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GEOLOGÍA

BIOSTRATIGRAPHY

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Table of Contents. Page

Table of Contents

Selección de artículos:
Responsabilidad de J. Wyatt Durham.

706

Reprinted from
JOURNAL OF PALEONTOLOGY
Vol. 41; No. 3, May, 1967

PRESIDENTIAL ADDRESS

THE INCOMPLETENESS OF OUR KNOWLEDGE OF THE FOSSIL RECORD

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ABSTRACT.—Consideration of the doctrine of evolution and the implications of the biological species concept indicate that our knowledge of the fossil record will not be complete until we have a continuum of morphologies between all taxa with preservable parts. As an important corollary to the biological species concept, it is emphasized that species boundaries between sequential taxa will have to be arbitrary.

The recorded California Pleistocene marine invertebrate fauna is only about two-thirds as large as the living fossilizable fauna of the same region. Tertiary marine faunas of the reasonably well studied California area are even smaller. For contrast a probable 657 species of molluscs have been recorded from a 1 to 2 foot bed in the Miocene of Bowden, Jamaica, and over 3000 taxa have been recorded from the Eocene of the Paris Basin. On the basis of a sample of over 67,000 molluscs collected by screening a late Pleistocene marine pocket near Newport, California, 427 taxa were recognized. A 1 per cent sample obtained in the same manner would have yielded only 153 taxa, while a sample of 68 specimens (0.1% of original collection) would yield only 48 taxa. These data emphasize the deleterious effect of small collecting samples.

The occurrence of the coral genera *Dasmia* and *Dendrosmilia* in the Pacific Coast Cenozoic, when previous records were restricted to Western Europe, underscores our poor knowledge of the geographic distribution of fossils. The occurrence of the Helicoplacoidea, Eocrinoidea, Edrioasteroidea, Camptostromoidea and an unnamed class of echinoderms in the Early Cambrian indicates that echinoderms equipped with hard parts existed in the Precambrian. Analysis of fossilizable marine invertebrates and the known fossil record suggests that we know only about one of every 44 (and probably fewer) taxa of those that have existed in this environment since the beginning of the Cambrian.

INTRODUCTION

MUCH has been said and written about the incompleteness of the fossil record but relatively little consideration has been given to the status of our knowledge of the record. Norman D. Newell (1959), a past president of the Paleontological Society, presented a paper on the "Adequacy of the Fossil Record" as his retiring address in 1958. Although his main theme was with the fossil record and not particularly our knowledge of it, I find that he anticipated many of my conclusions. It is the purpose of this paper to emphasize and document the incompleteness of our knowledge of this record.

Published discussions indicate that few investigators have distinguished between the two aspects of the fossil record noted above, and many have confused them and attributed the effects of both to the incompleteness of the record. "Incompleteness of the record" refers only to the deficiencies of the existing fossil record whereas "Incompleteness of our knowledge of the record" concerns the deficiencies of our knowledge of the existing record. Unless so qualified, neither category is concerned with lo-

cal gaps in the record. "Knowledge" as here used, refers to information that is published or disseminated in some documentary form and thus available to all. For the present purposes, "fossil record" refers to the remains of organisms preserved in the rocks on a world-wide basis, and the major part of the following discussion is further restricted to a consideration of the remains of organisms that have hard parts. I am not concerned with unusual types of preservation such as those responsible for the occurrence of the recently discovered soft bodied *Tullymonstrum gregarium* (Richardson, 1966) in the concretions at Mazon Creek, Illinois, but rather with the more common, "run of the mill" kinds of fossils preserved in the usual modes.

IMPLICATIONS OF DOCTRINE OF EVOLUTION

The doctrine of evolution and a biological species concept in some form are now universally accepted by paleontologists, yet few of us have bothered to concern ourselves with their implications for the fossil record. The biological species concept carries the corollary that any individual is at least potentially capable of interbreeding with its offspring and its parent. Within the practice of taxonomy, either paleontologic or neontologic, this is usually taken to signify that the morphology of parent, offspring, and grandparent is such that all three generations are assigned to the same species. A principal corollary of the doctrine of evolution is that there is a continuum of generations back to the origin of life. Thus theoretically, for all easily fossilizable organisms there is the possibility of having a continuous sequence of generations preserved as fossils.

Although the purpose of this paper is not to discuss the problems of establishing the limits of species, it should be emphasized that a logical consequence of acceptance of the doctrine of evolution and the biological species concept is that the limits, at least in the dimension of time, of any species are arbitrary, and that somewhere a boundary must be drawn between parent and offspring. This of course signifies that when our knowledge of the fossil record is adequate, the convenient morphologic breaks (due to local gaps in the record or to incomplete examination of the record) now used to separate sequential species will no longer exist, and that our species boundaries will be arbitrary points in a continuum. As yet our knowledge of the record is such that we rarely need to use arbitrary points in the separation of sequential species, but in a few cases our available data have increased to the point where this method is necessary. For instance, in Rowe's (1899) pioneering work on the British species of *Micraster*, as further supported by Kermack (1954) and Nichols (1959a, 1959b), ". . . *Micraster*, shows a continuously changing series in which all intermediates between any two easily distinguishable forms occur," (Nichols, 1959a, p. 401). In the late Cretaceous and Early Cenozoic of California ". . . the evolution of *Glycimeris veatchii* is found to continue in an unbroken line . . . " and "The number of ribs on a valve is found to vary inversely with the geologic age of the specimen" (C. T. Smith, 1945, p. 36). In the late Jurassic and Early Cretaceous of Western North America the pelecypod *Buchia* [formerly known as *Aucella*] is often very abundant, and sequential species of the same lineage are only arbitrarily separable. For instance "*B. okensis* s. lato and *B. uncitoides* s. lato are connected by uninterrupted series of transitional forms at all levels . . ." (Jeletzky, 1965, p. 26). Only when we can demonstrate such continuity between all our species and their ancestors can we say that our knowledge of this aspect of the fossil record is satisfactory.

EXPLORATION OF THE SEA-FLOOR

A major gap in our knowledge is due to the lack of exploration of the sea-floor. The oceans cover about 70 per cent of the surface of the earth, with the area of the Pacific Ocean alone being greater than that of all the continents. In most places the oceans are immediately underlain by fossiliferous sediments. In the last 20 years our knowledge of the sea-floor has grown apace, but as yet the number of fossiliferous samples from it is comparatively minute, with most of them suitable for micropaleontological studies only. Only around the extreme margins of the oceans do we have anything approaching even a reasonable reconnaissance level of sampling. The oldest fossils known from the deeper ocean basins are the Mid-Cretaceous shallow water megainvertebrates described by Hamilton (1956) from the Mid-Pacific submarine mountains about 1000 miles southwest of Honolulu. These are known only from seven samples on two guyots. Samples of Cretaceous age are also known from the Atlantic but the age of these samples is based on smaller foraminifers and their faunas do not include larger benthonic organisms. In view of the relatively minute number of samples from the ocean floor and the widespread blanket of younger sediments, the absence of Pre-Cretaceous fossils from the ocean basins does not appear to be anything more than a resultant of the type of sampling (or lack of it) conducted to date.

In terms of the potential significance of the data, the sampling of the ocean floor and the sedimentary deposits beneath it for fossils is one

of our most urgently needed (albeit extremely expensive) projects. The high degree of incompleteness of our knowledge of the fossils that occur in this realm cannot be over emphasized.

QUALITY OF AVAILABLE SAMPLES

Another aspect of our knowledge (or lack of it) of the fossil record that I wish to emphasize is the poor quality of our collections from readily accessible and often highly fossiliferous strata. Most collectors go in the field and look for particular kinds of fossils and disregard (or fail to record) the remaining biota: a cephalopod specialist will collect only cephalopods; an echinologist may gather only echinoids; a foraminiferologist will emphasize foraminifers; in some instances specialists have been known to collect only members of a particular genus or family. Few of us stop to realize how biased the majority of fossil collections are, yet these collections form the basis of most of our published records and studies. To illustrate this point I cite an incident from my own experience.

As an aspiring senior student in college, in 1932, I was sent by the late professor C. E. Weaver to study the Oligocene sequence on the Quimper Peninsula, near Port Townsend, Washington. One of the better fossil localities was on Discovery Bay, at a place then known as Woodman's Wharf. From this locality I ultimately recorded as part of the fauna, 8 species of corals, a hydrocoral, and 3 species of brachiopods (Durham, 1944, p. 188, loc. A-1802). Three of these 12 species (a coral, a hydrocoral, and a brachiopod) were among the numerically dominant individuals in the assemblage. Prior to my examination several geologists and paleontologists including Weaver, Harold Hannibal, H. G. Schneck, Nellie M. Tegland, and possibly Ralph Arnold and B. L. Clark, had made fossil collections from this locality. Before my account was presented (1944) at least two lists of fossils from Woodman's Wharf had been published (Weaver, 1916, p. 29–31, locs. 158–159; Effinger, 1938, table 1, Woodman Wharf). In neither list were any of the corals, brachiopods or hydrocoral noted although Effinger recorded a similar coral from another area.

Another factor contributing to the poor quality of our collections can also be illustrated from my own experience. In 1943 I was sent into northeastern Colombia to study the marine Cretaceous of the region. From previous reconnaissance work by others it was known that ammonites were abundant in some of the limestones and shales. It was nearly two weeks before I recognized my first ammonites even though I was searching for them. I then found that I had been overlooking them (sometimes in beds where they were abundant) because I had not previously learned how to recognize them in the rock (my previous experience had all been with specimens in the laboratory). It has been my experience that few students are taught how to recognize different kinds of fossils in the field —in the laboratory they have been given only specimens prepared to illustrate particular aspects of their morphology and not material showing their aspect in rock outcrops. As a result most fossil collections are highly biased towards the groups with which the collector was most familiar.

Most of our present fossil collections from individual depositional basins or regions include only a minor percentage of the total preservable biota of the area. Part of this of course is due to the fact that the rocky substrate biota does not live in an environment that is favorable to its preservation but even in this special case extensive exploration will usually uncover places where they can be obtained. However even the biotas of the environments favorable to preservation are rarely well collected. Most collections contain only the most common members plus an accidental few of the rarer elements. A few statistics will document this.

The known living marine molluscan (gastropods and pelecypods) fauna of the California coast from Monterey Bay to Cedros Island, from the shore out to the base of the continental slope numbers about 1428 species (courtesy James W. Valentine, November, 1966). Valentine estimates that the recorded marine Pleistocene gastropods and pelecypods of the same region total about 990 species. The Pleistocene fauna of this region has been the object of intensive studies in the last 20 years (see bibliographies in Addicott, 1966, and Valentine, 1961) and the rocky substrate habitat is well represented in some of these studies, yet the recorded fauna is only about two-thirds as large as the living fauna. It might be argued that the smaller size is due to colder marine temperatures during the Pleistocene but it should be noted that some intervals of the Pleistocene were warmer (e.g. Valentine & Meade, 1961) than at present, thus counterbalancing the effects of the cooler temperatures at other intervals. I believe that the small size of the recorded fauna can be attributed only to a lack of sufficiently intensive collecting. A few data on a worldwide basis and the resultant inferences add support to my contention. Although precise data are difficult to gather, information given in Abbott (1954) and Easton (1960) indicate that there are about 80,000 living species of gastropods, over half of which are marine, and about 12,000 species of living pelecypods, of which most are marine.

From this it seems probable that there are over 50,000 living species of marine clams and snails, most of which are shelled and thus fossilizable. Inasmuch as Pleistocene faunas have a close degree of similarity to living faunas, it seems that on a worldwide basis, if the record were fully known, that we should have nearly 50,000 Pleistocene species of these two groups of mollusks. Nevertheless Easton (1960, p. 5) records only a total of about 30,000 extinct species from all ages. Thus our knowledge of fossil gastropods and pelecypods is manifestly very incomplete, even if all the extinct species were confined to the Pleistocene.

The marine molluscan faunas (mostly gastropods and pelecypods) of the Tertiary of California have been studied more than those of any other region in western North America and even on a worldwide basis appear to be better known than most faunas, yet the check list of Keen & Bentson (1944) records only the following totals (approximate):

Paleocene	170 species
Eocene	630 species
Oligocene	260 species
Miocene	370 species
Pliocene	300 species

Studies since the Keen & Bentson compilation have added but few species to these lists. Inasmuch as faunas of the older epochs represent intervals when the marine climate was warmer (tropical from the Paleocene to Oligocene—see Durham, 1950, 1952) at these latitudes, their representation of contemporary biotas is much poorer than that of the Pleistocene. For comparision, the living marine molluscan fauna of the Panamic region, presumably a comparable tropical province, is estimated to number more than 2500 species. The faunas of marine Eocene strata of the Paris Basin have been more intensively studied than those of any other region and as a result over 3000 taxa have been recorded. As an example of a well described fossil tropical marine molluscan fauna, from a single bed, Woodring (1925, 1928) has recorded 610 species (not including an estimated 47 taxa of the gastropod families Pyramidellidae and Melanellidae) from a bed "... not more than 2 or 3 feet thick..." in the Miocene of Bowden, Jamaica, and he notes that (Woodring, 1928, p. 23) "The rock-clinging, rock-boring, and mud-burrowing species are almost entirely unrepresented." Further he lists 85 molluscan genera known to occur in contemporary Caribbean faunas but unrepresented at Bowden. I would estimate that this fauna, large as it is, does not represent more than a fourth of the contemporary Caribbean shelled marine molluscan fauna. Nevertheless, it, like the following example, demonstrates that careful collecting, preparation and sorting of material from a locality where fossils are well preserved can produce much larger faunas than those commonly recorded.

Probably the best (taxonomically) studied locality of the California Cenozoic is one from the late Pleistocene reported on by Kanakoff & Emerson (1959). At their locality 66-2, on the east side of Newport Bay, as the result of sorting and counting over 67,000 specimens, they recorded 427 taxa of mollusca. This collection was made over a period of several years by completely removing and screening a 21 foot thick pocket of highly fossiliferous sediments. Analysis of their lists produced the following table:

ANALYSIS OF KANAKOFF AND EMERSON LOCALITY 66-2
67,419 specimens representing 427 taxa

Original Sample					One percent Sample		0.1 percent Sample	
Specimens per taxon	Total specimens	Percent specimens	No. taxa	Percent taxa	Number specimens	Max. No. taxa	Number specimens	Max. No. taxa
over 5000	7,548	11.2	1	0.2	75	1	8	1
1000-4999	30,005	44.5	17	4.0	300	17	30	17
500-999	11,890	17.6	18	4.2	119	18	12	12
100-499	12,106	18.0	58	13.6	121	58	12	12
10-99	5,206	7.7	153	35.8	52	52	5	5
4-9	474	0.7	80	18.7	5	5	1	1
1-3	190	0.3	100	23.4	2	2	0	0
Totals	67,419	100.0	427	99.9	674	153	68	48

In the 1-3 specimens per taxon group, 37 taxa are represented by one specimen each, 36 taxa by two specimens each, and 27 taxa by 3 specimens each.

Presenting the statistics for the locality in another form we find that: nearly one-fourth

(over 23%) of the known taxa are represented by less than one-third of one per cent of the individuals; over 11% of the specimens represent a single taxon; nearly 45% of the specimens represent 4% of the taxa; 73% of the specimens represent 8.4% of the taxa; and 91% of the specimens represent less than one-fourth (22%) of the taxa. Thus it is theoretically possible (but not probable) that if only 67,229 instead of 67,419 specimens had been collected that only 327 taxa instead of 427 would have been recorded.

A sample as large as Kanakoff and Emerson's is rarely collected. To emphasize the effects of small samples, a one percent (674 individuals) and a 0.1 per cent (68 individuals) sample have been calculated in the above table. Many collections of megafossils do not include 68 individuals, yet in the above assemblage (collected in the same manner) such a sample would represent, at most, only 48 taxa instead of 427. Few megafossil collections total 674 individuals, yet such a sample would represent, at most, only 153 of the 427 taxa known to occur in this assemblage. It is clearly evident that in order to have a good representation of megafossil biotas we must greatly increase the size of the samples that we collect. A majority of the individuals in a fauna represent only a minor proportion of the number of taxa present, and extensive careful collecting is necessary to insure even a reasonable representation of the total diversity. Fortunately for the "peace of mind" of stratigraphic paleontologists the dominant elements in similar sequential environments are usually comparable and age evaluations based on the usual small sample are thus reasonably significant.

DATA FROM PALEOBIOGEOGRAPHY

The incompleteness of our exploration of the fossil record is also documented by paleobiogeographic data. The genus *Dasmia*, a small solitary coral with very distinctive morphology, has long been known from the lower Eocene of the London-Hampshire basins in England but not recorded elsewhere. Some years ago specimens difficult to distinguish from the British species were found in the late Eocene of Western Oregon. I believe that I can separate the Oregon specimens from the British ones at the specific level but there is no denying their assignment to the genus *Dasmia*. I take these two occurrences on opposite sides of the world to indicate that the genus once had a continuous distribution from Britain to Oregon, and perhaps it was even cosmopolitan.

The recorded distribution of the coral genus *Dendrosmilia* is somewhat similar to that of *Dasmia* (see Durham & Barnard, 1962, p. 5). The genus was based on a single species from the Eocene-Oligocene of the Paris Basin. A single specimen of *Dendrosmilia* has been found living in the Channel Islands off the coast of Southern California. Further, the coral described as *Astrangia boreas* by Nomland from the Pleistocene near Juneau, Alaska, is also referable to this genus. Thus a few specimens have greatly extended the range of *Dendrosmilia*, both geographically and geologically. Many similar instances are known throughout the fossil record and for all major groups of animals. The living coelacanth fish *Latimeria* and the monoplacophoran mollusc *Neopilina* only dramatize the incompleteness of our knowledge. All the "connecting links" between them and their ancestors had hard parts that were fossilizable. I believe that we have looked neither long enough nor critically enough to find them. Perhaps some of us have not learned how to recognize more than a small segment of the spectrum of organic diversity present but most probably it is lack of critical examination that is responsible.

THE PRECAMBRIAN RECORD

Finally a word about the Precambrian and its apparent lack of fossils. Part of the difficulty is of course semantic. For some, once the remains of a complexly organized animal is found, the containing rocks are no longer Precambrian. This I believe is a fallacious argument, and I am not concerned with it here. We all recognize that most major groups of animals are represented in the Cambrian and many of them in the Early Cambrian. We also recognize that in certain places there are seemingly continuous sequences of unmetamorphosed rocks that extend from the Cambrian into the Precambrian and that few if any fossils have been recorded from the older part of these sequences. I believe the evidence indicates that this absence is an artifact, either of our lack of critical observation or of our lack of ingenuity in our searches. My arguments for this are theoretical but I believe substantial, and I will again draw upon my own experience to illustrate them. The Echinodermata are represented in the Early Cambrian by at least 5 classes: Helicoplacoidea, Eocrinoidea, Edrioasteroidea, Camptostromoidea, and a new class based on the genus *Lepidocystis* (see Durham, 1964, 1966, and in press, Treatise on Invertebrate Paleontology, part S). The morphologies of these groups are very distinct, with no known intermediates. All have well developed hard parts and inasmuch as the test of the various groups of echinoderms is universally accepted as homologous, their common ancestor also must have possessed one. If one accepts a rate of evolution for the ancestral echinoderm similar

to that displayed in later times, the group must have had a long Precambrian history, and even if an accelerated rate is postulated during their early diversification one is still faced with the necessity for a considerable period of time to enable the known diversification to occur. I believe the evidence demonstrates that there was a diversity of Precambrian echinoderms and that the Later Precambrian seas were replete with organisms of many kinds. It is up to us to sharpen our tools, techniques, and powers of observation. Once this is done and we intensify our search, I predict that these fossils will be found.

Although I have not discussed the findings of micropaleontology and palynology, I would like to emphasize that many rocks once described as barren of fossils, are now known to be highly fossiliferous because of the techniques developed in these two fields. Likewise I would like to point out the great amount of new vertebrate material found as a result of the adoption of micropaleontological washing techniques in recent years. For instance, the collections of the Museum of Paleontology of the University of California contained only 5 specimens of Late Cretaceous mammals in 1950. Now they have over 5000 specimens, almost all obtained by application of the washing and screening technique. It appears highly improbable that we will not develop any more new tools or techniques in paleontology, and it seems to me that some such breakthrough will reveal to us the Precambrian spectrum of fossils.

DIVERSITY IN THE MARINE ENVIRONMENT VERSUS OUR KNOWLEDGE

One final set of statistics. Using the data in Easton (1960, p. 5), the information in Abbott (1954), and a few "educated guesses" on some of the numerically less important groups of living invertebrates exclusive of insects, it appears that there are about 150,000 species with hard parts living in the marine environment. All these are potential fossils. Our knowledge of Early Cambrian faunas is poor, but I would estimate that at least 100 marine species are known. It is difficult to assess the rate of increase of past biotas but by the Ordovician all major groups of marine organisms are represented and the recorded faunas are much larger than in the Early Cambrian. Nevertheless to be conservative I have assumed a gradual increase in size of the marine biota through the Cretaceous. Cenozoic marine faunas all appear to be reasonably comparable with those now living. Because of varying rates of evolution it is difficult to assess the time necessary for a fauna to be completely replaced by a new one, but Teichert (1956) has arrived at a span of 12 million years and this was accepted by Newell (1959). Using 600 million years as the interval of time since the beginning of the Cambrian and approximately 60 million years since the beginning of the Cenozoic, Teichert's span for complete faunal replacement, and the above evaluations of the size of the biota, we arrive at the conservative estimate 4,127,250 taxa of "fossilizable" marine organisms that have existed since the beginning of the Cambrian. Using Easton's data on the total number of fossils and using the same techniques as above to arrive at those found in the marine environment, I find a total of about 93,000 species recorded. Thus conservatively we now know about one out of every 44 species of invertebrates with hard parts that has existed in the marine environment since the beginning of the Cambrian. I think this ratio is unrealistically conservative, probably one out of every 100 is closer to reality. In case you consider this too pessimistic an estimate, I call your attention to Simpson's (1952) estimate that between 50,000,000 and 4,000,000,000 species of organisms have existed since the beginning of life, with 500,000,000 as a possible approximation.

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MANUSCRIPT RECEIVED DECEMBER 2, 1966

from: Eicher, 1976. Geologic Time

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biostratigraphy

The term "biostratigraphy" refers to the dating and correlating of rocks by means of fossils. Fossils have left a record of life on this planet that stretches back more than 3 billion years. This record testifies that all organisms have undergone constant evolutionary change. In the Precambrian rocks this record is meager, but in the Phanerozoic rocks it is elaborate indeed. Geologists have arranged the myriad of species from these richly fossilferous strata in their proper sequence and have thus established a time framework for the Phanerozoic.

However, not all changes in a vertical succession of fossil-bearing strata are caused by organic evolution. Particular plants and animals have always been adapted to particular environments. Thus, fossils contain much information about the ever-changing conditions on the Earth's surface. In this role they add significantly to the environmental record that is readable from rock types alone.

The Earth's record of life is thus a result of environmental influences superposed on the basic evolutionary changes. And while similar environments occurring at widely different times in the geologic past have commonly produced similar sedimentary rocks, similar environments widely spaced in time have never yielded the same faunas and floras. Faunas and floras have continually changed as new species appeared and the old ones became extinct. Thus, the total organic spectrum at any given time in the geologic past was unique. Properly interpreted, fossils provide the most accurate means of determining geologic ages of Phanerozoic rocks.

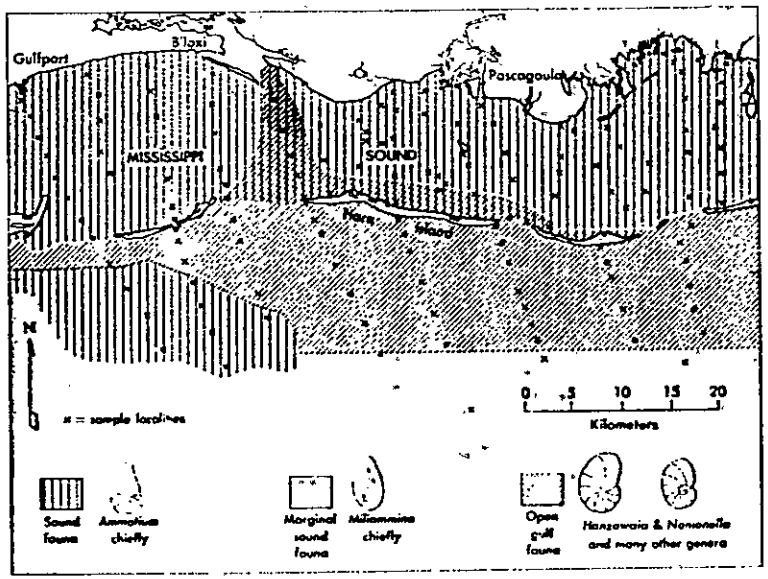
GEOGRAPHIC DIFFERENCES IN ORGANISMS

Species of animals and plants today are distributed in complex local patterns governed by environments. Most species are also confined to large geographic regions bounded by barriers to dispersal. *Ecology* deals with the relationship of organisms to their environments. *Biogeography* deals with the broad distibution of animals and plants on the Earth's surface. *Paleoecology* and *paleobiogeography* are the sciences of ecology and biogeography applied to fossils.

Biofacies

Within a given region today certain organisms occur together repeatedly. Each of these assemblages of species favors a particular habitat—an area that may be small or large—having specific environmental conditions. Adjacent areas with differing environmental conditions support different assemblages. Figure 5-1, for instance, shows the distribution of three different assemblages of benthonic foraminifera in the northern Gulf of Mexico. The *Miliammina* assemblage occurs near the shore in waters of low salinity. The *Ammotium* assemblage occurs in water of moderate salinity, chiefly in the Mississippi Sound. The open

FIG. 5-1 Present-day distribution of benthonic foraminifera in a portion of the northern Gulf of Mexico. (After F. B. Phleger, 1954.)



sea south of Horn Island supports a varied benthonic foraminiferal assemblage including *Hanzawaia* and *Nonionella* among others. Farther seaward a sequence of similarly distinct bottom assemblages (not shown) occurs with increasing water depth. Presently accumulating sediments that contain the organic remains of these diverse assemblages will appear as distinct foraminiferal biofacies in the future sedimentary record.

Each species of animal or plant produces more young than can survive in its living space, and thus each tends to expand into every area where environments permit. Highly mobile animals like birds have obvious means of rapid dispersal. But even sessile organisms like land plants produce seeds that may be borne widely by animals or by wind, and many sessile benthonic marine animals have free-swimming larvae that may be carried widely by ocean currents. When a new species is introduced into a new region, it migrates rapidly into favorable environments throughout that region.

Biogeographic Provinces

Few species of plants or animals are distributed throughout the entire world. Most occur only within the confines of large regions called biogeographic provinces. Biogeographic provinces are separated by physical or climatic barriers to the dispersal of organisms. Land areas are barriers for marine organisms and open water is a barrier to the dispersal of most land animals and plants. For marine organisms adapted only to shallow water, a deep ocean basin poses as great a barrier as a land mass. Climatic barriers are effective for many other groups of animals and plants. Barriers that are impenetrable for one group of organisms may be overcome by another group. Some species, for example, have much wider temperature tolerances than others. Geographic limits of swimming marine organisms likewise differ from those of bottom dwellers.

From the ecologic and geographic differences in living species today, we infer that similar differences must have existed in the past. This is verified by the geologic record. Phanerozoic strata contain a geographic variety of fossil organisms comparable to that of modern biologic communities and provinces. The result in stratigraphic terms is an array of biofacies in the rocks that is fully as complex as the lithofacies discussed earlier.

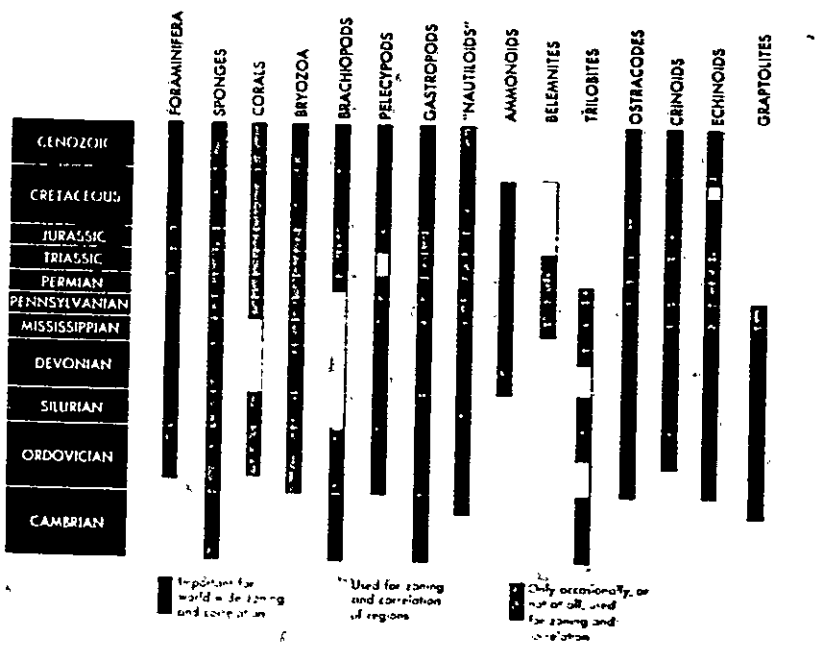
CHANGES IN ORGANISMS THROUGH TIME

Each species today is delicately adjusted to a set of specific environmental circumstances, sometimes termed an "ecologic niche." If conditions remained absolutely fixed, species might never change. Most genetic mutations could only interfere with their delicate ecologic adaptations, and mutating individuals would be selected against. But in nature conditions are nowhere perfectly static

for long, and environmental change is the rule, not the exception. Since their first appearance on this planet, animals and plants have accommodated to these changes by slowly evolving through the natural selection of those random mutations that happened to bring the species into better adjustment with shifting environmental conditions. The evolutionary process has been one-directional and nonreversible.

Rates of evolution vary greatly. Some groups of organisms have evolved very little over long stretches of time, while others have evolved at tremendously fast rates, comparatively speaking, and have left a record of striking change in the rocks. Such groups, if they became widely dispersed, provide valuable short-ranged species for time stratigraphy. Paleontologists very early became aware that every geologic period has its characteristic groups of short-lived species or genera and that the stratigraphic value of biologic groups varies greatly from system to system. Figure 5-2 illustrates the time-stratigraphic utility of the major groups of marine invertebrates for various times in the Phanerozoic.

FIG. 5-2 Relative time value of major groups of marine invertebrates during the Phanerozoic. (After C. Teichert, 1958.)



COMBINED EFFECTS OF GEOGRAPHIC DIFFERENCES AND TIME CHANGES IN ORGANISMS

The complications of biofacies and biogeography seem to be bothersome impediments when one is attempting to work out time-stratigraphic significance of fossiliferous stratigraphic successions. In a broader sense, however, we are fortunate to have organic records of ancient environments and provinces, just as we are fortunate to have the time utility provided by evolution. Both the environmental and temporal records are important for interpretation of geologic history.

If faunas and floras of the geologic past had not been confined to specific environments and to biogeographic provinces as they are today, and if all evolutionary changes had been simultaneous and worldwide, then even small evolutionary changes would be reflected everywhere in sedimentary rock sequences. We would be able to correlate sedimentary rocks everywhere with great confidence, because all over the world at a given time they would contain identical fossil species. On the other hand, fossils would provide no aid in detecting different ancient environments. In the absence of environmental and provincial distinctions, diversity would be monotonously low, and if only one biotic assemblage existed over the Earth's surface at any one time there would be no faunal basis for interpreting paleogeography or paleoclimates. The world in geologic history would indeed be biologically so monotonous, so unlike that of the present day, that there would be little of interpretive value to be gained from all the precise correlations that the biologically uniform circumstances would permit.

If on the other hand, organic evolution had never occurred and if living things throughout all past time were the same as they are today, all changes in fossil assemblages in sedimentary rock successions would be due either to local changes in environmental conditions or to the breakdown of barriers between biogeographic provinces. Successive fossil assemblages would potentially differ as dramatically as elephants differ from sea shells, but as environments recurred, they would bring with them identical organisms time and time again. On a local scale we would be able to interpret ancient environments with great confidence because fossil assemblages would contain exactly the same species as modern organic communities. However, in our hypothesized absence of evolutionary changes with time, we would not be able to correlate our elaborate local chronologies.

Fortunately, the real situation lies somewhere between the extremes outlined above. This means that with discrimination fossils permit both environmental and temporal interpretations. The effort required to untangle the effects of the two causes is the key to correct reconstructions of geologic history.

USE FOR BIOSTRATIGRAPHIC ZONATION

No plant or animal has existed for all geologic time. Each species evolved from some ancestor and so had a beginning. If it is extinct today, it also had an ending. Each extinct species therefore must divide geologic time into three parts: the time before it evolved, the time during which it existed, and the time since it became extinct. Any rocks that contain the species must have been deposited within the time during which the species existed. If the total time during which the species existed is short, then its presence in the rocks provides precise placement in the geologic time scale. But if the total time during which the species existed is great, then sedimentary rocks in different regions might well contain the species and yet differ widely in age. The total time range of some species is much shorter than that of other species, and short-ranging species are potentially of superior time value. If such short-ranging species occur widely and are readily recognizable they are sometimes referred to as "guide fossils" or "index fossils."

The strata that actually contain the fossil remains of a species constitute that species' *range zone*. The range zone at most localities represents only part of the total time during which the species existed because the species did not appear everywhere at exactly the same time and did not expire everywhere at exactly the same time. The total time during which a species existed must generally be inferred from the results of extensive collecting over wide regions in order to find the very oldest and youngest strata in which the species occurs. The total time range of a fossil species is always subject to extension upward or downward by new fossil finds. Yet, as more and more observations are made, the probability becomes small that ranges of individual species will have to be revised significantly.

At a locality where a species' range zone is overlain by strata containing its direct descendents and underlain by strata containing its immediate ancestors, the range zone very likely represents the species' total range in time. This situation is rare. Far more commonly a species appears in the fossil record fully developed with no indication in the strata below of its ancestors. We may infer that the range zone of such an abruptly appearing species represents only a part of its total range in time. Yet such a species may be of great biostratigraphic value in certain regions, particularly if its first appearance represents the breakdown of a barrier and its sudden migration into a new biogeographic province. However, if its first appearance in an area is due merely to the shifting of a local environment in a province where the species has existed for a long time then the species is probably an environmentally sensitive *facies fossil*, and of little value in time correlation. The proper interpretation of a species' range zone boundaries is thus important and must generally be based on the evidence from more than one locality.

If the species first appears at a lithologic change (for example, at the base of a sandstone unit whereas it does not occur in an underlying shale), then the environmental change responsible for the new lithology was probably favorable for the species and the appearance is of no biostratigraphic significance. But if the regional evidence indicates that the abrupt appearance is synchronous, or as nearly so as we can tell, then it may represent the species' sudden dispersal throughout the province some time after it evolved elsewhere. The appearance thus represents the surmounting of a barrier by the species, and its immediate migration beyond its former confines. This migration event provides a time-stratigraphic marker that is as useful as a first appearance due to evolution. The biostratigraphic utility of the abruptly appearing species is simply based on that part of its time range during which it existed within the biogeographic province in question.

The top of a species' range zone is commonly abrupt also. If the last appearance accompanies a lithologic change it may signify a mere environmental shift. But if regional evidence indicates that the disappearance represents an extinction event, then it has biostratigraphic value.

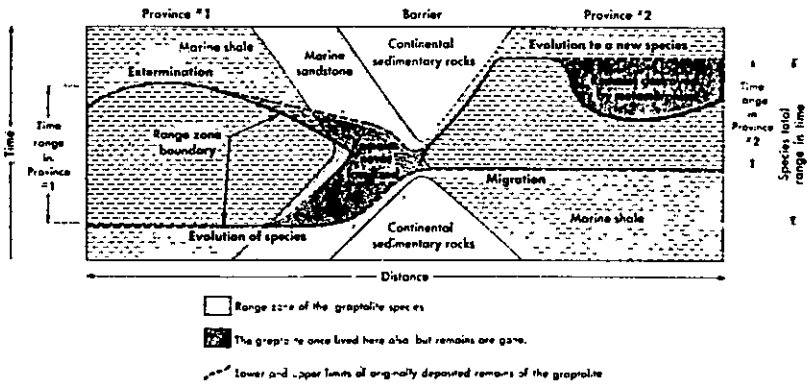


FIG. 5-3 Relationship of a hypothetical graptolite's range zone to its total range in time in two biogeographic provinces. (Modified from H. D. Hedberg, 1965.)

In summary, the correct interpretation of the fossil record requires the discrimination of local environmental effects from time-significant events. Such time-stratigraphic events may be grouped into three categories: evolutionary events, migration events, and extinction events. Figure 5-3 shows an example of these for a graptolite species, and it shows the relation of the rocks that contain the species (that is, its range zone) to the total time during which the species existed and to its time range in two different faunal provinces.

INTERPRETING THE RECORD

Three examples will help to illustrate how range zones, which are the fundamental biostratigraphic units, are recognized and interpreted in the field.

Discriminating Time-Significant Events in Range Zones

This example focuses particularly on the kind of evidence one actually looks for in order to distinguish the effects of time-significant events from the local effects of shifting environments. Refer for the following discussion to Fig. 5-4. The middle of this diagram shows three widely spaced stratigraphic sections, A, B, and C. At each locality a black shale, calcareous in its lower portion, is overlain conformably by limestone. Reconnaissance examination of the three sections reveals that the limestone and the lower calcareous part of the shale contain "shelly" faunas consisting chiefly of brachiopods, and that the upper, noncalcareous part of the shale contains only graptolites. Immediately this distribution suggests a threefold division into gross biostratigraphic units. The strata that contain these diverse assemblages may be called *assemblage zones*. The recognition of these zones, shown in the top part of Fig. 5-4, simply takes into account the overall aspect of the different successive faunas without regard to ranges of individual species. These assemblage zones reflect changing environments, and thus they are of interest in interpreting environmental history. However, as they are followed laterally they will surely cross time boundaries. In order to work out the time stratigraphy we must seek out synchronous events on the species level. For further analysis we will select only a few species that show particular promise as time indicators.

Careful collecting from the shale beds throughout assemblage zone 2 at locality A reveals three successive graptolite species (2, 3, and 4), which are selected for interpretation. These are illustrated next to the column for locality A. Careful collecting from assemblage zones 1 and 3 reveals several distinctive brachiopod species. One from each zone is also selected for interpretation, and these are labeled 1 and 5 adjacent to the column for locality A. The vertical ranges of species 1 through 5 are carefully determined in the field at locality A and at localities B and C as well. The actual vertical limits of each of these species constitutes its range zone. The five range zones for each locality are plotted next to the stratigraphic columns.

Study of the 3 graptolite species from assemblage zone 2 at locality A reveals gradual vertical changes between species 2, 3, and 4, which we infer to be a phyletic lineage. That is, graptolite species 3 is ancestral to 4 and descended from 2. The range zone of graptolite 3 may thus be interpreted as a time-stratigraphic zone because its boundaries are inferred to be unique evolutionary events. They are the bases for inferred time lines W and X in the lower portion

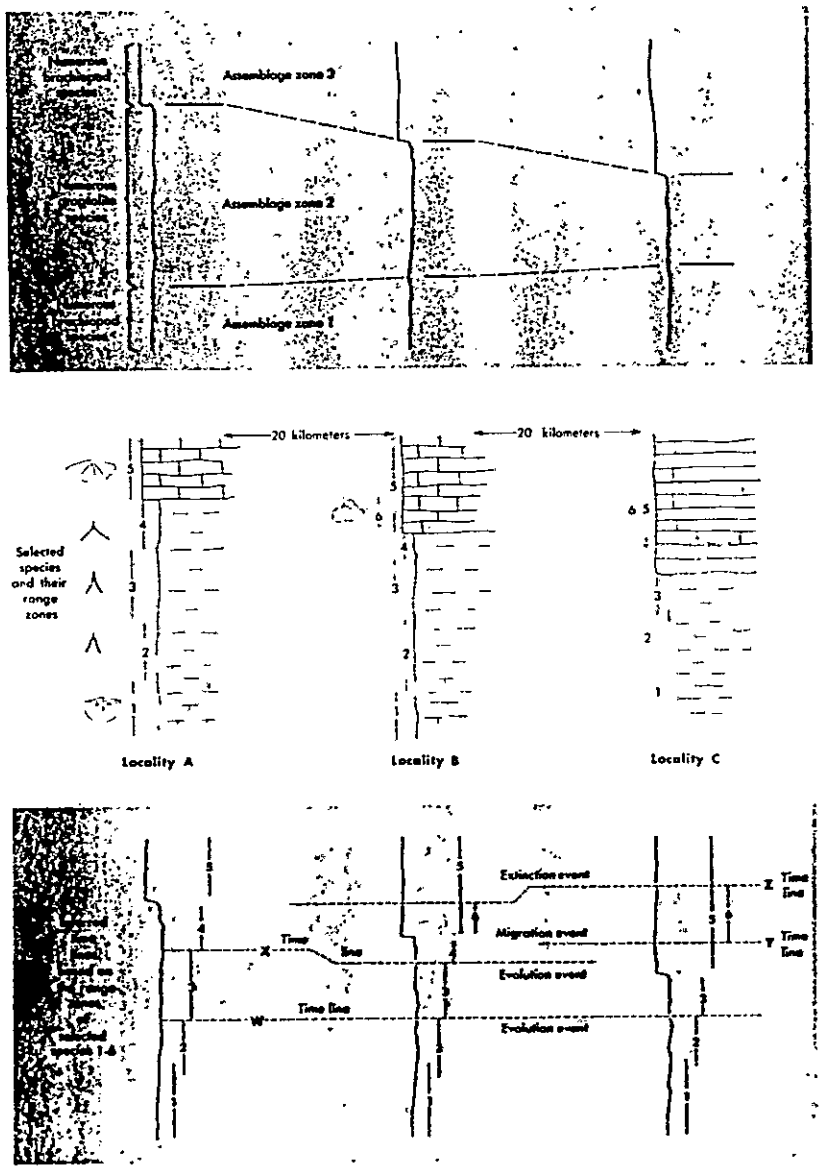


FIG. 5-4 Assemblage zones, selected range zones, and inferred time lines in a time-stratigraphic interval at three localities.

Fig. 5-4 The most obvious faunal changes in the section—those between the graptolite-bearing and the brachiopod-bearing strata—are interpreted as wholly environmental in origin and hence probably of no time value. Obviously these changes cannot be evolutionary; brachiopods did not evolve into graptolites and then graptolites back into brachiopods.

Locality B seems to bear out these interpretations. Gradations between graptolite species 2, 3, and 4 occur here in the same way as at locality A, verifying the inference that they constitute a phyletic lineage. However, species 4 appears only for a short stratigraphic interval before it is truncated by the brachiopod-bearing strata of assemblage zone 3. This suggests that the base of assemblage zone 3 is older at locality B, which is to be expected if assemblage zones 2 and 3 are environmentally controlled facies. This relationship is verified at locality C where graptolite species 4 has been replaced entirely by the descending limestone facies, which here truncates the upper part of the range zone of graptolite species 3. There is no way to extend time line X into the stratigraphic section at locality C with precision because the evolutionary appearance of species 3, on which it is based, is not recorded there. However, its approximate position is apparent.

At locality B, the lower portion of the limestone unit contains a distinctive new brachiopod (species 6), which is clearly not ancestral to any of the species in the upper part of the limestone. Its lowest occurrence is at the limestone-shale contact, like that of species 5, and thus it is probably environmentally controlled. At locality C, however, the lower limit of species 6 lies well within the limestone unit, suggesting that its introduction at this locality might possibly be due to something other than local environmental conditions; yet, just as it has no overlying descendants, species 6 has no underlying ancestors. Apparently species 6 first evolved somewhere else and was later introduced into our area by either (1) shifting local environments or (2) the breaking of a distant barrier between biogeographic provinces.

Inasmuch as biofacies and lithofacies boundaries do not necessarily coincide, shifting local environments cannot be ruled out simply because the limestone appears identical below and above the first appearance of species 6. In searching for additional evidence, we learn that the phyletic lineage of brachiopods to which species 6 belongs is well represented in strata of this age in another part of the world. We also find that throughout our own biogeographic province species 6 commonly first appears alone and not in conjunction with other species. From these facts we infer that the level at which species 6 first appears at locality C is not due merely to shifting local environments, but instead that it is probably due to migration from another province following the breakdown of a distant faunal barrier. Immediately upon immigrating, species 6 dispersed rapidly throughout our province wherever environments were suitable. Although only part of the total time range of species 6 is represented in our

province, the "migration event" with which species 6 is introduced (see the bottom diagram in Fig. 5-4) is considered as good a time marker as an evolutionary event, and it provides the basis for time line Y; obviously, however, it must be interpreted with caution. Locally, as at locality B, the first appearance may be environmentally controlled.

The simple disappearance upward of species 6 is less certainly time-significant. Inasmuch as it left no descendants in our province, there is no evolutionary event to mark its termination. If widespread environmental change caused its disappearance, then the top of its range may mark a nearly synchronous event. However, if local changes caused its disappearance, then even within one province it might persist in some areas long after being removed from others. If species 6 inhabited more than one province, the probability is low that it disappeared at exactly the same time from all of them. In this case its disappearance from each province is only an extermination and the final extermination its extinction. We find that species 6 seems to disappear everywhere in our province at about the same level as it does at localities B and C. Hence we may consider the top of its range zone at these localities a time-significant extermination or extinction, which is labeled on the bottom diagram of Fig. 5-4 simply as "extinction event."

In summary, this example has shown how the three principal kinds of time-significant events in biostratigraphy typically appear in the stratigraphic record. The primary ones are provided by evolutionary changes along phyletic lineages. Migrations and extinctions provide secondary time-significant events. These may be as valuable as evolutionary events, particularly when they involve rapidly evolving groups.

The Mapping of Range Zones

The Upper Cretaceous Pierre Shale, a thick, widespread formation in the Great Plains of the western United States, has had its key range zones mapped throughout large areas. This is unusual. The common practice is to map only rock units, and to express their component fossil range zones only in plotted stratigraphic columns such as those shown in Fig. 5-4. Hence the Pierre Shale provides rare insight into the extent and continuity of range zones. Figure 5-5 is taken from a portion of a larger map showing the areal distribution of range zones of 15 species of the ammonite genera *Baculites*, *Didymoceras*, and *Exiteloceras* in a region where the Pierre is about 2,500 meters thick. The map was constructed from faunal occurrences at several hundred localities in the field. In addition to the 15 range zones the map also shows two sandy members (Kph and Kplr) near the middle and another (Kpt) at the top of the Pierre. A striking characteristic of the map patterns of the range zones is the way in which they illustrate the geologic structure in areas of thick homogeneous lithology where they otherwise would not show.

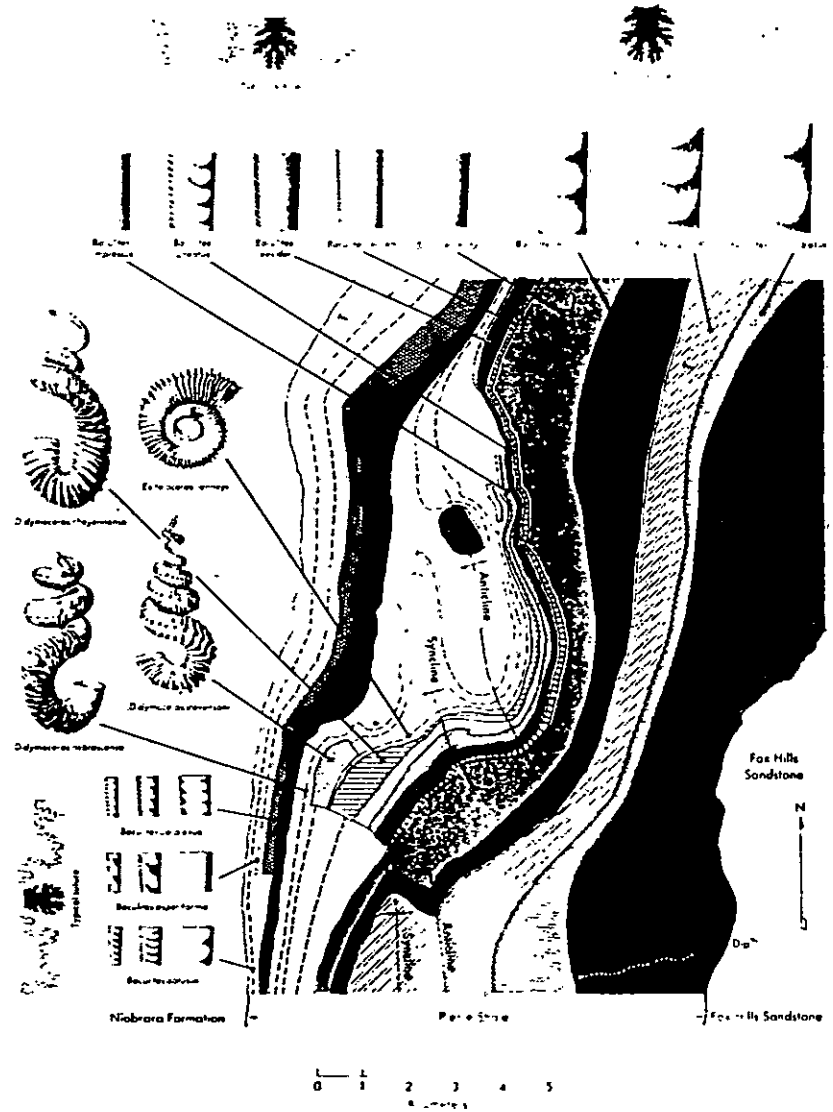


FIG. 5-5 Map of range zones in the 8,000-foot thick Pierre Shale of Cretaceous age in an area in northern Colorado. The three stippled patterns represent sandstone members of the Pierre. The other mapped units are distinguished solely by the fossils the strata contain. The dashed lines indicate areas where fossil collections are sufficient to map a zone's presence but are inadequate to locate its boundaries accurately. (After Scott and Cobban, 1965.)

The Pierre Shale in the area shown in Fig. 5-5 is not crowded with ammonites. Most of them occur in calcareous concretions, some scattered, others closely spaced in nearly continuous beds. The shale between concretion-bearing beds contain few fossils, probably because of conditions unfavorable for their preservation. Where concretion beds are locally covered by soil or alluvium the boundaries of the range zones cannot be ascertained with confidence, and the zones are represented on the map only by dashed lines known to fall within their limits. Fossils other than those mapped also occur in the Pierre Shale, but their distribution is not shown. Those whose range zones are shown have been selected for abundance and inferred time-stratigraphic significance.

The species of *Baculites* mapped in Fig. 5-5 belong to three closely related phyletic lineages. The earliest includes the species *B. obtusus* to *B. perplexus*, the next includes the species *B. compressus* to *B. eliasi*, and the youngest includes *B. baculus* to *B. clinolobatus*. The earliest representatives of each lineage segment appear as migrants from other regions, but their partial ranges in the Pierre are short and hence of great value. In each of the three lineages the succeeding species evolves through transitional forms and its range zones are believed to approximate the total ranges of these species in time.

Range zones of the three species of *Didymoceras* do not record a continuous lineage, but only fragments of one. Range zones of these species, however, are believed to approximate their total time ranges in this biogeographic province. The upper two *Didymoceras* zones are separated by the range zone of *Exiteloceras jenneyi*, a migrant with no apparent ancestors or descendants in this region. Its range zone is also believed to approximate its total time range in this province.

Species of *Baculites* are excellent for time-stratigraphic zonation. Their lineage is well known. They evolved rapidly so that the total range in time of each species is short. Moreover, they were swimmers and hence their distribution was not controlled by environmental subtleties of the sea floor. Most of the baculite species illustrated in Fig. 5-5 appear to be restricted largely to this single biogeographic province. It contains a relatively complete record of their evolution, which permits detailed correlation within the province. Because their record is sparse outside this province, however, they are of limited value for correlations with other provinces.

It should be re-emphasized that only a small minority of range zones appear to represent the total time range of a species. Most range zones, at best, represent a species' time range within a province. However, one must keep in mind that such ranges are delineated empirically, and that the finding of the species in a new area always carries the possibility of extending its known stratigraphic range higher or lower.

Gradual Faunal Migrations

Normally a species migration into a given province requires only a geologic instant once a barrier is overcome. However, the time significance of its initial appearance must be inferred with caution. All barriers in geologic history were not breached suddenly. Apparently some were gradually swept out of the way.

A. R. Palmer has shown that the Late Cambrian migration of the Pterocephaliid trilobite fauna into the shallow shelf seas of the Cordilleran region (southern Nevada and adjacent areas) took a long time (see Fig. 5-6). From west to east the Pterocephaliid fauna appears in progressively younger strata. As the new fauna migrated eastward across the region, it slowly replaced the previously established Crepicephalid trilobite fauna. Much later the Pterocephaliid fauna itself was similarly replaced from west to east by the still younger Conaspid fauna. The basic stock of the Pterocephaliid and Conaspid lineages developed in another province, one that was separated from that of the Cordilleran region, not by a clear-cut physical barrier, but by one more subtle, possibly maintained by temperature. There, migrations of profoundly new faunas into a province produce time-transgressive faunal changes like those produced on a much smaller scale by the shifting of local environments.

This example does not invalidate the temporal value of most migrations. It simply reiterates that any *single* line of fossil evidence is subject to greater error than several lines interpreted collectively. For reliable interpretations all available evidence should be taken into account.

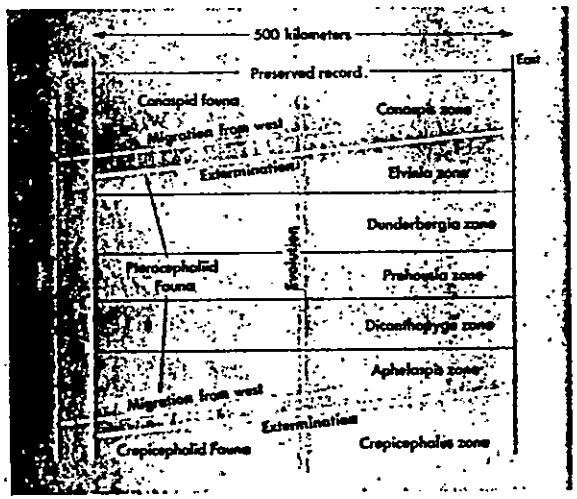


FIG. 5-6 The Pterocephaliid trilobite fauna slowly migrated eastward across the Cordilleran province in Late Cambrian time and replaced the established Crepicephalid fauna. Later the Pterocephaliid fauna was similarly replaced by the gradually migrating Conaspid fauna. (After A. R. Palmer, 1965.)

CONCURRENT RANGE ZONES

The narrowest time-stratigraphic zones with the most consistent boundaries provide the most accurate correlations. Logically, more precision results from utilizing the overlapping ranges of two or more species rather than the range

zone of one species alone, because the probability of encountering an older or younger occurrence of several species at a new locality is much lower than that of encountering an older or younger occurrence of just one of them. Zones based on overlapping ranges have been called *concurrent range zones*. Zones of this kind were invented and extensively used (1856–58) by Albert Oppel in the Jurassic rocks of Europe, and no one since Oppel's time has been able to devise a more precise and reliable kind of time-stratigraphic fossil zone.

Oppel plotted the range zone of every species he found in numerous stratigraphic sections in a wide area. Some of the stratigraphic ranges were short, some were intermediate in length, and others were long. Species ranges tended to begin and end independently and somewhat randomly, rather than jointly, in each section. Not only did Oppel carefully note vertical ranges of each species, but where he could he also inferred phyletic lineages. He placed the boundaries of his zones at the first appearances of a new lineage. Other selected species were equally important, however, for definition of the zone; some first appeared within it, others terminated within it. The fossils selected to depict a concurrent range zone were thus chosen for maximum reliability in time-stratigraphy. Typically many long-ranging species also occur in a given zone, but since they also occur in zones below and above, they are not included in the definitive association.

Concurrent range zones may include fossils from deposits formed in many environments, and in such cases their boundaries tend to be independent of minor changes in depositional environments. By the same token some of the characteristic species may never actually occur together in the same bed. A concurrent range zone is named after one of its species, but that species has no more significance in recognizing the zone than does any other single member of the diagnostic association. The name-giver need not be limited to the zone and it need not occur throughout the zone. Oppel pointedly noted that zones could just as well have been named after localities.

Most concurrent range zones can be recognized only within a single biogeographic province. The minor events of migration and evolution on which they are based typically have no synchronous counterparts in other provinces. When characteristic zonal species that have evolved within a province happen to spread suddenly into another province, they can provide invaluable tie points between the independent zonal sequences of each, but exact zonal *boundaries* can rarely be carried from one province to another.

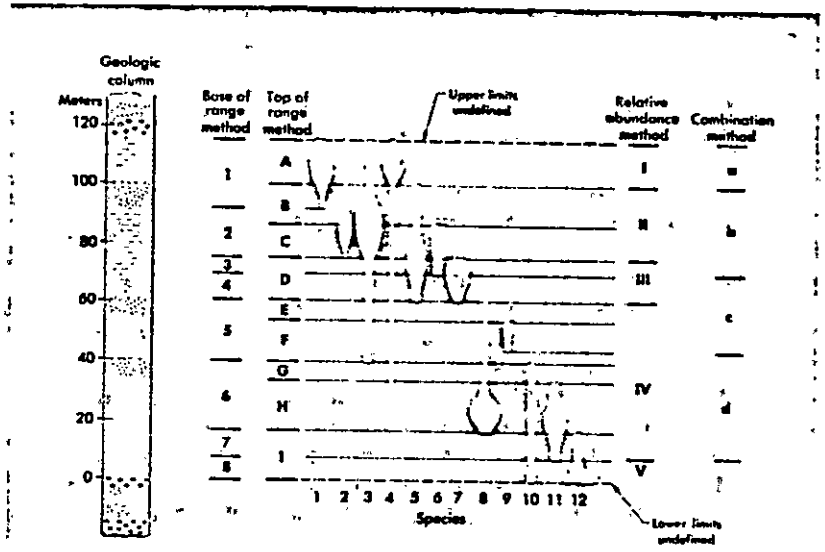
Although most fossil zones are too narrowly defined to be recognizable beyond their provinces, correlation can be established among provinces by utilizing groups of zones, or stages. Stages are recognized in the same way as zones; the difference is in refinement. Stages are based on larger faunal changes than zones and they can be recognized over the geographic extent of adjacent provinces; some can even be recognized worldwide. On a global basis, however, stages generally present the same difficulties as do zones when traced beyond their provinces. Most are simply refined too highly for worldwide extension. Hence, they are lumped into still larger units—series—which are recognized on even more gross organic changes than stages. With local exceptions, series can be traced fairly confidently all over the world.

Methods of Selecting Zone Boundaries

Workers since the time of Oppel have adopted various means of defining concurrent range zones to suit their special needs. Some paleontologists have selected boundaries that encompass certain combinations of bottoms and tops of ranges. Others, impressed with the very large numbers of particular species in some beds and their relative scarcity in others, have attempted to weave the idea of peak abundance into the concept of concurrent ranges. Still other paleontologists, dealing with subsurface information obtained by drilling, have focused their attention particularly on the upper limits of range zones. They do so partly because the geologic record is unfurled in reverse order in drilling, and partly because down-hole cavings obscure the lower limits.

Figure 5-7 illustrates four ways in which fossil ranges in one section could be divided into concurrent range zones. The scheme that Oppel might have selected, and which most European workers prefer today, is represented by

FIG. 5-7 Four methods of recognizing concurrent range zones in a single section. Width of lines indicates the relative abundance of specimens. (Modified from Schenck and Graham, 1960.)



Arabic numbers on the left side of the range chart. In this method a zone is bounded below by the lowest appearance of a significant species (preferably representing a new lineage), and above by the lowest appearance of another significant new species. In addition, each zone contains within it the first appearance of some species and the last appearance of others, and these aid in its recognition.

A method that might be applied by a subsurface geologist is shown by the capital letters on the left side of Fig. 5-7. One that takes abundances of each species into account is shown by the Roman numerals on the right side. Finally, a method designed to include as many species as practicable within each zone is shown by the lower case letters in the far right column of Fig. 5-7. The last method includes more lower and upper limits of ranges within each zone than the others do, and extensions of ranges in new areas tend to disrupt these zonal boundaries less than with the other three methods.

None of these methods is consistently superior to the others. In theory Oppel's approach, which emphasizes lower limits of range zones, may be the most sound, but in subsurface work where bases of zones may be impossible to ascertain within acceptable limits of accuracy, the use of upper boundaries may be the only method that works. In very small areas, zones based on abundances may actually be the most accurate. The method of zoning should depend on the information that is necessary to the task at hand and that can be collected under the circumstances.

INDEX FOSSILS AND PEAK ZONES

The term "index fossil" suggests to most geologists a fairly abundant, distinctive species, narrowly limited in time and widely distributed geographically. Species that actually possess these attributes are valuable aids in correlation. So-called index fossils typically appear in the stratigraphic record fully formed with no indication of ancestry. This is one reason they are distinctive, but lineages of such species are poorly known. The ranges that are actually utilized are simply range zones, which, of course, may represent different durations of time in different areas. In correlation based solely on such index species there is no independent way of checking whether or not the stratigraphic range at a distant locality is the same as that known previously. Although many so-called index fossils appear to be reliable time indicators, others have been found to be unreliable. This lack of "quality control" has narrowed the use of index fossils considerably in modern paleontologic correlations.

Index fossils were initially conceived as a shortcut in correlation. The impetus for seizing upon particular index fossils may have actually stemmed from Oppel's method of naming concurrent range zones after just one of its representative species. Although Oppel had emphasized that each of the several species in the concurrent range zone association was equally significant, the one whose name the zone bore became somehow special to early geologists. The single species idea took root and by the end of the nineteenth century, paleontologists had acquired the habit of designating a zone's most abundant and characteristic species as "index." This species was supposed to represent the zone, and it came to be considered, particularly among nonpaleontologists, the key to the zone's recognition. The common practice of relying on just one species generally promoted reliance on simple range zones rather than concurrent range zones.

Later the term "index fossil" took on another undesirable connotation, particularly in the United States where it came to be thought of as a species that was characteristic of a particular formation. Saying that "this species is index for that formation" implies that a fossil found anywhere in the formation will be present throughout. This practice also implies that, because the index fossil has time value, the formation also has time value, thus confusing rock units and time-stratigraphic units and lending credence to the old fallacy that formations are time-parallel.

If a fossil species ranges throughout a formation in a given region, the species provides no events indicative of time. Probably it merely accompanied the environment that produced the formation's distinctive lithology. The species might aid mapping if the formation is one of several in the area that have similar lithologies, but this is not time correlation; it is only a means of identifying a part of the local section. To establish time correlation we must seek species that do not range throughout a formation, but which appear or disappear as a result of time-significant evolutionary or migration events. Thus, it is most important that stratigraphic occurrences of fossils be reported accurately *within* formations.

Another concept, closely allied to the concept of index fossils, was the idea that a great abundance of a fossil species could be interpreted as having time significance. In this view, it was not the organism's range, but its time of flowering, or "peak abundance," that provided the basis for a time-stratigraphic unit. Now, if there were some point in the history of a species when numerical abundance was a distinct maximum, and if this abundance were actually recorded everywhere in the strata that contain it, then the use of "peak zones" as time-stratigraphic units would be theoretically sound. In reality, however, maximum abundance may be reflected in some areas and not in others. The strata containing the most specimens may represent one of several things: sporadically favorable environments, sudden unfavorable conditions that resulted in mass mortality, a time of exceptionally slow sedimentation but sustained organic productivity, or mechanical accumulations of dead shells.

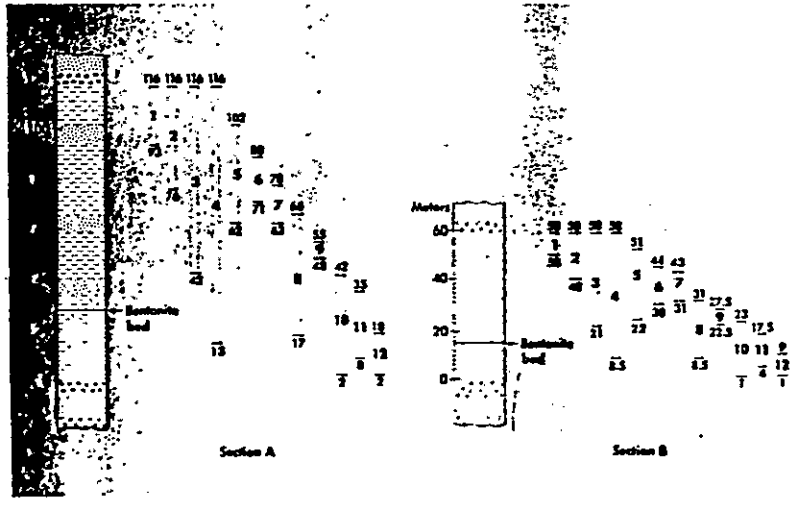
QUANTITATIVE BIOSTRATIGRAPHIC METHODS

Graphing the Correlation Line

Alan Shaw has proposed a correlation technique that utilizes the appearances and disappearances of all the species which two stratigraphic sections have in common. First, the range of zones are carefully established in the measured sections. Then the bases and tops of the range zones are plotted on a graph (see Fig. 5-8), using section A as the horizontal axis and section B as the vertical axis. These points tend to cluster around a "correlation line," like that shown in Fig. 5-9, whose intercepts depict precise correlation between the two sections. This kind of diagram is thus a good stratigraphic tool because it takes into account every potentially time-significant event in the two sections. In applying it one need have no concern for the often arbitrary selection of zone boundaries.

The points in Fig. 5-9 that fall well off the correlation line represent species which appear or disappear in one section much earlier than in the other. Such species are strongly facies-controlled. Hence judgments as to which fossils will be useful for biostratigraphic correlation and which ones will not can be made easily and objectively once the diagram is plotted. Physical events can also provide points for the correlation line. A bentonite bed that occurs in both sections represents an identical time level. This helps greatly in locating the correlation line, which should pass directly through it (see Fig. 5-9).

FIG. 5-8 (Left) Schematic representation of the sections shown in Fig. 5-9. (Right) Another section with an identical time span and identical fossil content but only half the rate of rock accumulation. Small numbers at limits of range zones indicate stratigraphic positions in meters above base.



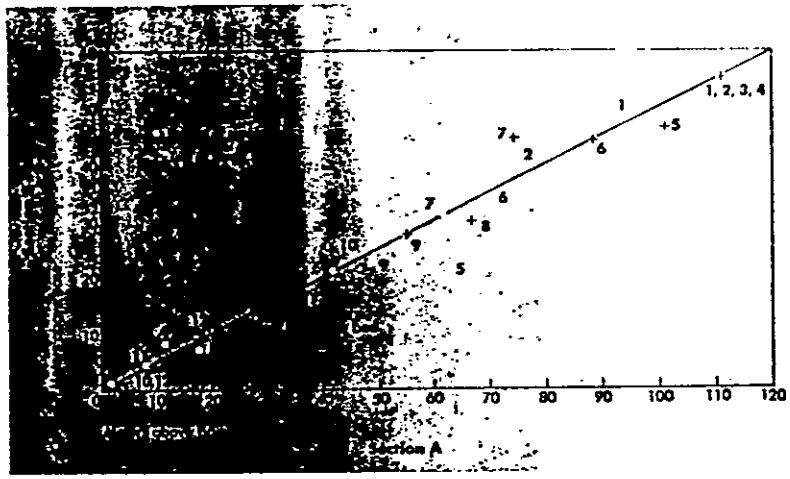


FIG. 5-9 Correlation line of the sections shown in Fig. 5-8.

Changes in slope of the correlation line tell much about the geologic history of an area. If the rate of sedimentation at one section increased or decreased significantly, the result is an expanded or condensed interval, and this shows up as a doglegged correlation line (see Fig. 5-10). A hiatus appears as a horizontal or vertical segment in the line (see Fig. 5-11).

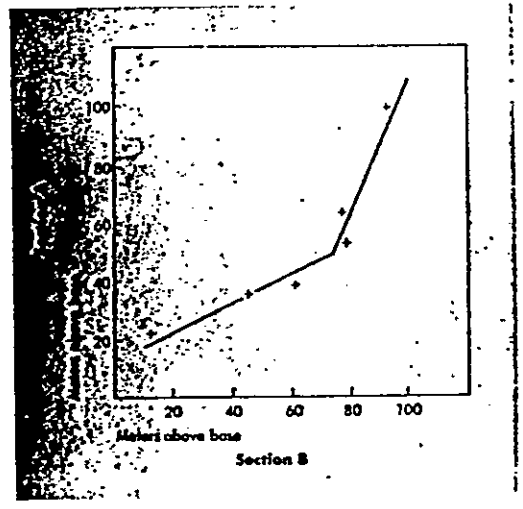


FIG. 5-10 Dog-legged correlation showing change in sedimentation rate.

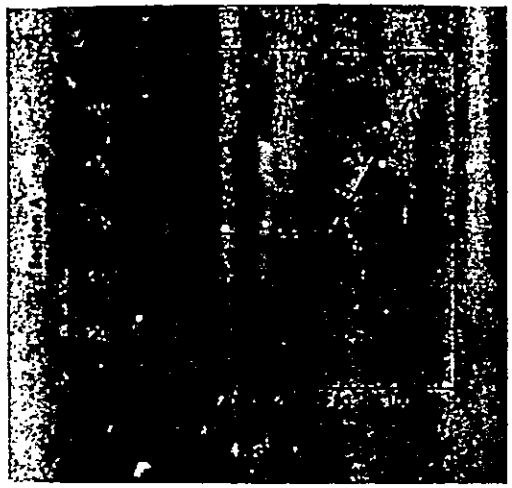


FIG. 5-11 A hiatus in Section Y appears as a horizontal line which offsets the correlation line.

Coiling Ratios in Planktonic Foraminifera

Planktonic foraminifera make their many-chambered shells out of calcite. Most are trochospirally coiled; that is, they coil in a spiral with all the chambers visible from one side of the shell and only those of the last whorl visible from the other side (see Fig. 5-12). Individuals belonging to a given species may coil either to the left or to the right. Some existing species of planktonic foraminifera occur in dominantly right- or left-handed populations, depending upon the temperature. For example, *Globorotalia truncatulinoides*, which is widespread in today's oceans, is dominantly right-handed in areas of warm waters and left-handed in areas of cold water. At times during the Pleistocene Epoch, when glaciers periodically covered much of the land areas of the Earth, the oceans cooled considerably. During these times dominantly right-coiled populations of *G. truncatulinoides* were replaced in middle and low latitudes by dominantly left-coiled populations.

These coiling changes provide a correlation tool capable of resolving Pleistocene climatic events that occurred over time periods of tens of thousands or hundreds of thousands of years, an order of magnitude less than the time that can be resolved using conventional zoning criteria. Figure 5-12 shows *G. truncatulinoides* coiling ratios in three cores that recovered Atlantic Ocean bottom sediments deposited over the last 1.5 million years. The proportion of right- and left-handed specimens fluctuates similarly throughout all three cores, and provides the basis for correlations. This method of biostratigraphic correlation is applicable only to a part of a given ocean basin, and even in a small region it is best supplemented by other correlation tools. Nevertheless, it provides a precision for the Pleistocene that surpasses that of most faunal zones.

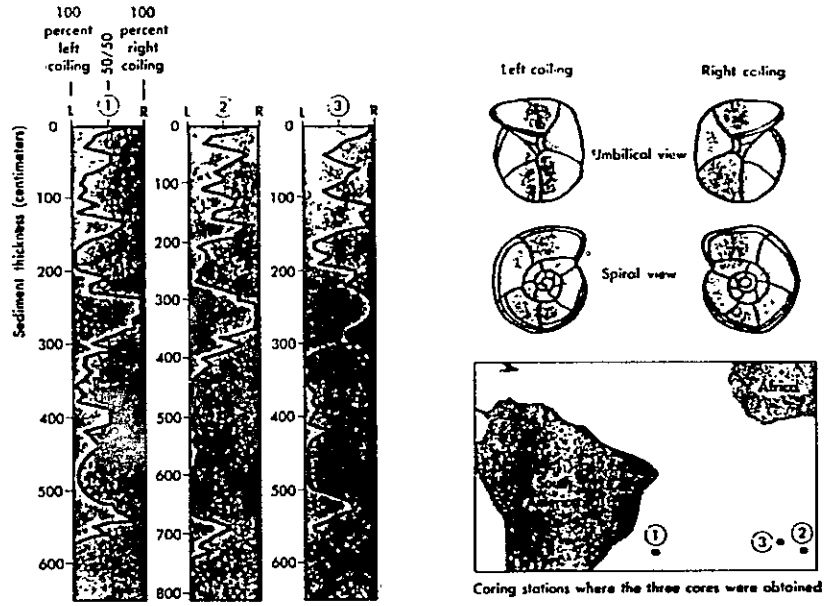


FIG. 5-12 Coiling ratios of *Globotruncana truncatulinoides* in three South Atlantic Ocean cores. Correlations are apparent for the 1.5 million years represented. (Data from Ericson and Wollin, 1968.)

A Quantitative Paleontologic Indication of Geologic Time

This final example does not deal with a correlation tool, but with a rare quantification of geologic time using fossil shells. It is based on the gradual decrease in the number of days in the year throughout geologic time.

Astronomers have long inferred that the Earth's rate of rotation must be slowly decreasing due to friction of the tides. Tidal energy comes from the rotation of the Earth itself, and because this energy is spent largely in the work of ocean currents, which must finally produce heat, the overall effect is like the everyday drag of friction that slows a rotating wheel. Although tidal energy is huge by civilizations' standards, it is extremely small compared with the kinetic energy of the Earth, so small that its retarding effects have only recently been measured. Tidal retardation is causing the length of day to increase by about two seconds every 100,000 years. At this rate the length of day at the beginning of the Paleozoic Era—570 million years ago—would have been about 21 hours. Meanwhile, the period of revolution about the sun would be expected to remain constant. A year was just as long as it now, but because the day was shorter it contained more days, about 420 at the beginning of the Paleozoic.

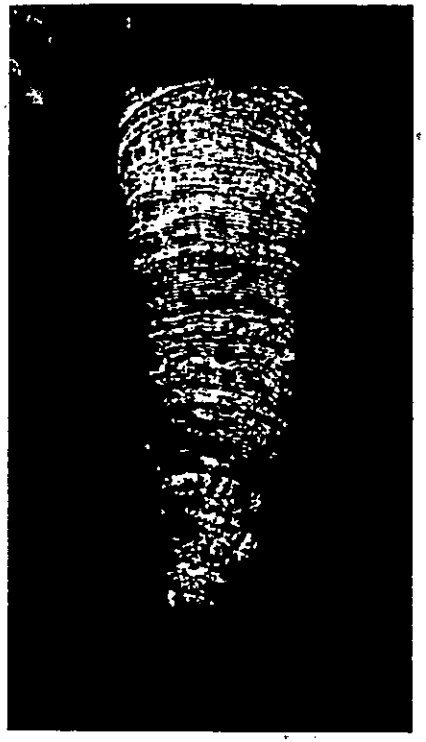


FIG. 5-13 A specimen of the Silurian coral, *Holophragma calceoloides*, with a total of 240 striations interpreted to represent 240 days' growth. (Magnified four times.) (Courtesy J. W. Wells.)

John Wells, an American paleontologist, has found evidence for both daily and yearly growth increments in Paleozoic corals. Wells suggested, on the basis of modern counterparts, that the prominent ridges girdling many Paleozoic horn corals represent yearly rings. Similar ridges are known to be produced yearly in modern corals and this inference appears to be sound. Thus, the age of a horn coral specimen can be ascertained by counting the ridges that encircle it. In addition to these ridges, well-preserved horn corals also show extremely fine, closely spaced striations that encircle the coral on the outer surface (Fig. 5-13). These striations, too, almost unquestionably represent growth increments. In modern corals similar increments occur daily, and the same was probably true for fossil corals. Therefore, by counting the number of fine ridges between the large yearly growth rings on the Paleozoic corals, Wells was able to infer the number of days in a year at the time the coral lived.

Only exceptionally well-preserved fossil corals show the fine striations, and even in the same specimen growth rates vary with short-term environmental fluctuations, thus scattering growth-line counts. But in three coral genera from Middle Devonian rocks of New York and Ontario, the numerous counts range

between 385 and 410 and they cluster near the median of 398. The scatter is shown by the vertical bar A in Fig. 5-14, and the indicated age of about 380 million years is essentially the same as that obtained by radiometric dating of rocks of this age. Corals from the Pennsylvanian of two different regions of the United States indicate 390 and 385 days per year (bar B, Fig. 5-14), only slightly fewer than the 392 days expected for rocks formed 300 million years ago, the radiometric age determined for the mid-Pennsylvanian.

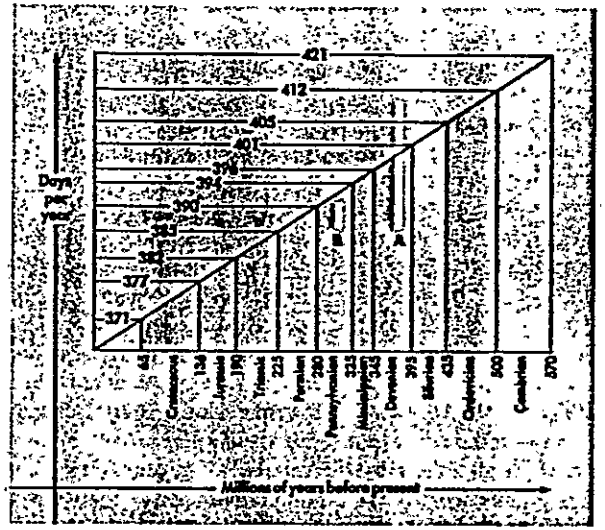


FIG. 5-14 Predicted number of days per year plotted against quantitative time scale. Vertical bars show results from daily striations and annual rings on fossil corals. (From J. W. Wells, 1963.)

In summary, the ages in years indicated by the fossil corals agree remarkably well with radiometric ages in years obtained from rocks of the same age. This verifies that radiometric dates, which are our conventional source of quantitative ages, are in the right ball park. This is particularly reassuring because the verification comes from a biologic system—a source of support as different from that of radioactive minerals as could be envisioned. These results suggest that the quantitative ages yielded by radiometric dating are reliable in general terms. Numerous cross-checks using various radiometric dating methods are internally consistent and further attest to the accuracy of the radiometric dating process. The following discussion in Chapter 6 will briefly explain these radiometric methods.

Population Systematics, Radiometrics and Zonation—A New Biostratigraphy

ERLE G. KAUFFMAN 1970
Smithsonian Institution, Washington, D.C. 20560

INTRODUCTION

Biostratigraphy is singularly the most important tool of sedimentary geology. It is now and perhaps always will be our primary means of dating and correlating rocks in detail. It is a reflection of evolutionary patterns and ecological responses to ancient environments in many lineages of organisms, and in whole assemblages. It is our most practical matrix of relative geologic time, without which the historical relationships of geological and biological events, or the interpretation of facies would not be possible to any confident degree of accuracy.

The historical development of American biostratigraphy has been phenomenal in many respects. In a little over a hundred years we have constructed for many parts of the column some of the most detailed biostratigraphic matrices found anywhere in the world, and have used them with great success for correlations within and between continents. The system has had a somewhat unique evolution, producing an American "school," strong in micropaleontology and highly detailed analysis of certain macrofaunal groups—including trilobites, brachiopods, graptolites, molluscs, mammals—in the development of broadly applicable systems of zonation and correlation, and characterized by its clear distinction and use of lithostratigraphic and biostratigraphic units. This success is related to several factors: a remarkably complete, well exposed and accessible stratigraphic record; a sound systematic base derived for many organisms early in the history of the science; considerable numbers of workers physically and monetarily supported at a comparatively high level in biostratigraphic research; and, perhaps most significantly, a rich conceptual and methodological base derived from early European work, which was incorporated into the American system and applied to the solution of a variety of stratigraphic problems with little change. Perhaps only the work of Alan Shaw (1964) can be considered a major contribution to biostratigraphic philosophy in America during this century.

The vitality of any scientific discipline is marked by a history of frequent challenge and innovation of its working concepts, and a continuous search for the interpretive potential of its data base. Measured against this, the field of biostratigraphy is virtually stagnant in the United States. Considering the large number of active biostratigraphers, the scope of available data, and the importance of the discipline to the solution of a broad spectrum of biological and geological problems, this complacency cannot be justified.

Proc. North American Paleontological Convention; 612–666 1970

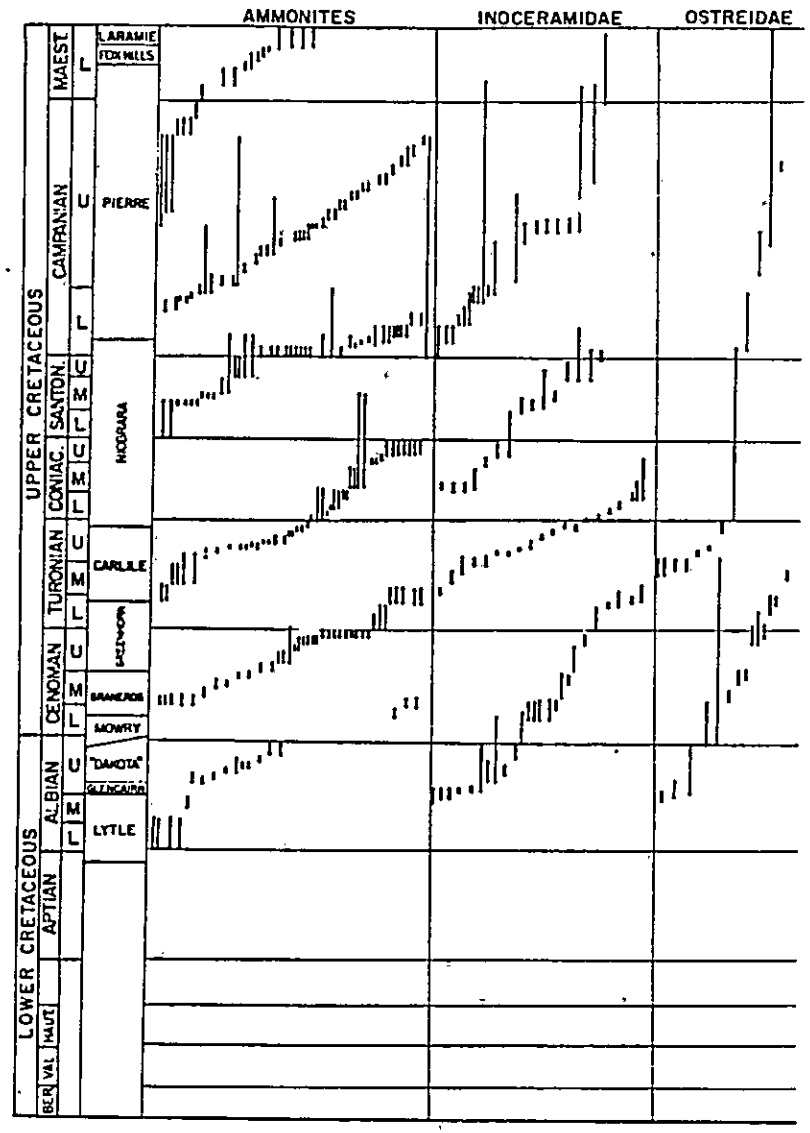
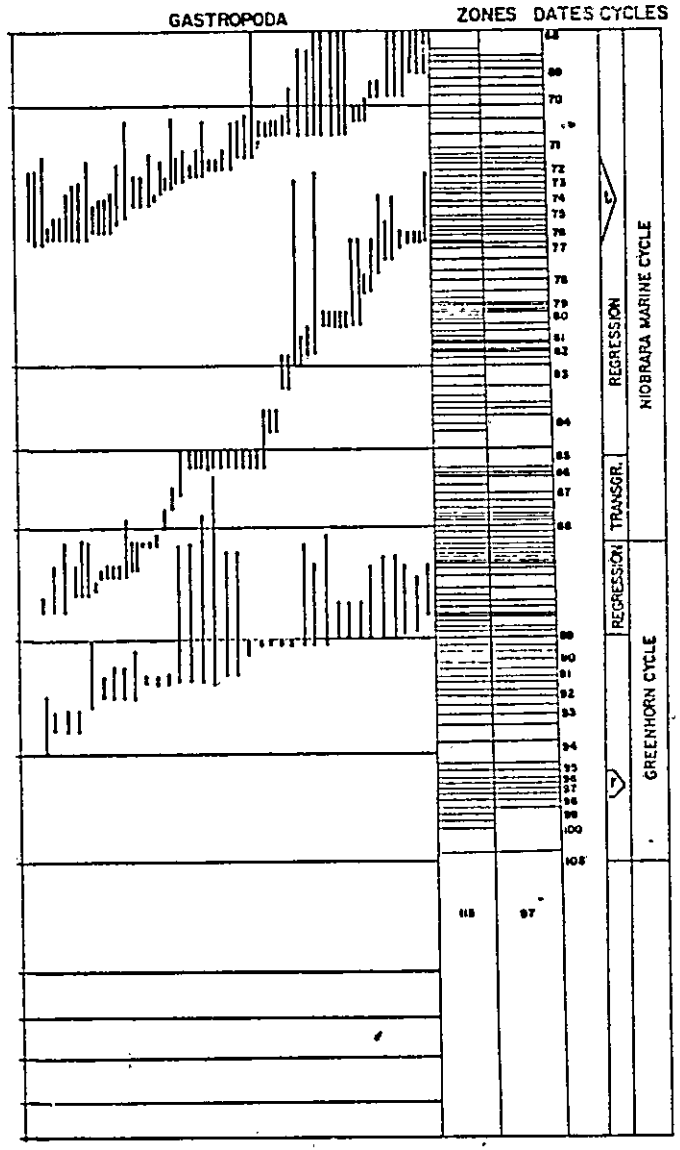


FIG. 6. Preliminary collective plot, against a standard base, of range zone data for some key molluscs employed in revision of the Western Interior Cretaceous biostratigraphic system, and two composite overlap assemblage zone hypotheses from just these data. This is presented as an example of actual data used in the revision; integration of numerous other groups permits various zonal hypotheses that will actually be used to be based on many more stratigraphic points per zone. Left hand, low confidence



level, zonal column based on 1-2 stratigraphic points (origins or extinctions) per zonal boundary; right hand column (high confidence level) based on 3 or more coinciding points per boundary. Absolute time points fitted to data from a calculated scale based on 21 radiometric dates. t–transgression; r–regression. Note crowding of zones during regression, explained as increased evolutionary rates for key molluscan taxa (see Figs. 5, 9).

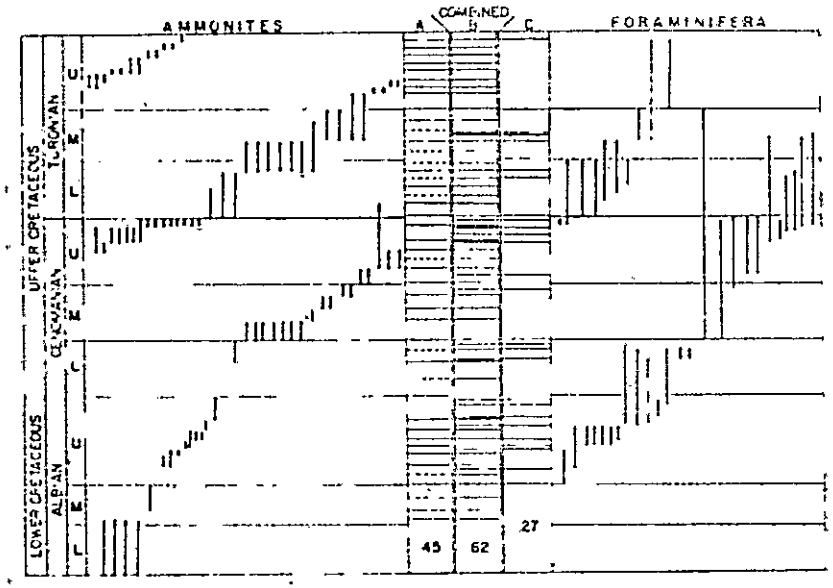


FIG. 7. Comparative range zone plots of ammonites and foraminifers from the Cretaceous Albian, Cenomanian, and Turonian stages of the Western Interior United States; chart shows relatively longer ranges, probably reflecting slower evolutionary rates, for the Foraminifera and the less refined overlap assemblage zonation that results (compare column A with C). Note that assemblage zone boundaries of Foraminifera do not coincide with those of ammonites in many cases, reflecting varying patterns and rates of evolution between them and suggesting that the most refined zonation is one combining all data (column B) rather than separate zonal systems based on distinct organisms. This phenomenon may account for various conflicts regarding stage boundaries which arise between micropaleontological and macropaleontological evidence in certain parts of the column.

and covers a far greater number of stratigraphic intervals and lithologic facies.

3). Range plotting for marine microfossils is not fully completed, or totally integrated with macrofossil data at the present time. In parts of the column where it is now possible to make comparisons between them, the assemblage zonation based on marine macrofossils, and the individual range zonation for any group, is 2 to 5 times as refined as similar zonal systems based exclusively on microfossils (Fig. 7). This appears to be a function of greater diversity and faster evolutionary rates among the macrobiota of the Western Interior Cretaceous. For convenience, microfossil and macrofossil data will be presented separately, and as an integrated system in the current project. Of critical importance is the fact that range and assemblage zone boundaries of microfossils do not coincide with those of

Proc. 2nd Working Group Meeting. Biostr. Datum-Planes of the Pacific
IGCP Project 114 Bandung, May 30 - June 1, 1977

MOLLUSCAN BIOHORIZONS IN THE INDO-WEST PACIFIC NEOGENE

By
Tsugio Shuto *)

Marine Neogene formations are extensively developed in East, Southeast and South Asia and their rich molluscan faunas have been documented in some detail. Basing upon those molluscan data, local biostratigraphical standards have been settled in Indonesia, Burma, Pakistan and Japan (bibliography: see Shuto, 1975 and 1977). In keeping pace with advances in local biostratigraphy, efforts have been made for interregional correlation by molluscs, but the results are not necessarily fruitful.

Difficulties in the interregional correlation of the Neogene formations may be attributed to certain facts about the distribution of molluscs in space and time, as I discussed elsewhere (Shuto, 1978a). Firstly, the relative number of common taxa among Neogene molluscan faunas of distant regions is remarkably lower than those among the Paleozoic and Mesozoic faunas, reflecting a critical difference in conditions of paleobiogeographical distribution of marine faunas of the older and younger ages in question. To be exact, common features among Neogene faunas at generic and subgeneric level are not so low, but that at the specific level they are extremely low compared with interregional similarity among faunas of the respective regions the older ages (Table 1). As a consequence, the accuracy of interregional correlation by the same method based on species is inevitably lower in the Neogene than in the Paleozoic and the Mesozoic, when the same method is adopted. Secondly, Neogene molluscan species are not only limited in geographical distribution, but also in the stratigraphical one, reflecting facies-dependent nature of the benthic molluscs. Furthermore fully continuous Neogene successions with abundant marine molluscs are not developed in every region, but the mollusc-bearing Neogene formations are limited in their age in respective regions.

Under such circumstance mentioned above, recognition of any common Neogene biohorizons by means of molluscan taxa can not be executed without difficulties. When any taxon is chosen for the index of a biohorizon, this biohorizon must be practically applicable with reinforcement by concurrent occurrence of other index species. This situation provides a reason for adopting the Lyellian method of correlation. The method, though very convenient, carries counter-balancing faults as discussed by several authors. One of the most severe faults among them must be the fact that accuracy of age determination depends upon the number of species contained in a faunule examined (Bird, 1967). As indicated in table 2, a Lyellian figure of 47 percent of a faunule consisting of total 100 species means a confidence interval between 40 and 54 percent at significance level of 95 percent. That is to say, the faunule may be correlated with any part of the Sondian, Cheribonian or Tjiodengian. Accuracy of correlation of the Neogene, particularly of younger Neogene, by means of the Lyellian method is by no means satisfactory. Hence we are now faced with the keen necessity to explore a refined method of correlation.

As is well known, the first appearance of certain taxa, particularly of micro organisme, has been currently used to define the Neogene biohorizons and to correlate formations. Not a few genera and subgenera among flourishing molluscan taxa common in South and Southeast Asia are also expected to serve for defining biohorizons by their first appearance. However, highly accurate biohorizons can not be expected to be settled by this method at the present moment because of rather sporadic data owing, firstly, to the facies-dependent nature of stratigraphical occurrence of benthic molluscs

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Table 1. *Generic and specific similarity of the selected Japanese faunas to the European and North American contemporaneous faunas*

faunas SW Japan	numb. gen. subgen.	% common gen. subgen.		numb. spp.	% common spp.	
		Europe	N. America		Europe	N. America
Carbo. – Perm. fusulines	27	78	89	112	0	3
Carbo. brachiopods	19	89	42	21	33	0
Jura. ammonites	24	100	58	41	20	0
Jura. bivalves	29	93	45	48	17	2
Low. Mio. bivalves	26	89	87	29	3?	0?
Low. Mio. gastropods	15	73	67	19	5	0?

Carboniferous – Permian fusulines: Akiyoshi Limestone Group, Toriyama, 1958.
Carboniferous brachiopods: Akiyoshi Limestone Group, Yanagida, 1962 and 1965.
Jurassic ammonites: Toyora Group, Hirano, 1971, 1973a and 1973b.
Jurassic bivalves: Toyora Group, Hayami, 1959.
Lower Miocene bivalves and gastropods: Ashiya Group, Anan, 1977 and Shuto, unpublished data.

Table 2. *Revised Lyellian percentage of Oostingh's stages in Java*
Note the changing confidence intervals corresponding to the number of constituting species of the faunules.

Stage	Lyellian Percentage	Confidence interval		
		1000 spp. identified	250 spp. identified	100 spp. identified
Bantamian	60	58 – 62	56.5 – 62	53.5 – 66.5
Sondian	53	51 – 55	58.5 – 57	46 – 60
Cheribonian	47	45 – 49	42.5 – 51	40 – 54
Tjiodengian	42	40 – 44.5	38 – 47	35 – 49
Up. Preangerian	35	33 – 37	31 – 39	28.5 – 42.5
Lw. Preangerian	20	18 – 22	16 – 24	15 – 26.5
Rembangian	10	8.5 – 11.5	7.5 – 12.5	6 – 15

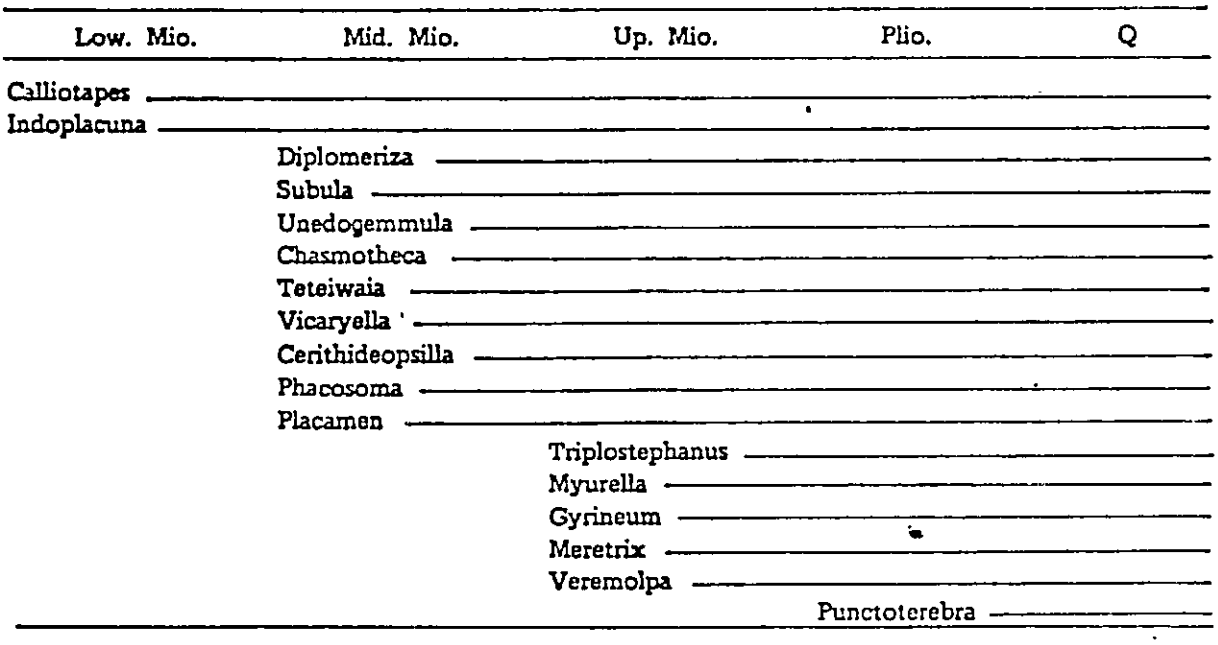
at significance level of 95 percent

and, secondly, to the scarcity of exhaustive biostratigraphical works done meter by meter in a continuous sequence. So far as the available data are concerned, even here it is not the rare case that the first occurrence and the first appearance of the same taxon is not distinguishable. Younger Neogene, upper Upper Miocene and later, of Southeast Asia fulfils the condition for subdivision of stages by means of molluscs in a suitable section, because mollusc-bearing formations are extensively and even continuously distributed there in contrast with the sporadic distribution in South Asia. And yet zonation is not easy without much more exact and minute surveying than has been done hitherto because of a very continuous and imperceptible change of molluscan faunas through the younger Neogene. From Middle Miocene through lower Upper Miocene, innumerable molluscs have been reported from a number of formations both in South and Southeast Asia and they seem to provide a basis for subdivision of the current stages. If any zones are defined in a local section by use of the first appearance and concurrent occurrence of selected taxa, those zones, however, can not necessarily be applicable for faunal sequences in distant areas. The present state of information only allows to adopt stages instead of zones for interregional correlation of the South and Southeast Asian Neogene.

We find out several genera in the Veneridae useful for interregional biostratigraphy. For example the subgenus *Calliotapes* of *Paphia* defines the lower limit of the Pyawbwean stage, while the subgenus *Phacosoma* of *Dosinia* and *Placamen* have their first appearance in the Rembangian (=Kyaukkokian) and *Meretrix* and *Veremolpa* (a close ally to *Timoclea*) do in the Preangerian. Among terebrid gastropods *Diplomeriza* and *Subula* appeared in the Rembangian and *Myurella* and *Triplostephanus* do in the Preangerian. Bursid gastropods *Chasmotheca* of *Gyrineum* and *Gyrineum* (s.s.) appeared respectively in the Rembangian and Preangerian. The first appearance of *Indoplacuna* defines the Pyawbwean and *Unedogemmula* of *Gemmula*, *Siphonofusus* of *Buccinulum*, *Cerithideopsilla* of *Cerithidea*, *Tateiwaia* and *Vicaryella* appeared in the Rembangian (Table 3). Although the above noted taxa with the first appearance in a single stage have not been necessarily confirmed quite contemporaneous to one another in regard to their first appearance, recognition of boundaries of any stage is expected practically by use in combination of concurrent taxa.

More detailed chronology and correlation should put the basis on the branching in any definite evolutionary lineage. Molluscan lineages which have been verified reliable for biostratigraphic

Table 3. *Index molluscan genera of the Neogene stages in South and Southeast Asia*



purpose are not many among widely distributed species of South and Southeast Asia. Preliminary examination suggests that lineages in the Arcidae, Veneridae, Turritellidae, Potamididae, Cerithiidae, Buccinidae, Turridae and Terebridae are expected serviceable for this purpose. Here I selected a few lineages. They are the lineages of *Anadara (Anadara) verbeeki* (Woodward) (Shuto, 1978d), *A. (A.) poethensis* (D'Archiac) (Shuto, 1978c), *Strombus (Strombus) canarium* Linnaeus (Abbott, 1960), *S. (Dolomena) marginatus* Linnaeus (Abbott, 1960), *Buccinulum (Siphonofusus) wanneri* Beets (Shuto, 1978b) and *B. (S.) martini* (Wanner & Hahn) Shuto, 1978b) (Table 4). Each of the above lineages illustrates a morphoseries and provides a reliable basis for correlation. Even the isolated occurrence of any species belonging to those lineages leads to a comparatively accurate age-determination.

Species of different geological ranges belonging to a single genus or subgenus, even though they have not been verified to be comprised in a single lineage, are also useful to distinguish stages by their first appearance. They are *Gemmula (Unedogemmula) ickei* (Martin) (Rembangian) and *G. (U.) gendinganensis* (Martin) (Tjiodengian to Sondian), *Terebra (Triplostephanus) jenkinsi* Martin (Preangerian), *T. (Triplostephanus) martini* Vredenburg (Rembangian to Preangerian) and *T. (Triplostephanus) samarangana* Martin (Rembangian to Sondian), *Terebra (Diplomeriza) smithi* Martin (Rembangian to Tjiodengian), *T. (D.) duplicata* Linnaeus (Tjiodengian to Recent), *Cerithidea (Cerithideopsilla) preangerensis* (Martin) Rembangian), *C. (Cerithideopsilla) jenkinsi* (Martin) (Preangerian to Sondian) and *C. (Cerithideopsilla) djadjariensis* (Martin) (Sondian to Recent) (Table 5).

Biohorizons suggested in this report are defined by the first (Table 6) appearance of species of the lineages of *Anadara*, *Siphonofusus* and *Strombus* mentioned above. Further they are reinforced for practical use by the almost contemporaneous first appearance of other species. Eight molluscan biohorizons (Biohorizon 1 to 8) of the Neogene together with the ninth one which defines the base of the Quaternary are proposed here (Table 6). Those biohorizons provide for the base of the Pyawbwean [1], Rembangian [2], Preangerian [3], Tjiodengian, Stothomasian, Cheribonian [2], Sondian [2] and Bantamian [2], respectively. Biohorizon 1, 2, 4 and 7 are tentatively correlated to the datumplane of *Globigerinoides*, *Orbulina*, *Globorotalia acostaensis* and *Sphaeroidinella*, respectively. The stages limited by those biohorizons are characteristic of their molluscan species listed in table 7. Most of the listed characteristic species of each stage are expected to be revealed similar in their first appearance through minute examination.

This framework of Neogene biostratigraphy must be oversimplified as pointed out before because of lack of necessarily minute data on the stratigraphic occurrence of the index species. Further accumulation of data must show more or less a diversified first appearance of the indices of each biohorizon.

Appendix

Sto-thomasian, a new stage, and Tjiodengian/Cheribonian hiatus.

According to the principle that the serial stages in a region are desirable to be continuous stage by stage and should not be separated by any hiatus of long duration, the hiatus between the Tjiodengian and Cheribonian in Java should be replaced or filled by a stage. It seems there are four possible ways to solve the problem. The boundary between the Tjiodengian and Cheribonian may be settled at the middle of the hiatus, base of the Cheribonian or top of the Tjiodengian considering a continuous nature of the molluscs of the two stages. And another way is to establish a new stage with a definite type section. The former three must be discarded because they have neither a paleontological nor stratigraphical basis.

The Sto Thomas molluscan faunules of the upper Dingle formation of Panay, the Philippines (Shuto, 1969 and 1971), show close affinity both to the Tjiodengian and Cheribonian faunas. That is to say, the Sto Thomas faunules have an intermidiate feature between the latter two, although the former is remarkably closer to the Tjiodengian.

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1) Lepper, 1933. 2) Oostingh, 1938. 3) Odengian (Shuto, 1972 and 1977) should be emended as Tjiodengian because the stage name was adopted from the geographical name Tjiodeng

REVISED PALEOGENE POLARITY TIME SCALE[1]

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ABSTRACT

A synthesis of radiometric data from continental volcaniclastics and volcanics that are tied to mammalian faunas reveals that an acceptance of recently revised age estimates on Eocene glauconites results in an offset in correlation between Eocene marine and continental stratigraphies by as much as an entire stage. A unified Eocene geochronology is maintained by retaining the earlier age estimates of the marine scale. The recent modification to the Paleogene part of the Cenozoic time-scale by Tarling and Mitchell (1976) is rejected.

INTRODUCTION

A time-scale provides a conceptual framework within which to interpret earth history. Only two ordinal scales are widely used today, that of *radiochronology* (based on isotopic decay rates) and that of *biochronology* (based on organic evolution). Both are aspects of geochronology. Geomagnetic polarity reversals are non-ordinal repetitions but because of their wide applicability have been closely correlated to the ordinal time-scales for the Neogene. As a result, the reversal sequence has taken on a secondary, shadowy ordinality of its own where the paleomagnetic record is so complete that its more distinctive variations can be securely identified. This is not true yet for the early Cenozoic (Paleogene, ca. 23–65 Ma [Geochronological notation: the abbreviation Ma (megaannum) refers to units of years × 10^6 measured from the present (1950 A.D. by international agreement) pastwards. It means the same as the cumbersome "millions of years before present" and is a fixed chronology analogous to the calendars tied to historical events. The abbreviation m.y. (million years) is used to express simple duration in units of years × 10^6 in any given past interval.]) where the relationships between radiochronology and paleomagnetic stratigraphy remain to be delineated. Heirtzler et al. (1968) utilized an assumed constant rate of sea floor spreading beyond 3.35 Ma in deriving their relativistic magnetic polarity time-scale. It soon became apparent that there were discrepancies (which increased with increasing age) between biostratigraphic and magnetic anomaly age determinations in DSDP cores. An attempt at rectifying these discrepancies was made by Sclater et al. (1974) who were able to demonstrate that the Cretaceous/Tertiary boundary at Site 216 (Indian Ocean), dated at 64.1 ± 1 Ma is located between anomalies 29 and 30, rather than anomaly 26 as indicated by Heirtzler et al. (1968). They adjusted Paleogene anomalies assuming a constant spreading rate in the South Atlantic of 2.04 cm/yr and compared the resulting chronology with the time-stratigraphic scale proposed by Berggren (1972). More recently Tarling and Mitchell (1976) have presented a revised Cenozoic polarity time scale. While disagreeing with their revisions to the Neogene parts of the scale as well, we shall direct our attention solely to the Paleogene portion inasmuch as the chronologic change is of a significantly larger order. We believe that in suggesting this revision Tarling and Mitchell have depended upon a rather uncritical acceptance of new radiometric data, neglected the implications for regional geology, geophysics, biostratigraphy and paleobiogeography, and that this revised time-scale is incorrect.

[1] Manuscript received January 25, 1977; revised May 9, 1977.

[JOURNAL OF GEOLOGY, 1978, Vol. 86, p. 67–81]

p. 68

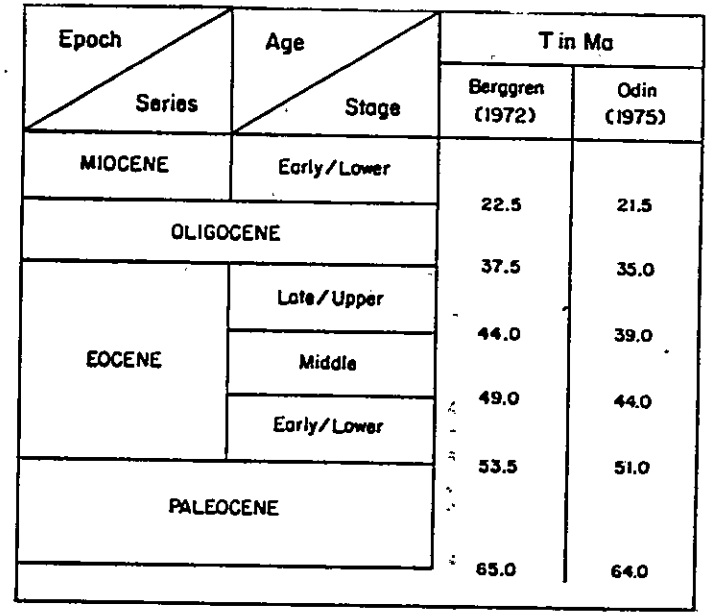

FIG. 1.—Paleogene geochronology. Note major intra-Eocene differences. The Middle/Upper Eocene boundary shown here is based on age estimates on the base of the Bartonian Stage. Recent studies (see text) indicate that the Bartonian is biostratigraphically equivalent to calcareous plankton zones generally associated with the concept of Middle Eocene. Thus we (W.A.B. and J.H.) have recently expanded the Middle Eocene to include both the Lutetian and Bartonian stages. The Middle/Upper Eocene boundary is now drawn at the Bartonian/Priabonian boundary with an estimated age of ca. 40 Ma.

DISCUSSION

Tarling and Mitchell (1976) have based their intra-Paleogene revisions primarily upon: (1) acceptance of Odin's (1975) new glauconite-based dating of the European type sections and (2) acceptance of a 48–49 Ma age on the Blosseville Group basalts of East Greenland which they presume to be associated with the initial opening of the NE Atlantic and to provide an age for magnetic anomaly 24. This comment is directed to a critique of both points.

We start with point 1 above. Odin (1975) has reanalyzed a large number of glauconites from the classic European sections and has derived consistently younger (ca. 3–5 m.y.) ages for the same stratigraphic levels as analyzed earlier (see Berggren 1972, for compilation). On the basis of this he has proposed an upward (younger) revision to the epoch and age boundaries of the Paleogene as shown in fig. 1.

Berggren's (1972) time scale was based on K—Ar ages from Europe and North America, including many of Odin's original results. K—Ar ages determined on Gulf Coast glauconites (Ghosh 1972), whose (bio)stratigraphic position have been recently evaluated by one of us (JH), as well as biotite ages (see below) from continental volcanics in North America

agree well with the original time scale. Odin's 1975 age determinations, however, do not fit in this framework and the consequences of these new ages for the Paleogene time scale are of such a magnitude that a careful analysis of their validity should precede their application in a drastic revision of the Paleogene time scale.

Glauconite is known to be "one of the least reliable chronometers for providing accurate age data" (Obradovich and Cobban 1975) and somewhat older boundary ages were estimated by Berggren than the "minimum" ages that the glauconite ages were believed to represent. It would appear, however, that Odin's geochronologic work up to 1970 is essentially invalid owing to instrumental insensitivity in detecting the presence of Argon 36. As a result Odin's pre-1970 ages are considered to be too old because no correction was made for the presence of atmospheric Argon 40. At the same time one may question the reliability of Odin's (1975) revised glauconite ages due to the possibility of appreciable Argon loss at the elevated bakeout temperatures (180°C for periods of up to 12 hours) to which he subjected his samples. Although Odin has demonstrated that his standard glauconite sample GL-0 can withstand this temperature without loss of radiogenic Argon, there is no assurance that all glauconite samples will behave in the same manner. Evernden et al. (1960, 1961) showed that appreciable Argon could be driven out of glauconite at temperatures of 150°C. As a consequence one may well question whether these new glauconite ages may not be too young. The tendency for glauconites to lose radiogenic Argon in the environment by diffusive processes was also pointed out by these same authors. In a tabulation of then existing data, Obradovich (1964) showed that as much as 50% of the radiometric data obtained on glauconite deviated from its inferred age by more than 10%. Glauconite generally yields ages which are anomalously young and younger than ages obtained on biotite–sanidine for the same level (compare results in Owens and Sohl 1973, vs. Obradovich and Cobban 1975).

The North American chronology is based overwhelmingly on ages determined on biotite–sanidine, the European on shallowly buried glauconites. The chronology shown in figure 2 is seen to match closely with that suggested by Berggren (1972). The Paleogene part of the Berggren time scale depended to a large part upon K—Ar determinations (mostly glauconite) in Europe (many of them by Odin) and North America. In view of the questionable reliability of the Paleogene glauconite dates it would seem that the most satisfactory means of choosing between the two geochronologies (Berggren 1972, vs. Odin 1975) lies in the assessment of K—Ar ages in continental stratigraphic sequences and (bio)stratigraphic correlations with their marine equivalents.

The geological implications of this chronology are serious. Interzonal correlation of Late Paleocene–Early Eocene marine calcareous, siliceous, dinoflagellate and larger foraminifera zones and their correlation to the classic European succession provides a biostratigraphic framework for correlating between shallow and deep water (oceanic) environments (Caro et al. 1974). Soper et al. (1976, fig. 4) have correlated the latest dinoflagellate flora (actually just one species in common) beneath the Blosseville Group basalts on East Greenland with marine rocks that have been called lower Sparnacian. They equate these with the Landenian = Upper Paleocene), however, and consider the flora wholly pre-Ypresian. However, the Sparnacian has been shown to be a brackish-lagoonal and continental facies essentially of the lower part of the marine Lower Eocene Ypresian Stage (Blondeau et al. 1965; Gruas-Cavagnetto 1968; Pomerol 1973). Its base (*marnes et Calcaire de Physa columnaris*) appears to be equivalent to the Conglomerat de Meudon near Paris and the *Glomalveolina levis* beds in the Plantaurel region, Northern Pyrenees (Spain). The latter are, in turn, approximately equivalent to the *Planorotalites*

p. 70

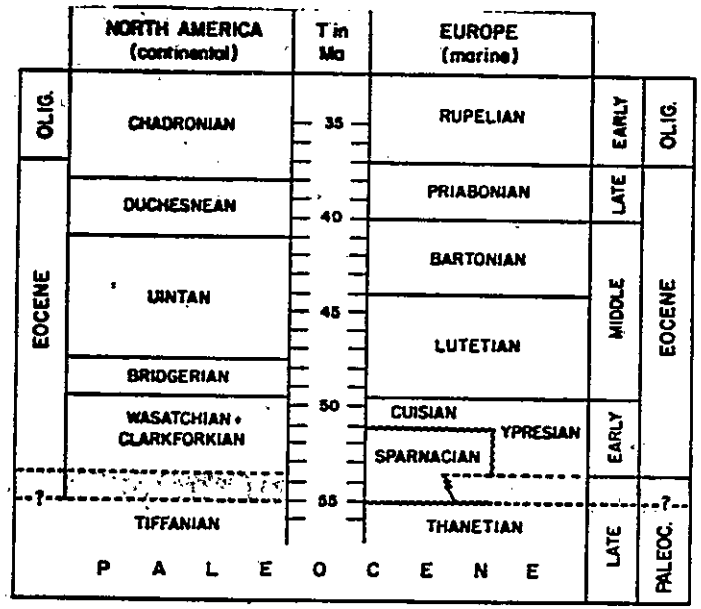

FIG. 2.—Recalibration of Eocene North American land mammal "ages" and European ages (after McKenna et al. 1973; with modifications, from Hardenbol and Berggren 1976, in press).

pseudomenardii/Morozovella velascoensis boundary (Plaziat 1975). The marine Sparnacian facies (its continued use as a time-stratigraphic term in marine stratigraphy should be abandoned) is essentially equivalent to the Ilerdian Stage of the Spanish Pyrenees (Caro et al. 1975; Plaziat 1975) and spans the *Morozovella velascoensis/Morozovella subbotinae* (P5/P6) boundary. The base of the Ypresian (= Paleocene/Eocene boundary) is drawn by many marine stratigraphers at the P5/P6 boundary (Berggren 1971, 1972), whereas others equating base Sparnacian = base Ypresian would place the Paleocene/Eocene boundary at the *Planorotalites pseudomenardii/Morozovella velascoensis* (P4/P5) boundary (Russell et al., in preparation). In figure 2 the uncertainty as to the biostratigraphic position of the Paleocene/Eocene boundary is reflected in the estimate of 53.5–55 Ma for its location.

The term Sparnacian has been commonly used by non-marine stratigraphers to denote the land mammal "age" of Early Eocene age typified by the strata and fossils of the *Sparnacian* exposed at Mt. Bernon, south edge of Epernay (Marne). The North American Wasatchian land mammal "age" has long been correlated with the "Sparnacian" of Europe and the North American Clarkforkian land mammal "age" probably correlates with the earliest Sparnacian Conglomérat de Meudon (see further discussion below).

The markedly high similarity at the generic level (about 50% in common) of European Sparnacian and North American Wasatchian vertebrate mammalian faunas has been stressed by numerous authors (Simpson 1947; Kurtén 1966; Russell 1968; Sloan 1969; Savage 1971; Szalay and McKenna 1971; McKenna 1971, 1975) and suggests a transatlantic (Holarctic) corridor along which early Cenozoic mammalian faunas were free to move (McK-

enna 1971, 1972*a*, 1972*b*, 1973, 1975). This transatlantic route was severed during Early Eocene time as shown by the subsequent development of endemic faunas on both sides of the Atlantic (op. cit., see below).

The geochronologic framework of North American land mammal "ages" was initially developed by the integrated K—Ar dating-mammalian vertebrate studies begun by Evernden et al. (1964) (see summary of Funnell 1964). American K—Ar ages calibrating the Wasatchian/Bridgerian time boundary (Wood et al. 1941; Evernden et al. 1964) are taken from volcanics and volcaniclastics in northwestern Wyoming. A significant increase in volcanic activity characterizes the latest Wasatchian of the Rocky Mountain area and that activity was sustained long past the Eocene. Fossil vertebrates, floras, and rocks datable by the K—Ar method occur abundantly in thick stratigraphic sections. Important published dates are as follows:

1. Lost Creek Tuff Mbr., Sepulcher Formation (Smedes and Prostka 1972, p. 10; sample dated by J. D. Obradovich on sanidine). 49.2 ± 1.5 Ma. This rock unit overlies the Willwood Formation, whose uppermost sediments are late Wasatchian in age (Van Houten 1945). The date could be either Bridgerian or latest Wasatchian.

2. Halfway Draw Tuff, Wind River Formation (Evernden et al. 1964, p. 188, KA 1012, biotite; Love 1970, p. 48). Dates late Wasatchian sediments. 49.2 Ma.

3. Unit 1 of Wagonbed Formation (Evernden et al. 1964, p. 189, KA 1021; Love 1970, pp. 52, 53). Bentonitic tuff, dates early Bridgerian sediments. 49.0 Ma.

4. Unit 20 of type section of Aycross Formation (Love et al. 1976, p. 17). Gray biotite tuff directly overlying bed containing Bridgerian vertebrates. 49.2 ± 0.5 Ma.

5. Biotite from White Pass Bentonite (Rohrer 1974, p. 16). Dates latest Wasatchian or earliest Bridgerian sediments. 49.3 Ma.

6. Tuff immediately below locality 20 of Duchesnean age, Hendry Ranch Member of "Tepee Trail Formation," Badwater area, Wyoming (Black 1974, p. 151). 41.2 ± 1.4 Ma. Dates base of Duchesnean.

A number of additional ages (Smedes and Prostka 1972, p. 10; Rohrer and Obradovich 1969) for various post-Wasatchian rocks are nevertheless older than 44 Ma, the upper limit of Tarling and Mitchell's (1976) Lower Eocene. Forty-four Ma is the age of the upper part of the Wiggins Formation in northwestern Wyoming, a rock unit which overlies an early Uintan fauna in the type section of the Tepee Trail Formation (McKenna 1972) containing the Uintan genera *Epihippus*, *Achaenodon*, *Dilophodon*, a *Tapocyon*-like miacid, primitive selenodont artiodactyls, an amynodont rhinoceros, and various species of additional genera that are more advanced than related species of the Bridger A–D faunas or are unknown in Bridgerian rocks. Moreover, published ages for the Wiggins Formation range from 43.1 Ma at the top (Love and Keefer 1975, p. 37) to 47.1 Ma, with the majority older than 46 Ma and several (46.7 ± 1.5; 47.1 ± 1.3) younger (by reason of superposition) than the early Uintan fauna in the type section of the Tepee Trail Formation (Smedes and Prostka 1972, p. 10; McKenna 1972; Love and Keefer 1975). This means that early Uintan (i.e., post-Bridger D and therefore post-Bridgerian) time had begun by about 47 or 48 Ma at the latest. A Bridgerian fauna (McKenna 1972) in sediments exposed at the summit of Togwotee Pass in eastern Teton County, Wyoming, contains *Tillomys*, *Sciuravus*, cf. *Trogosus*, *Hyrachyus eximius*, *Orohippus*, and *Palaeosyops*, and is underlain by volcanics identified by Smedes and Prostka (1972, p. 11) as Two Ocean Formation and dated at 47.9 ± 1.3 Ma (sanidine) and 48.5 ± 1.3 Ma (same sample, biotite). A dated sample from 400 feet below the top of these sediments yielded 47.8 ± 1.3 Ma (sanidine) and 47.9 ± 1.3 Ma (same sample, biotite) (Smedes and Prostka 1972, p. 10).

Recently an age of 48.5 ± 0.5 Ma has been obtained from pumice from which the glass has been removed, derived from a tuff in the Bridger Formation near Tabernacle Butte, Wyoming at a site overlying Bridgerian mammals (G. H. Curtis, personal communication, 1976).

Bridgerian time in North America would thus appear to be compressed into the interval between approximately 47 or 48 and 49 or 50 Ma. Post-Bridgerian Eocene is thus a longer interval than has previously been accepted (McKenna et al. 1973).

Early Uintan mammalian faunas occur in the Poway Group (Savage and Downs 1954; Durham et al. 1954) and underlying Friars Formation of the San Diego coastal area of southern California. The marine Poway Group (Narizian provincial stage) has been equated with the late Middle Eocene (Steineck and Gibson 1971; Gibson and Steineck 1972). The Friars Formation is a time-transgressive unit which is at least partially correlative with the mid-upper bathyal Ardath Shale (Kennedy and Moore 1974) which was formerly, or alternatively, known as the Rose Canyon Shale (Gibson 1971; Gibson and Steineck 1972). Calcareous nannoplankton floras from the Rose Canyon Shale (Ulatisian provincial stage) are assignable to the *Rhabdosphaera inflata* Subzone of the *Discoaster sublodoensis* (NP 14) Zone (Bukry and Kennedy 1969; Bukry 1973), whereas the planktonic foraminifera (Steineck and Gibson 1971; Gibson and Steineck 1972; Steineck et al. 1972) are correlative with (but not assignable to) the *Hantkenina aragonensis* (P10) and/or *Globigerapsis kugleri* (P11) (*vel Globigerinatheka subconglobata*) Zone. The type level of the *Hantkenina aragonensis* Zone in Trinidad contains a calcareous nannoplankton floral assemblage apparently assignable to either the *D. sublodoensis* (NP14) (Bukry and Kennedy 1969) or the *Nannotetrina quadrata* (NP15) Zone (Hay et al. 1967; Gartner 1971) as do the lower Lutetian strata of the Paris Basin at Gibret, France (Bouché 1962). The Lower/Middle Eocene boundary is drawn by virtually all modern marine micropaleontologists at the base of Zone P10 (initial evolutionary appearance of the genus *Hantkenina*) (see further discussion in Berggren 1971; consult also various Initial Reports of the Deep Sea Drilling Project). Thus regional marine and continental biostratigraphic correlations and radiometric ages provide additional supportive evidence of the 49–50 Ma estimate adopted here for the Early/Middle Eocene boundary and suggest that the base of the Bridgerian and Lutetian are essentially time-stratigraphically equivalent. Odin's (1975) estimate of 44 Ma for the Early/Middle Eocene boundary is seen to be *younger* than dated levels well within the Middle Eocene by biostratigraphic correlation.

The Bridgerian land mammal fauna of North America and a land mammal fauna of Europe correlated there with the Lutetian show strong endemism and have been interpreted to record faunal differentiation following the break-up of a previous land connection of Europe with Greenland. Earlier, the Ypresian (Europe) and Wasatchian (North America) mammal faunas, in contrast, indicate free interchange of species at some point early in the interval and perhaps during all of it and are no more different from each other than the faunas of opposite sides of a single continent at present (Savage 1971; McKenna 1975). For the early Ypresian (Sparnacian as used by mammalian biostratigraphers) 34 of 60 mammalian genera known from Europe also occur in North America in Wasatchian and even Clarkforkian deposits (ibid., p. 349; Gingerich and Rose, in preparation). For this reason correlation of the Wasatchian and Clarkforkian of North America with the European Ypresian is especially secure. The length of time for endemism to become evident through evolution of the animals involved after break-up in the North Atlantic is not known, but is assumed here to have taken about the same time on both resulting continents. The end of Ypresian

time is thus accepted here as indistinguishable from the end of Wasatchian time at approximately 49–50 Ma, not 44 Ma as suggested by Odin (1975) and accepted by Tarling and Mitchell (1976). This could have been and probably was somewhat after the inundation of the last available dry land linking Greenland with England and France.

The position of the Euramerican corridor has been discussed extensively (McKenna 1975, and references). Two possibilities of connection of Greenland with Europe exist, one via Svalbard to Norway and Sweden, the other via proto-Iceland to England and France. The first would have been a cul de sac because of marine conditions connecting the North Sea eastward across Denmark, Germany, and Poland (Ziegler 1975) as far as the Turgai marine connection between Tethys and the Arctic Ocean, but the second is especially attractive at present because of increasing evidence of the former subaerial nature of the aseismic ridges leading away from Iceland and because of ever more detailed studies of the enormous outpourings of both submarine and subaerial lavas in East Greenland and the Faeroes. The connection of the North Sea via the Baltic area with the Turgai area is strong evidence that the only possible land route to England and France must have been by way of proto-Iceland and that therefore the thick Brito-Arctic lavas of the Blosseville Group of the Kap Dalton area of East Greenland (Soper et al. 1976; Brown and Whitley 1976), which formed the west end of the subaerial route, must have been emplaced during or before Ypresian time; this event must therefore have occurred by at least 49 or 50 Ma, presumably somewhat earlier. Although coastlines appear to have been widely divergent in the Middle Eocene (Pitman and Talwani 1972), more recent reconstructions based on aeromagnetic surveys (Phillips et al., in preparation) show that Greenland–Svalbard continental margins (500 m isobath) were still in contact until at least Anomaly 13 (ca. 36 Ma) and probably until Anomaly 12 (ca. 34 Ma) time. The Blosseville is overlain by marine sediments of the Kap Dalton Formation dated on paleontological grounds as Lutetian near the base.

Beckinsale et al. (1970), using decay constants that give slightly older ages than the constants recommended by Smith (1964), dated volcanics of the Blosseville Group using the K—Ar method on whole rock basalt samples from well up in the Blosseville, concluded that these rocks were 55–60 Ma in age. However, if we employ the constants suggested by Smith (1964) to bring all ages cited into conformity and plot the results of Beckinsale et al. (1970) on a $^{40}Ar(total)/^{36}Ar$ vs. $^{40}K/^{36}Ar$ isochron diagram it is clear that some of the data form a linear array (samples 7127, 7139, 7147, 7147R, 7150, 7151, and 7168) with a resulting age of 50.8 ± 3.6 Ma. The uncertainty is more than one might like but an older age is just as likely as a younger age. The isochron plot also suggests that these same samples may contain excess radiogenic Argon as the intercept is 320 ± 46 (fig. 3). The isochron plot also reveals that some of the Blosseville basalt samples have obviously lost radiogenic Argon. A late stage in the igneous activity in the area has been dated as 49.2 ± 1.2 Ma (all ages have been recalculated) on biotite from the Kangerdlugssuag intrusion (sample 4583) and as 49.2 ± 2 Ma on the basis of a Rb—Sr mineral isochron by Hamilton (1966). Other ages on the Kangerdlugssuag intrusion include 51.0 Ma (amphibole) on sample 7026, 48.1 Ma (amphibole) on sample 7058, and 50.6 Ma (amphibole) on sample 736. As the preceding samples are from rocks intruding the Blosseville Group this would indicate that the Blosseville is older than 49.6 ± 1.2 Ma.

Tarling and Mitchell (1976) claim that the whole of the Blosseville was erupted during 2–3 m.y. centering around 48–49 Ma but have not yet documented their results. They would, however, make the upper part of the Blosseville quite a bit

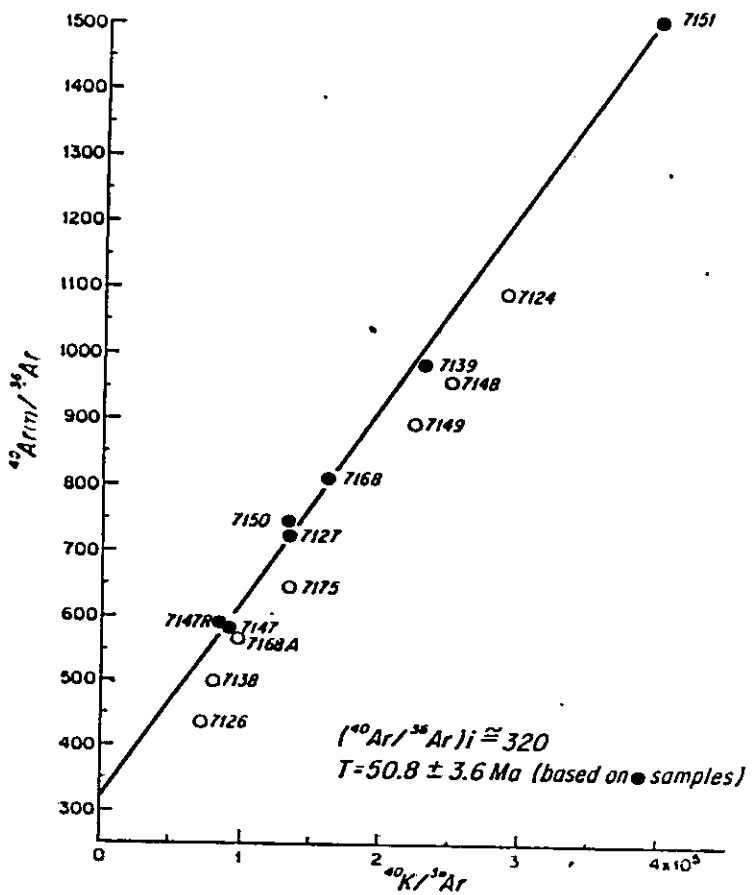

FIG. 3.—$^{40}Ar/^{36}Ar$—$^{40}K/^{36}Ar$ isochron plot of the data for the Blosseville basalts, taken from Beckinsale et al. (1970).

younger than the preceding arguments would indicate.

Soper et al. (1976, pp. 92, 98) offer additional but tentative evidence for the age of the Blosseville basalts. They regard the Blosseville basalts as beginning in what they consider to be the early Sparnacian, this on the basis of a dinoflagellate species correlated with Sparnacian and later fossil assemblages in Europe (Costa and Downie 1976). A correlated assemblage from the Butte de Reneuil in France has been dated as 53.6 ± 2.5 Ma by the Rb—Sr method on glauconite (Bonhomme et al. 1968). Bonhomme et al. assumed a $^{87}Sr/^{86}Sr$ initial value of 0.7154. A more realistic value for the Strontium isotopic composition of sea water for the early Tertiary of 0.708 (Peterman et al. 1970) would result in an even older age of 59.2 Ma, however.

In summary, K—Ar control based mainly on biotite and sanidine ages from volcanic rocks interlayered with fossil mammal bearing sediments in North America may be interpreted to show that the Ypresian–Wasatchian fauna of Eur-

america had a time range ending at about 49.5 Ma rather than 44 Ma as claimed by Odin (1975) and accepted by Tarling and Mitchell (1976) on the basis of recent work on glauconites by Odin (1975). The Wasatchian (plus or including Clarkforkian) and Ypresian are equivalent time intervals on biostratigraphic criteria involving a large number of rapidly evolving mammalian taxa. The K—Ar calibration from volcanics in North America therefore indirectly date the end of the Ypresian as well. Additional support for this estimate is seen in the recalculated ages, using the values cited above, of the Asschian (= Lower Bartonian) sample in Bonhomme et al. (1968) of 44.0 Ma ($(^{87}Sr/^{86}Sr)_i = 0.708$) and 43.7 Ma ($(^{87}Sr/^{86}Sr)_i = 0.709$). In contrast to the other glauconite samples dated by Bonhomme et al., this sample is fairly radiogenic (≈ 18%) and thus would be less sensitive to the initial value of ($^{87}Sr/^{86}Sr$) selected. The Bartonian has recently been shown (Cavelier 1976; Cavelier and Pomerol 1976; Hardenbol and Berggren 1976, in press) to correspond biostratigraphically to the *Discoaster tani nodifer* (NP16) and *D. saipanensis* (NP17) calcareous nannoplankton zones, which are essentially equivalent to planktonic foraminiferal zones P13–P14. Our French colleagues have left open the question of assigning the Bartonian to the Middle or Upper Eocene. If one were to retain the Bartonian in the Upper Eocene it would extend its biostratigraphic content to include zones P13–P14 and NP16 and NP17. We have chosen, on the other hand, to place the Middle/Upper Eocene boundary between the Bartonian and the Priabonian, thus retaining zones P13 and P14 and NP16 and NP17 in the Middle Eocene and expanding the Middle Eocene to include both the Lutetian and Bartonian stages. The age of ca. 44 Ma on lower Bartonian, corresponding to zones P13 ≈ NP16 in the upper Middle Eocene makes the use of a similar age inappropriate for the Ypresian/Lutetian boundary (Odin 1975), which corresponds to the base of the *Hantkenenia aragonensis* (P10) Zone at the boundary between Lower and Middle Eocene.

In conclusion, the Early Eocene on the Berggren (1972) scale would be 49–53.5 Ma; on the Odin (1975) scale it is 44–51 Ma. Since the correlations within the marine and continental Lower Eocene stratigraphies are well understood, a change in chronology of one stratigraphy necessitates a change in the other, which would result in an offset to the extent of an entire stage and result in serious miscorrelation. Yet the biotite–sanidine ages of the North American mammal ages support the Berggren (1972) time-scale much better than the new glauconite ages of Odin (1975).

Magnetic Anomaly Chronology (Point 2)

Tarling and Mitchell (1976) have recalibrated Paleogene sea-floor magnetic anomalies based on their correlation with the revised chronology of Odin (1975). Thus anomalies 13, 21, and 24 are assigned ages of 34.5, 44, 49 Ma, respectively.

One of the main calibration points in the Paleogene time-scale proposed by Tarling and Mitchell (1976) in revising the Cenozoic time scale is their estimate of 48 Ma for the age of magnetic anomaly 24, which they assume is essentially correlative with, or only slightly younger than, the Blosseville basalts of East Greenland. At the same time they infer that the Blosseville lavas coincide with the initial rifting of the Laurasian land mass between the Greenland and Norwegian margins. This dual role for the Blosseville lavas is unlikely (i.e., that it coincides with initial rifting and with anomaly 24). Although Anomaly 24 is the oldest identifiable anomaly in the Greenland–Norwegian Sea (and for that matter in the Arctic Eurasian Basin and North Atlantic between Rockall and Greenland) it is not found immediately adjacent to the continental margins in any of these regions. In fact it does not even closely parallel the margin trends, particularly in the Greenland–Norwegian Sea. The anomaly band typically trends at a 20–30° angle relative to the margin trend and is about 50 km from the shelf break (Talwani and Eldholm, in press; Phillips et al., in press). Also a narrow but distinctive anomaly band has recently been charted along much of the Greenland Lomonosov Ridge margin (Phillips et al. 1976). This may correlate with Anomaly 25 or be even older. Clearly the initial separation of Greenland from Europe must predate Anomaly 24 and therefore cannot be equated with the Blosseville lavas if these denote the opening. In the scheme of Tarling and Mitchell (1976) Anomaly 24 must be even younger than the 48 Ma age they assign it (say 44–45 Ma) if the spreading rate from initial opening to Anomaly 24 time is on the order of 1 cm/yr. However, this is quite impossible. The interval of 40–45 Ma encompasses a time-tratigraphic sequence above (younger than) the Early/Middle Eocene boundary (Ypresian/Lutetian ≅ Wasatchian/Bridgerian) in both the time scale of Berggren (1972) and Odin (1975). Magnetic Anomaly 24 has been shown to be associated with the *Morozovella subbotinae* (P6) and *Marthasterites contortus* (NP10) zones at DSDP Site 39 (Sclater et al. 1974) which essentially straddle the Paleocene/Eocene boundary and can be assigned an age of 53–54 Ma on the Berggren (1972) time-scale. Earlier drilling at DSDP Site 117 on the western margin of Rockall Bank, adjacent (eastwards) to Anomaly 24 bottomed in Upper Paleocene sediments (above basement) dated at 54–56 Ma on the Berggren (1972) time scale (Laughton, Berggren et al. 1972, chapter 8) which supports the suggestion that anomaly 24 is younger than latest Paleocene. An estimate of 53 Ma for Anomaly 24 is made here.

Thus it appears that there is room for interpreting the age of extrusion of the Blosseville Group basalts in East Greenland and questioning their connection with the initial opening of the Norwegian Greenland Sea. A more realistic estimate would be 51–53 Ma (based on the Berggren 1972, time scale) which is in line with one of two alternatives suggested by Soper et al. (1976, p. 100). In any event there seems to be no reason to believe that the basalts are of the same age as Magnetic Anomaly 24 formed 50 km off the continental margin. If anything, one would suspect that major land volcanic belts (such as the East Greenland sequence) associated with the breaking up of continental masses precede the initial rifting and the initiation of sea floor spreading type anomaly bands.

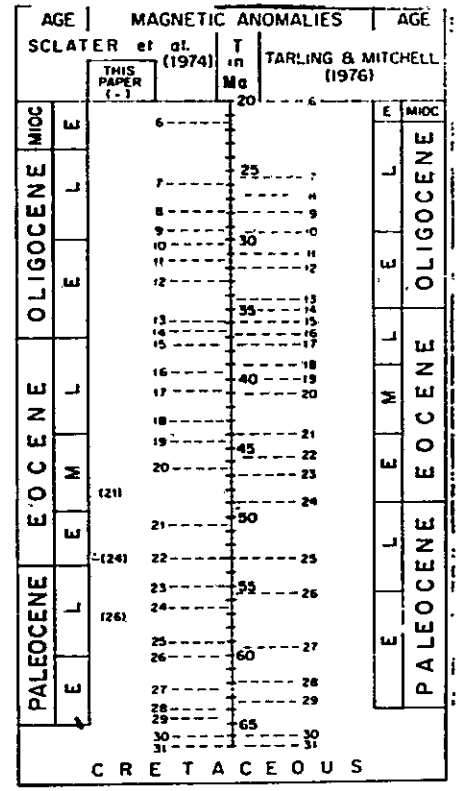

FIG. 4.— Comparison between Paleogene magnetic polarity time-scale of Sclater et al. (1974) and Tarling and Mitchell (1976). Suggested ages of several magnetic anomalies (this paper) are shown to the left. Age of Middle Late Eocene boundary changed to ca. 40 Ma in this paper

TABLE 1

COMPARISON OF CALIBRATION OF MAGNETIC ANOMALIES 10, 21, AND 30 AND RESULTING DIFFERENCES IN ESTIMATES OF RATES OF SEA-FLOOR SPREADING

K IN km		ANOMALY	AGE (Ma)		SPREADING RATE cm/yr	
Incremental	Total	Interval	Tarling and Mitchell (1976)	Berggren et al. (this paper)	Tarling and Mitchell (1976)	Berggren et al. (this paper)
600	600	0–10	0–30	0–30	2.0	2.0
329	992	10–21	30–44	30–48	2.8	2.2
286	1,279	21–30	44–66	48–66	1.3	1.6

Anomaly 26 (younger part) corresponds to the *Discoaster mohleri* Zone which, in turn, correspond to the middle of the *Planorotalites pseudomenardii* (P4) Zone. An age of 57–58 Ma is estimated for Anomaly 26. Magnetic anomaly 21 is within, or only slightly younger, than the *Hantkenina aragonensis* (P10) Zone and is assigned an age of 48 Ma here. A comparison of the Paleogene part of the Cenozoic polarity time scale of Sclater et al. (1974) and Tarling and Mitchell (1976) is shown in figure 4. Suggested ages for several anomalies in terms of the Berggren (1972) time scale are also shown. It should be borne in mind that the chronology of Sclater et al. (1974), Tarling and Mitchell (1976) and that presented here start with the same two basic calibration points:

1. Magnetic anomalies 29 and 30 straddle the Cretaceous/Tertiary boundary at ca. 64–65 Ma.

2. Magnetic anomaly 6 lies near the Oligocene/Miocene boundary near 20–22 Ma.

The chronology of Sclater et al. (1974) is based on a linear extrapolation of assumed constant rate of sea-floor spreading between these two points. That of Tarling and Mitchell (1976) is based on intra-Paleogene extrapolations based on the new calibration points obtained from Odin's contested time scale. Our own estimate of the chronology of anomalies 21, 24, and 26 is shown to the left in figure 4.

The sea-floor magnetic chronology of Heirtzler et al. (1968) is based upon the assumption of a constant sea-floor spreading rate (1.90 cm/yr) from the present to Anomaly 32 (Late Cretaceous) time. Comparison of the calibration of anomalies 10, 21, and 30 by Tarling and Mitchell (1976) and ourselves is shown in table 1. The calibration of Tarling and Mitchell (1976) implies significant changes in the rates of sea floor spreading during the early Cenozoic, changes which would have had a significant effect on global tectonic plate motions.

CONCLUSIONS

Synthesis of results from various branches of geology depends in large part on the acceptance of a common time-scale. The importance of a precise correlation between biostratigraphy and geochronology was stressed in a discussion (Berggren et al. 1975) to reply (Larson and Pitman 1975) on the correlation of Mesozoic magnetic anomalies and its implications. Nowhere is this more clearly evident than in attempts to relate marine magnetic anomalies to events in evolutionary history of organisms and to radiometrically dated events in the geologic history of continents. Marine magnetic anomaly 24, for example, has been assigned values as different as 60

Ma in the extrapolation of Heirtzler et al. (1968) and 49 Ma by Tarling and Mitchell (1976). We attempt here to sharpen the calibration of ages of Eocene marine magnetic anomalies in relation to biostratigraphy, using radiometric data from continental volcaniclastics and volcanics that are tied to mammalian faunas. At the beginning of the Eocene a Euramerican continental fauna existed, permitting high resolution biostratigraphic correlation between K—Ar controlled sites in Wyoming and those of the Paris–London basins. Such control in the Early Eocene is superior to the extrapolation from 3.35 Ma of Heirtzler et al. and also to the glauconite-based K—Ar dating of Odin, which are relied upon by Tarling and Mitchell. By the Middle Eocene, the Euramerican fauna had broken up into endemic faunas, but the Early Eocene Wasatchian and Clarkforkian faunas in North America are correlated closely with Ypresian faunas in Europe, thus suggesting an extension of North American K—Ar calibration based on biotite, sanidine, and hornblende via a biostratigraphic extrapolation to European sites during an interval from about 53.5 to about 49.5 Ma. We suggest further that the thick Blosseville Group basalts of East Greenland are about 51–53 Ma in age and that the Euramerican fauna was continuous at that time from North America and Greenland to Europe via proto-Iceland, the Faeroes, and the British Isles.

In view of the known difficulties in determining reliability criteria in dating glauconite by the K—Ar method, the significantly younger ages derived by Odin (1975) for the Paleogene are viewed here with suspicion. We are of the opinion that they scarcely warrent immediate, uncritical acceptance nor the modifications to the Paleogene part of the Cenozoic time-scale that Tarling and Mitchell (1976) have made, based on them.

ACKNOWLEDGMENTS—Reviewed by J. G. Sclater; J. D. Phillips; D. E. Russell; D. E. Savage; P. Gingerich; and R. Z. Poore. Contribution by W. A. Berggren supported by Grant OCE76-21274 from Submarine Geology and Geophysics Branch, Oceanography Section, Division of Earth Sciences of the National Science Foundation. We thank, in particular, J. D. Phillips for helpful discussions on the Paleogene chronology of the evolution of the Norwegian-Greenland Sea and Arctic region. Contribution No. 3799 from the Woods Hole Oceanographic Institution.

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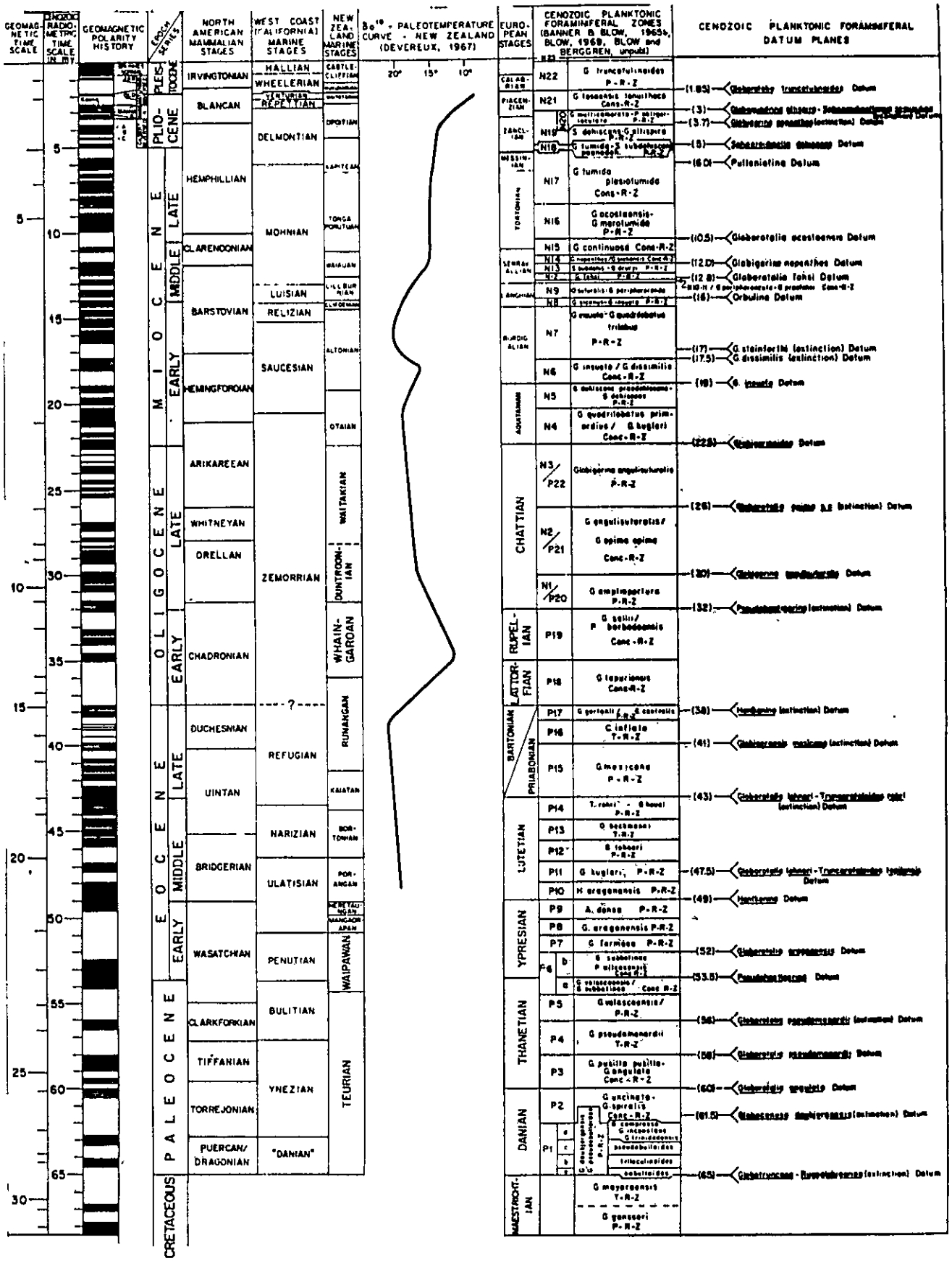

Fig. 1. Cenozoic radiometric time-scale, chronostratigraphy, planktonic foraminiferal zonation and datum levels.

from: Berggren and Van Couvering, 1974

The Binomial Distribution Applied to the Percentage Method of Stratigraphic Correlation

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Abstract: Lyell's percentage method of stratigraphic correlation is interesting and useful. However, the method has been used at times to support correlation on a more detailed level than data warrant. By treating the number of extant species as successes and the number of extinct species as failures, samples may be treated as following the binomial distribution. The percentage of Recent species in the sample thus becomes the sample mean. The mean and variance of the sample may then be used to calculate a confidence interval and thereby to determine the limits of correlation at the desired confidence level. In this way samples can be referred to the proper epoch and the reliability of the reference can be stated. Treating samples as representatives of binomial populations also permits direct comparisons between two or more samples; the technique holds whether the sample mean is computed on the basis of percentage of extant species or on the basis of percentage in common with some standard interval from the geologic column.

Simpson (1953) and Umbgrove (1946) have shown the importance of epoch by epoch comparisons of percentages of extant species in widely different systematic groups. In addition, it should prove fruitful to compare evolution rates of similar lineages from different geographic localities or faunal realms. A method of testing for significant differences of mean numbers of extant species for these two cases is made possible by applying the binomial distribution to percentage data.

CONTENTS

INTRODUCTION

Sir Charles Lyell, adviser and friend to Darwin, devised a method of correlation of Cenozoic strata at a time when evolution was part of the thinking of but few biologists, notably Lamarck. Yet Lyell's observation that Cenozoic faunas become progressively more Recent in aspect in younger strata is itself a consequence of and evidence for evolution. Lyell (1833) made his observation quantitative by characterizing each epoch of the Cenozoic by the number of extant molluscan species in that epoch.

This scheme of correlation has the problems that beset biologic correlation methods in the other eras; and, as in the other eras, in the Cenozoic the difficulty increases with increasing distance between localities compared and with decreasing stratigraphic intervals. Miscorrelation by any method may result for a variety of reasons including: differences in biofacies, recurrent species, time lags in migration, unequal evolution rates within different systematic groups and within the same groups at different conditions and geographic localities, and unique environments which foster a disproportionate number of conservative forms—either too many or too few. The relative anachronous influence of each of the above is decreased with increased sample size (number of species occurring). Accurate correlation by any method depends on recognition of error-producing factors of the type above.

Geological Society of America Bulletin, v. 78, p. 1507–1514, 1 fig., December 1967

Additional to these problems are human errors such as misidentification of species and species ranges, biased sampling, and drawing more detailed conclusions than a particular sample merits. It is this last item, that of statistical inference, that is to be considered here.

ACKNOWLEDGMENTS

I wish to sincerely thank Dr. William C. Krumbein, Professor of Geology, Northwestern University, who critically reviewed the manuscript and made many valuable suggestions.

PERCENTAGE DISTRIBUTION WITHIN THE EPOCHS

Different percentage values for the Cenozoic epochs have been derived by various workers. Those of Martin (1921), based on faunas of Java, have been used by Davies (1934), Keen (1940), Umbgrove (1946), and others. The percentages reported in Dunbar (1960), which are revised Lyellian determinations, are those primarily used in this report. Additional study of faunas from standard sections is needed before percentage data can be used with clear confidence, but the data presented in Dunbar are based on large numbers of species and are adequate for the purposes of this report. The percentages from Dunbar are: Paleocene, 0; Eocene, 1–5; Oligocene, 10–15; Miocene, 20–40; Pliocene, 50–90; and Pleistocene, 90–100. The gaps between the epochs have not been filled. It is reasonable at this time to assign to each of the epochs one half of the percentage gap separating the epochs. The revised percentages become: Paleocene, 0–0.5; Eocene, 0.5–7.5; Oligocene, 7.5–17.5; Miocene, 17.5–45; Pliocene, 45–90; and Pleistocene, 90–100. By plotting these percentages against the length in years of each of the epochs (Fig. 1) it is seen that the relative number of species ranging to the Recent increases in a nonlinear way through time. This is not surprising, since the time to the Recent is less for younger species than for older. A species that starts in early Pliocene, for example, would have to exist (that is, not die out or be completely replaced by a new species resulting from the gradual shifting of characteristics of the original species) 13 million years to be part of Recent faunas, whereas a lower Miocene form would have to exist 25 million years. The result is an ever-increasing steepness to the curve.

As a very gross approximation of the within-epoch curves based on Dunbar's data, the mean of the slope of the next younger epoch and the one considered and the mean of the next older and that of the given epoch can be calculated. These curves are represented by the dashed lines in Figure 1. These curves indicate that an epoch cannot be divided simply by giving lower, middle, and upper portions equal shares. The mean percentage of an epoch does not occur at the chronological middle of the epoch.

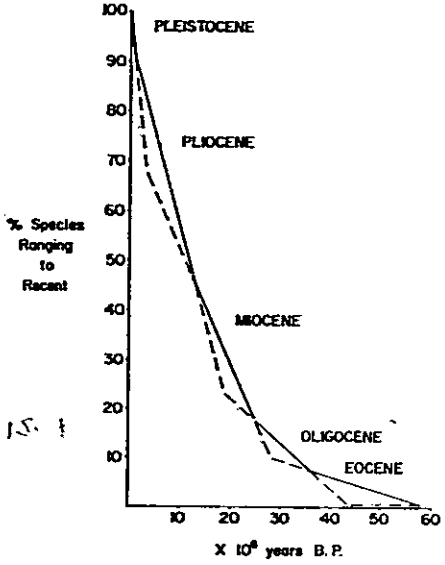

Figure 1. Percentage distribution of species within the epochs. Solid line connects end points of epoch percents. Dashed line represents intersection points formed by projecting epochal segments of solid line.

Equal percentage increments do not represent equal intervals of time; increments in younger horizons represent less time than increments of equal value in older sections. Slopes must be known before within-epoch assignment by the percentage method can be made with much precision.

LYELLIAN MODEL OF PERCENTAGE DISTRIBUTION

The Lyellian premise can be conceptualized by a statistical model—a white and black ball population from which binomial samples can be taken. Let the species that do not persist to the

Recent be represented by black balls and those that do by white ones; white balls can be recorded as successes and black ones as failures. Using the data from Dunbar, early Paleocene time would be represented by black balls only. Toward the end of the Paleocene epoch white balls would appear and by the end of Eocene time 5 percent of the population would consist of white balls. In successively younger epochs black balls are deleted from the population (extinction) as white balls are added. (White balls once present are not deleted; black balls are constantly deleted.) The process is completed in the Recent when all the balls are white.

In order to make the model fully usable, additional data are needed but unfortunately cannot be mustered. The missing bits of information are the rates at which black balls should be replaced by white balls. Again, Figure 1 shows that the rate of replacement is not linear. The question arises whether leaps in percentages should be incorporated into the model. Perhaps at the opening of epochs a large number of white balls should be added and perhaps at the close of epochs large numbers of black balls should be deleted. A related question is: "Are the breaks in percentages between epochs the results of such sudden changes in faunal composition?" or, perhaps more plausibly: "Are the breaks the result of incomplete knowledge of the geologic record?" In connection with these problems we need confirmation of the cutoff percentages for the respective epochs.

The population mean at any time is the ratio of white balls to the total number of balls in the population (number of successes divided by total number). The balls are randomly distributed and the progress of the changing population can be stopped to take as many samples as desired. Each sample of the same size has an equal chance of representing the population accurately in a statistical sense. One could correctly guess that the sample mean becomes a better estimate of the population mean with increasing sample size. The reliability of the estimate also depends on the sample mean, or better, on the population mean itself. The closer the population mean to 0.5 or 50 percent, the better the estimate of the mean for a sample of a given size; this is true because the variance is minimized when the mean is 0.5. These relations will be made clearer in a later section.

It is now necessary to see if the Lyellian scheme, dealing with natural populations, can meet the requirements of the model. First, are natural populations distributed in a random manner? The study of ecology tells us that they are not;[1] yet this is not as serious as it first appears. It is only (this word serves in a most relative way) necessary that each portion of the population have a combined evolution-extinction rate that is equal to other portions, that is, that neither white balls nor black balls cluster in any pattern whatsoever. Only scanty data are now available to test this assumption, and this on a broad scale. Brief examples follow.

The work of Baden-Powell (1955, p. 275) comparing Pliocene and Pleistocene deposits of Britain and the Mediterranean suggests that at least extinctions in these two areas progress in a closely similar way. His investigation did not include percentage data as such, however. Martin's study (1921) of molluscan assemblages of Java corresponds generally to Lyellian percentages but differs in that percentages are lower than those of Lyell. Martin's data are based on small numbers of species, however. Dickerson (1921), studying the Vigo group of the Philippines, derived a percentage much higher than the Lyellian percentage for supposedly equivalent beds. Dickerson referred the Vigo to the upper Miocene but it has since been shown that these beds range from Oligocene to Miocene to lower Pleistocene (Kleinpell, 1957, p. 4). Kleinpell further states that the Philippine Neogene shows percentages lower than those of comparable beds in Indonesia (in direct contrast to Dickerson's work) and suggests that the discrepancy may be due to slow extinction rates in the tropics. The comparisons are between Bandung, Indonesia (lat. 7°00′ S.), and the Bondoc Peninsula at Luzon (lat. 13°24′ N.).

These examples only show that additional work must be done to show to what extent Lyellian percentages hold true for different faunal realms. The discovery of consistent differences would be as exciting and rewarding as the discovery of constant percentages. It would seem that investigation of molluscan assemblages from temperate and arctic zones should be an early step in testing the utility of worldwide Lyellian correlations.

A second requirement of the model is that samples must represent the population. For the model problem, it is only necessary to stop the change of the population and take samples. In natural populations, however, samples must be taken as the clock runs, as it were. A population in the present scheme consists of all molluscan species living at a particular instant in time. If a sample be defined as a representative portion of a single population, then, because new species are arising as others become extinct, a sample is unobtainable from the geologic column. Rather, a geologic sample encompasses a series of populations.

The most usable unit for biological population studies is the assemblage zone. Successive assemblage zones, laterally and vertically, may be divided primarily either on age or ecologic differences or on both. Recognition of the controlling factors delimiting such assemblage zones is one of the most difficult tasks of paleontologists. In addition to the use of planktonic and nektonic organisms as well as the new paleo-community and oxygen isotope studies for resolving this problem, it is suggested that Lyell's method may produce rewarding results. Quantitative comparisons of percentages of Recent species in successive assemblage zones give another source of data on ideas of correlation.

The final requirement is that the sample mean be accurately calculated. In the model, black balls are clearly separated from white ones. In natural samples, however, species must be correctly identified and must be correctly compared to modern counterparts. This requires not only fossil but also extant species to be fully understood. This utopian state is required to some extent for all rigorous correlations. Errors or the importance of errors decrease with increasing sample size (number of species), with increasing competency of investigators, and, unfortunately, with decreasing numbers of independent investigators.

Species, the most objective of taxa, may be studied quantitatively to help resolve this problem, but even this technique leads to subjectivity and discord. Perhaps periodic group assessment of known species will become the method of standardizing species limits.

In sum, re-evaluation of the Lyellian scheme would seem appropriate and feasible. The work of Evernden and others (1961) has shown the reliability of glauconite- and illite-derived potassium-argon dates to be high enough to make good checks on the method when the Lyellian scheme is applied as suggested in the following sections.

BINOMIAL STATISTICS

With special considerations regarding the continuity of percentage distribution discussed above, Cenozoic populations may be treated as binomial populations in which the numbers of species ranging to Recent are counted as successes. Samples from the various populations, each characterized by its mean, are binomial. The mean is the only parameter of the binomial population—when the mean is known the variance can be computed. The population mean and variances in the model[2] are:

$$\text{Mean} \quad \mu = \frac{\text{no. of successes}}{\text{total no. in population}};$$

$$\text{Variance } \sigma^2 = \mu(1-\mu).$$

The sample mean and estimate of population variance are:

$$\text{Sample mean } \bar{y} = \frac{\text{No. of successes}}{\text{total no. of observations}};$$

$$\text{Estimate of } \sigma^2 = s^2 = \bar{y}(1-y)$$

A population in this scheme consists of all molluscan species living at a particular instant in time.

We now wish to know, with a certain amount of confidence, if a particular sample has been drawn from a particular population (epoch). To do this, a confidence interval is calculated. The interval is based on the sample mean, the estimation of population variance and the number of specimens (species) in the sample. The confidence value may be arbitrarily chosen and is taken here at 95 percent and 85 percent. With these values a confidence interval can be calculated as follows:

$$y \pm 1.96\sqrt{\frac{\bar{y}(1-\bar{y})}{n}} = \bar{y} \pm 1.96\sqrt{\frac{s^2}{n}},$$

$$\bar{y} \pm 1.44\sqrt{\frac{\bar{y}(1-\bar{y})}{n}} = \bar{y} \pm 1.44\sqrt{\frac{s^2}{n}},$$

where 1.96 is the value of the 95 percent confidence coefficient and 1.44 is the value of the 85 percent confidence coefficient.

The interval thus calculated denotes that 95 percent or 85 percent of a large number of sample confidence intervals, computed from samples from the same population and having the same size and the same confidence co-

[1] The recent work of Stehli and others (1967) is an interesting look at Recent species distribution on large scale. The well-known generalization that number of species increases with decreasing latitude is affirmed for Recent pelecypods.

[2] The notation used here is that of Li (1957). Different notations, with which the reader may be more familiar, are equated to that used here in Li (p. 425–426).

efficient, will include the population mean. In other words, a particular sample mean with its calculated interval has odds of 19 to 1 or 17 to 3 of including the population mean.

Again, the length of the interval varies with the estimate of population variance, the sample size, and the confidence coefficient. Holding the confidence level fixed, it becomes necessary to determine how long the interval should be to be of stratigraphic worth. Gaps of 5 or 10 percent lie between successive epochs. Earlier in this paper, one half of this gap was taken as belonging to a particular epoch. The upper limit for the Miocene epoch is 40 percent; any value greater than 45 percent could be considered as belonging to the Pliocene. Hence, a sample with a mean of 0.40 should have a confidence interval of no more than 5 percent. Solution of the equation below gives the sample size necessary to obtain the desired result of an interval 0.05 units long.

The length of interval equals confidence coefficient times $\sqrt{\frac{\bar{y}(1-\bar{y})}{n}}$.

For the example above and confidence level 95 percent:

$$\bar{y} = 0.40 \qquad \bar{y}(1-\bar{y}) = 0.24$$

$$0.05 = 1.96\sqrt{\frac{0.24}{n_1}} \qquad n_1 = 370$$

For confidence level 90 percent:

$$\bar{y} = 0.40 \qquad \bar{y}(y-1) = 0.24\,\frac{n_2}{n_1} = 0.704$$

$$0.05 = 1.645\sqrt{\frac{0.24}{n_2}} \qquad n_2 = 260$$

For confidence level 85 percent:

$$y = 0.40 \qquad \bar{y}(y-1) = 0.24\,\frac{n_3}{n_1} = 0.540$$

$$0.05 = 1.44\sqrt{\frac{0.24}{n_3}} \qquad n_3 = 200$$

The sample must consist of about 370 species for the interval to be sufficiently short to fall exclusively within the Miocene epoch at the 95 percent level, about 260 for the 90 percent level, and about 200 for the 85 percent level.

Estimation of the interval or, in this case, of the number of species in the manner above is only approximate. Tables in Snedecor (1942), Li (1957), and Krumbein and Graybill (1965) are available for precise determinations of the confidence interval for special values of n. In cases where the mean is close to 0 or close to 1, more involved computations are necessary. Equations for determination of confidence interval for these extreme values of the mean are given in Manning (1953). This involvement was not necessary in calculation for Tables 1 and 2.

Table 1 shows the approximate minimum sample sizes needed for epochal correlation. Only the lower, upper, and intermediate percentages are used. More detailed correlation is not attempted because the within-epoch distribution of the percentage values is not now known. Yet some individual horizons of the European standard section have well-fixed percentages (that is, they have short confidence intervals) owing to the large numbers of molluscan species (about 1000) contained in these horizons. The quantity of species enables rigorous correlation, assuming that samples compared to the standard horizon also have large numbers of molluscan species.

Table 2 is presented to show the approximate sample size for more precise correlation with a standard section in Indonesia. However, the confidence intervals from Martin's original data (presented in tabular form in Umbgrove, 1946) are not sufficiently short (because the number of species in the original horizons is not great enough) to allow correlation to the desired accuracy. The samples compared to the standard would have to have many more species than are present in the original horizons in order for the confidence intervals to have the desired length. Table 2 can be read in reverse to make this clear. For example, the Atcheen beds have 56 percent Recent species; for this bed to have a confidence interval short enough not to include the supposedly older Sonde beds at the 95 percent confidence level, the Atcheen beds would have to contain over 4000 species.

Of course, the sample size cannot be determined before the sample is taken and studied. The point here is that conclusions should be no more detailed than data permit. Percentage figures (sample mean) should be accompanied by either the sample size or the confidence interval or both.

COMPARISONS OF SAMPLES

A problem related to the one above is whether two or more samples have been drawn from the same or from different populations. Sample mean, sample size, and estimate of population variance are still the factors on which conclusions are based. As before, the more accurate the correlation desired, the larger must be the sample size. (It is worth noting here that reversals in percentage distributions are often due to small sample size.)

The *chi square test* of *independence* or its equivalent, the binomial *u-test* can be used to test the hypothesis that two sample means are the same. (Case 2 below is a hypothetical example of application of the test.) To test the same hypothesis on a greater number of samples, the *chi square test* of *independence* or the *test* of *homogeneity* of *means* can be used. These tests are explained in standard statistics texts and those in Li's are particularly good (1957, Chapter 21).

Similar approaches can be used to quantify two related correlation techniques commonly used: (1) comparison of a standard stratigraphic unit (counterpart of the Recent in the Lyellian method) with a test unit on the basis of the number of species they share; and (2) comparison of two or more test units based on their independent sharing of species with a standard unit (this is the same technique covered in the preceding paragraph).

Case 1.[3] Comparison of standard unit with test unit:

N, number of species in standard unit = 300
n, number of species in test unit = 50
z, number of species in common = 40

$$\bar{y} = \frac{z}{n} = 0.80.$$

Solution: If the sample is from the population represented by the standard unit, then we can ex-

[3] It is not possible to take a direct approach to solving this case as is possible in Case 2. The reason for this is that variance cannot be properly calculated for such data.

TABLE 1. APPROXIMATE MINIMUM MOLLUSCAN SAMPLE SIZE NECESSARY FOR EPOCH IDENTIFICATION*

Epoch	$\bar{y}$	*One-half interval length*	n(95 percent)	n(85 percent)
Pleistocene	0.95	0.05	73	39
Pliocene	0.90	0	..	..
	0.70	0.20	20	11
	0.50	0.05	384	207
Miocene	0.40	0.05	370	200
	0.30	0.125	52	28
	0.20	0.025	991	535
Oligocene	0.15	0.025	790	427
	0.13	0.045	215	116
	0.10	0.025	558	301
Eocene	0.05	0.025	292	158
	0.03	0.025	179	97
	0.01	0	..	..

* Data from Dunbar (1960, p. 353).

TABLE 2. APPROXIMATE MINIMUM SAMPLE SIZE FOR CORRELATION WITH INDONESIAN LOCALITIES*

Epoch	*Locality*	$\bar{y}$	*One-half interval length*	n(95 percent)	n(85 percent)
Pliocene	Putjangan beds, Java	0.67	0.055	281	152
	Atcheen, Sumatra	0.56	0.015	4302	2323
	Sonde Java	0.53	0.015	4350	2349
Miocene	Tji Odeng, Java	0.42	0.045	447	241
	Tji Lanang, Java	0.33	0.045	419	226
	Njalindung, Java	0.18	0.050	227	123
	Progo, Java	0.08	0.050	113	61

* Data from Umbgrove (1946, Table 4).

pect something like 100 percent of the species to be shared. To see if the test-case meets this requirement, we calculate a confidence interval for $\bar{y}$ for these data with confidence level of 95 percent: 0.80 ± 0.11. Hence the sharing of species is very likely between the values of 69 and 91 percent for this and comparable samples.

Interpretation: The investigator now must answer the question: "Does this interval include values close enough to 100 percent to conclude that the sample correlates with the standard?" Subjectivity is always present in interpretation, but if data are treated as shown here, investigators at least know approximately the basis of their agreement or disagreement (the value of which is too well known to need emphasis).

Case 2.[4] Comparison of two test units:

$N = 300$ species

$n_1 = 50$ species $\qquad n_2 = 30$ species

$\bar{y}_1 = 0.80 \qquad \bar{y}_2 = 0.70$

Hypothesis: $\bar{y}_1 - \bar{y}_2 = 0$ at significance level 95 percent, two-sided.

$$u = \frac{\bar{y}_1 - \bar{y}_2}{\sqrt{\bar{y}(1-\bar{y})\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

$$= \frac{0.10}{\sqrt{\frac{40+21}{80}\left(1 - \frac{40+21}{80}\right)\left(\frac{1}{50} + \frac{1}{30}\right)}}$$

$$= 1.018$$

Interpretation: Since the value is inside the confidence limits with 78 degrees of freedom, approximately 2.00, the two samples are treated as correlatives. The samples can now be separately compared to the standard, as in Case 1, or, more logically, can be combined and then compared to the standard.

Finally, direct comparison of species in common between samples rather than comparisons based on species shared with the Recent or with a standard stratigraphic unit is possible. This method of testing the correlation of many samples at a time has been used by Bird (1965); the technique is based on a quantitative tool devised by Rogers and Tanimoto (1960).

[4] The general mean $\bar{y}$ is calculated by pooling the samples and dividing number of successes by total number of individuals.

CONCLUSION

Lyell's scheme of correlation is sometimes criticized on the basis of the combinations of error-producing factors presented in the introduction of this paper. However, these factors are no more severe in the Cenozoic Era and probably have a better chance of being recognized in the Cenozoic than elsewhere. Until the species of Cenozoic type localities are better known and more detailed regional comparisons of faunas are made,[5] Lyell's method of correlation would seem preferable to other means.

The return of some leading geologists (Newell, 1962) to the concept of worldwide advances and retreats of the sea indicates the need for more accurate correlation. This problem has long confounded the science; investigation based on accurate correlation appears to be the only means of resolution. Eustatic changes in sea level should be recognizable by detailed examination of the types of curves in Figure 1.

Rigorous correlations seem possible with the application of quantitative methods to species distribution patterns, coupled with accurate radiometric age determinations from authigenic sedimentary minerals. At least the potential seems real enough; the test awaits the cooperation of many workers who are looking for a fuller understanding of faunal changes through time, or for less subjective methods of correlation, or for both. The percentage method has been largely overlooked as a tool for comparing evolution rates in various systematic groups and for relating evolution rates to differences in environment. Umbgrove (1946, Fig. 20) and Simpson (1953, p. 47) have made graphic comparisons of evolution rates in widely different systematic groups. These studies are highly interesting even for the sketchy data now available; more concrete comparisons seem possible with the techniques presented in this paper. One can compare percentages as in the example of Case 2 above.

[5] Extensive studies of the type made by Gardner (1924) and by Mongin (1958) are badly needed for Cenozoic faunas and offer a challenging line of attack for specialists on the various groups.

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Manuscript Received by the Society November 28, 1966

Preliminary Correlation of the Neogene Molluscan Faunas in Southeast Asia

Contributions to the Geology and Palaeontology of Southeast Asia, CLV

Tsugio SHUTO

Concerning the Neogene molluscan biostratigraphy of Southeast Asia, the Indonesian, particularly Javan stratigraphy may be taken as a standard because of its flourishing Neogene faunas as well of piles of accumulation of excellent descriptions of faunas.

K. MARTIN adopted the Lyellian method for correlation of the Indonesian Tertiary and revised the Lyellian percentages for Neogene stages to be adopted to the tropical faunas on the basis of his comprehensive studies on Indonesian Tertiary molluscs. He seems to have put more faith in his percentage method than in the role of guide species. Thereafter several paleontologists developed molluscan biostratigraphy in Indonesia on the foundation of MARTIN's work. Above all C. H. OOSTINGH contributed in this field of study attempting refined correlation with the aid of guide species which respectively show definite geologic ranges. He proposed six stages and one hiatus in the Javan Neogene (1938). Thereby he also designated the type formations and nominated molluscan guide species for each stage. Since this time molluscan biostratigraphic correlation of the Indonesian Neogene has been done on the synthesis both of the Lyellian percentage of living species in the fossil assemblage in question and of known stratigraphic ranges of constituent elements of that assemblage.

The Lyellian method implies a difficulty that respective Lyellian percentages are not equal in regard to their confidence intervals, even if the percentages themselves are the same. This fault is caused by relatively small number of constituent species of assemblages as well by unequal number of species between the assemblages compared. For example, the Lyellian percentages of the molluscan assemblages of the Menengten gorge (74 identified species, MARTIN, 1919) and Sondé (150 identified species, MARTIN, 1919) are respectively 54 and 53. These figures are superficially closely similar to each other but their confidence interval at 95 percent significance level are respectively 46–62 and 47–59, if extinct and living species are distributed binomially. More than 250 species are needed to separate the Upper Preangerian and Odengian stages at significance level of 95 percent. Furthermore about 1000 species are necessary for distinction of the Odengian and Cheribonian through only the Lyellian method because of complete continuity of the Miocene-Pliocene faunas as MARTIN pointed out (1919). While correlation by guide species is not necessarily perfect. Majority of the Neogene molluscan species in Southeast Asia, on one hand, show moderately or exteremely long stratigraphic range, although several species verify their short range. On the other hand, most species are limited in geographic range. In consequence all the fossil assembalges coming to hand of a biostratigrapher are not always efficient for refined correlation. Difficulty is promoted by limited occurrence of molluscan fossils through the Neogene strata like as other mega-fossils. In spite of difficulties mentioned above, accumulation of molluscan biostratigraphic data by efforts of several authors enables us to compare results of correlation by means of molluses with those by larger foraminifers and planktic foraminifers.

The present author, firstly, tries in this paper to correlate Neogene molluscan faunas in the Malay archipelago, including Borneo and the Philippines, by the comparison of them with the Javan standard. Secondly, he tries to clarify the geographical limit of correlation based on the Javan faunal standard for one step toward interregional correlation between Europe and East Asia by means of molluscan faunas.

Javan Neogene Stages Defined by Molluscan Fossils

The Javan Neogene stages defined by molluscan fossils, their stratotypes, equivalent formations in Southeast Asia and their revised guide species are given below.

Bantamian

Stratotype: Bodjong formation, west Java (OOSTINGH, 1938).

Equivalent formations: Tjikeusik fm. (west Java), Ligniferous fm., Operculina sandstone fm., Fossiliferous marl and sandstone fm. (north Sumatra), Upper Palembang fm. (south Sumatra), Zone 4 (Timor), Sta Barbara member of the Cabatuan fm. (Panay, Philippines).

Guide species: *Turritella terebra bantamensis* MARTIN, *Tritonalia bantamensis* (MARTIN), *Cantharus lulianus* (MARTIN), *Nassarius bodjongensis* OOSTINGH, *Trigonostoma bantamense* OOSTINGH, *Clavus malingpingensis* OOSTINGH, *Nucula bantamensis* OOSTINGH.

Sondian

Stratotype: Tjilegon formation, west Java (OOSTINGH, 1938).

Equivalent formations: Tjimantjeuri fm., Tjidjadjar fm., Beds of Menengten gorge, Sondé fm. (Java), Upper Palembang fm. (south Sumatra), Zone 3 (Timor), Fufa fm. (Celebes), Upper Ulian fm. (Panay, Philippines),

Upper Mandog sandstone (Davao, Philippines), Gwadar fm. (Pakistan).

Guide species: *Turritella terebra tjicumpaiensis* MARTIN, *Murex lebracanus* MARTIN, *Turris koolhoveni* OOSTINGH, *Conus sondeianus* MARTIN, *Terebra verbeeki* OOSTINGH, *T. insulindae* FISCHER, *Pecten gendinganensis* MARTIN.

Cheribonian

Stratotype: Tjidjurej formation, north-central Java (OOSTINGH, 1938).

Equivalent formations: Tjipatjar fm., Beds of Kali Bioek (Java), Zone 2 (Timor), Togopi fm. (northeast Borneo), Middle Mandog sandstone (Davao, Philippines).

Guide species: *Zaria acuticarinata* (DUNKER), *Strombus varinginensis* MARTIN, *Thais martini* OOSTINGH, *Siphonalia paradoxica* MARTIN, *Ancilla gerthi* OOSTINGH, *Olivancillaria cheribonensis* MARTIN, *Vexillum schepmani* KOPERBERG, *Aulica scapha ponderosa* MARTIN, *Clavus dammermanni* OOSTINGH, *Arca cheribonensis* OOSTINGH, *Ostrea tegalensis* MARTIN, *Cardium cheribonense* OOSTINGH, *Paphia vandermeermohri* OOSTINGH, *Aloidis cheribonensis* OOSTINGH.

Odengian

Stratotype: Kramat formation, west Priangan, west Java (OOSTINGH, 1938).

Equivalent formations: Genten fm., Tjigugur fm., Tjiodeng fm. (s. str.)*, Beser fm. (Java), Dingle fm. (Panay, Philippines), Nasipit fm. (north Mindanao, Philippines), Akauktaung stage (Burma), Talar fm. (Pakistan).

Guide species: *Zaria cramatensis* (MARTIN), *Acantinella javana* (MARTIN), *Phos palembangensis* OOSTINGH, *Benthomangelia vandervlerki* BEETS, *Triplostephanus jenkinsi* (MARTIN), *Venericardia javana* (MARTIN).

Preangerian

Stratotype: Tjitalahab near Njalindung, west Java (OOSTINGH, 1938).

Equivalent formation: Bodjongmanik fm. (s. str)., Tjilanang fm.,** Tjadasngamper fm., Njalindung fm.,** Tjidadap fm., Parung-Ponteng Beds (Java), Lower Palembang fm. (south Sumatra), Glingseh fm., Menkrawit fm., Lower Sandakan fm. (east and north Borneo), Obogon alternation, part (Burma), Upper Gaj, part (Pakistan).

Guide species: *Zaria angulata* (J. de SOWERBY), *Vicarya verneuilli callosa* JENKINS, *V. formosa* OOSTINGH, *Telescopium koolhoveni* OOSTINGH, *Siphocypraea caputviperae* (MARTIN), *Preangeria angsanana* MARTIN, *P. talahabensis* MARTIN, *Conus brevis* (J. de SOWERBY), *Talahabia dentifera* MARTIN, *Cardium talahabense* MARTIN, *Apolymetis grimesi elongata* (HANSTRA et SPIKER), *Cultellus dilatatus* MARTIN, *Paphia neglecta* (MARTIN).

Rembangian

Stratotype: Beds of Sedan near Rembang, central Java (OOSTINGH, 1938).

Equivalent formations: Rembang fm., West Progo fm., Badui beds (Java), Obogon alternation, part (Burma), Upper Gaj fm., part (Pakistan), Quilon beds (south India).

Guide species: *Turritella terebra talahabensis* MARTIN, *T. producta* MARTIN, *Archimediella* (*Torculoidella*) *spolongensis* (MARTIN), *Haustator* (*Kurosioia*) *sedanensis* (MARTIN), *H.* (*K.*) *teschi* (MARTIN), *Peyrotia sundanica* WANNER et HAHN, *Ranella pamotanensis* MARTIN, *Cerithidea progoensis* MARTIN, *Ancilla rembangensis* MARTIN, *Amussiopecten singkirensis* (MARTIN), *Cardium spolongense* MARTIN, *Lyria jugosa* (J. de SOWERBY).

Relation of the Molluscan Stages to the Foraminiferal Stages and Zones

The letter-classification of the Indonesian Tertiary proposed by Van der VLERK and UMBGROVE (1927) became refined by the revision by LEUPOLD and Van der VLERK (1931) and RUTTEN (1947). Concerning the stratigraphic relation of the letter stages to the molluscan stages, Van der VLERK (1931) is the first proposer, who gave the following scheme; namely the Sondé, Tjilanang, Njalindung and West Progo Beds respectively correspond to Th, Upper Tf, Middle Tf and Lower Tf. BEMMELEN (1949) gave a revised correlation of the letter- and molluscan stages. According to him the Sondian, Cheribonian, Cheribonian/Odengian hiatus to Odengian, Preangerian and Rembangian are respectively correlative to the Upper two-thirds of Th_2, Lower one-third of Th_2 to Upper half of Th_1, Tg, Tf_3 and Te_5 to Tf_2.

Recently BLOW gave a revision of the planktic foraminiferal zonation

*According to BEMMELEN (1949), the Tjiodeng formation is divided into the upper and lower parts, of which the upper is the Tjiodeng formation (s. str.) correlative to the Beser formation, Upper Miocene, and the lower part is assigned to the Njalindung formation of the Tjimandiri group, that is to say, to the Preangerian.

**The Preangerian includes younger and older parts represented respectively by the Tjilanang and Njalindung formations. Both formations yield very similar molluscan faunas with 91 species in common (91/192 in the Tjilanang and 91/193 in the Njalindung). Nevertheless several genera show different geologic ranges in the two formations. That is to say, *Marginella nanggulanensis* MARTIN, *Lyria jugosa* (J. de SOWERBY), *Mitra sedanensis* MARTIN and *Arca hulshofi* MARTIN extinct in the Njalindung formation. The first appearance of such genera as *Liotia, Thais, Anomia, Perna, Tridacna, Joannisiella, Paphia,* and *Cultellus* is in the Njalindung, while that of *Telescopium, Xenophora, Sconsia, Tonna, Argobuccinum, Metula, Acantinella* and *Dosinia* is in the Tjilanang. Furthermore the Lyellian percentage of the two formations are remarkably different; namely 37.5 percent (192 identified species, 31.5–42 percent of confidence interval at 95 percent significance level) in the Tjilanang and 19.8 percent (193 identified species, 17–24 percent of confidence interval) in the Njalindung. The faunal difference between these formations seems more pronounced than between the Odengian and the Cheribonian.

of Bodjonegoro well No. I section originally described by BOLLI (1966). In that occasion BLOW also showed a correlation of the letter-stages to the molluscan ones as following; the Cheribonian to the Bantamian being correlated to Th, the Cheribonian/Odengian hiatus and Odengian being included in Tg and the Preangerian and the Rembangian being respectively correlated to Tf_3 and Tf_{1-2}. In the present paper the author adopts BLOW's scheme of correlation appreciating his assignment of the Rembangian to Tf_{1-2}, the Odengian to Lower Tg and the Bantamian to Th.

Planktic foraminiferal zoning of the Indonesian Tertiary strata started only recently and published data are not many. BLOW (1969) correlated the Bantamian to Zone N. 20 on the basis of the Bodjong sample. He assigned the Sondian to Zone N. 20 and the Upper half of N. 19 by the Tjilegon sample. He also suggested that the Tjijaran sample represents an intermediate time span between the Cheribonian and the Odengian (OOSTINGH's Cheribonian/Odengian hiatus). While regarding the older stages, generally accepted correlation that Tf_{1-2} includes "*Globorotalia fohsi* zone" leads to a correlation of the Rembangian to Zone N. 10–12.

Notes on Correlation of the Selected Faunas in Southeast Asia

(*1*) *Borneo* (*Kalimantan*)

Menkrawit formation: C. BEETS (1941) described the Menkrawit fauna from Loc. 114, Mangkalihat. The fossil bed is situated at the lowest horizon of the Menkrawit formation, which is overlain by the Domaring limestone above and underlain by the Taballar limestone below. He correlated that fauna, consisting of 116 extinct and 44 living species, to the Tjadasngampar, Tjilanang and Njalindung faunas in Java. The present author agrees with BEETS' correlation of the Menkrawit fauna to the Preangerian fauna of Java so far as the molluscan fossils are concerned. BEMMELEN (1949), however, mentioned of a contradicting fact that larger foraminifers from the lower Menkrawit formation indicate Tf_1 age and express his suspicion about the mentioned horizon of Loc. 114.

Togopi formation: The Togopi fauna from the uppermost formation in the Dent peninsula consists of 58 molluscan species, of which 21 species (34.5 percent, 18–53 percent at 95 percent confidence level) are living according to COX (1948). It contains Javan Upper Miocene elements as well Pliocene ones besides many new species. Under such a situation mentioned above, the original author hesitated to give a decisive judgement but suggested a possibility of Upper Miocene or Lower Pliocene age. Although the Togopi fauna shows a particular feature noticeably different either from the Javan Upper Miocene or Pliocene because of its numerous indigenous elements, the present author considers the age of that fauna being not younger