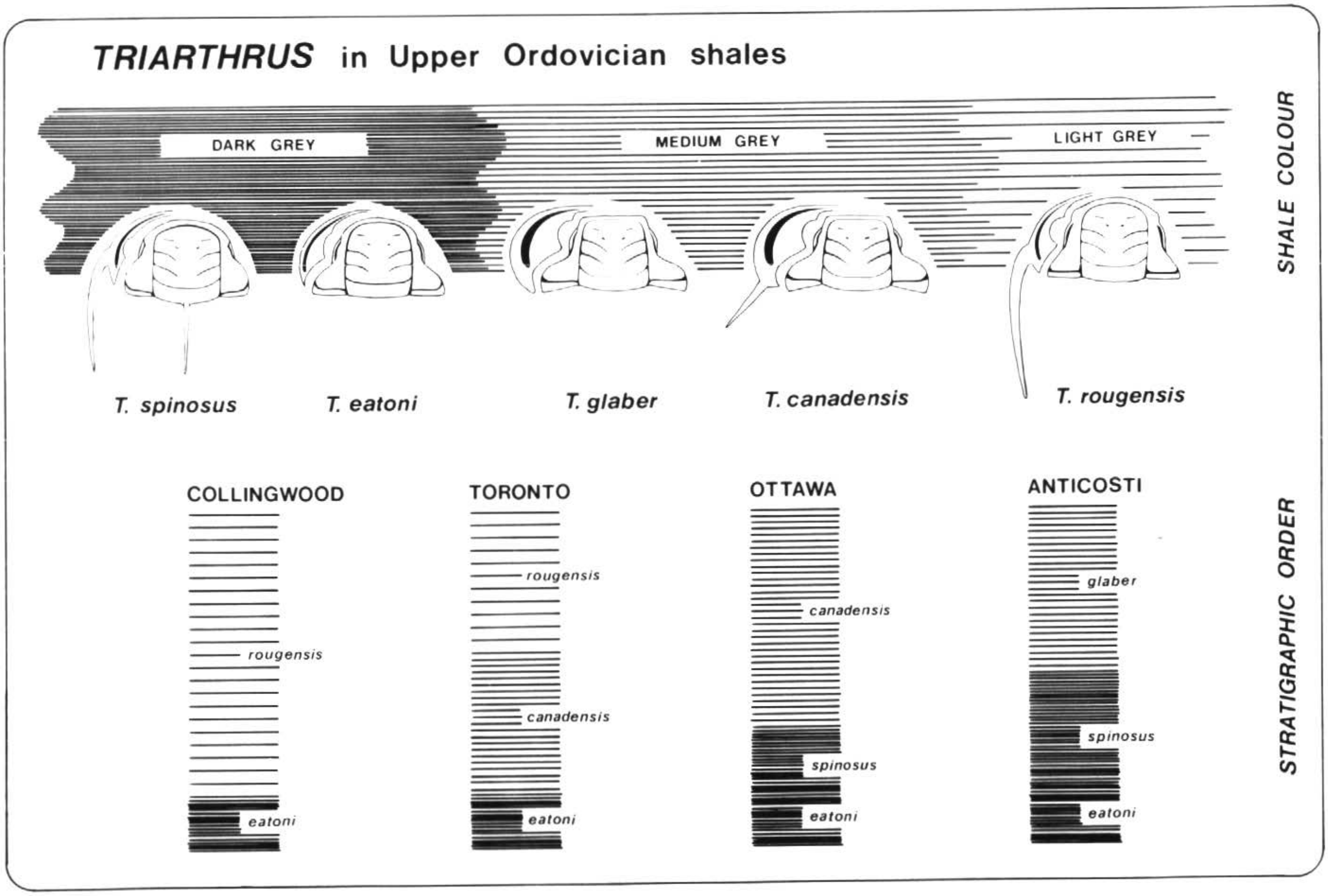

Figure 19 *Species and spatial biostratigraphy. Abundant occurrences of three species groups of the trilobite* Triarthrus *follow closely the appearances of different colour intervals of Upper Ordovician grey shales in Ontario and Quebec. The stratigraphic order of the species groups is controlled by spatial (environmental) factors, not by temporal factors.*

Conclusions

Biostratigraphy is concerned with the stratigraphic ordering of biotic remains in sedimentary rocks and with the temporal and spatial relationship of strata. It attempts to classify and to correlate strata on the basis of their contained fossils but, like other stratigraphic disciplines, it must operate within a facies framework. Dual biostratigraphy, as outlined here, emphasizes the influence of facies and provides a method and a nomenclature that facilitate identification of the temporal and spatial controls on the distribution of fossils in strata.

Biostratigraphy is also a paleobiologic discipline that is central to charting the nature and course of biotic patterns. The fossil record is historical in nature, but it does not comprise biotic history any more than unsorted archival material constitutes human history. Evolutionary relationships, extinction events, migration patterns, and ecologic associations are never directly disclosed by successions of fossils in rock; these historic patterns emerge only through interpretation of the fossil record. As a translator of the fossil record into a history of biotic events in environments, dual biostratigraphy is an essential step in that interpretation.

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