The Orbital Record in Stratigraphy

Alfred G. Fischer
Department of Geological Sciences
University of Southern California
Los Angeles, CA 90089-0740

Abstract

Orbital signals are being discovered in pre-Pleistocene sediments. Due to their hierarchical nature these cycle patterns are complex, and the imprecision of geochronology generally makes the assignment of stratigraphic cycles to specific orbital cycles uncertain, but in sequences such as the limnic Newark Group under study by Olsen and pelagic Cretaceous sequence worked on by our Italo-American group the relative frequencies yield a definitive match to the Milankovitch hierarchy. Due to the multiple ways in which climate impinges on depositional systems, the orbital signals are recorded in a multiplicity of parameters, and affect different sedimentary facies in different ways. In platform carbonates, for example, the chief effect is via sea-level variations (possibly tied to fluctuating ice volume), resulting in cycles of emergence and submergence. In limnic systems it finds its most dramatic expression in alternations of lake and playa conditions. Biogenic pelagic oozes such as chalks and the limestones derived from them display variations in the carbonate supplied by planktonic organisms such as coccolithophores and foraminifera, and also record variations in the aeration of bottom waters. Whereas early studies of stratigraphic cyclicity relied mainly on bedding variations visible in the field, present studies are supplementing these with instrumental scans of geochemical, paleontological and geophysical parameters which yield quantitative curves amenable to time- series analysis; such analysis is, however, limited by problems of distorted time-scales. My own work has been largely concentrated on pelagic systems. In these, the sensitivity of pelagic organisms to climatic-oceanic changes, combined with the sensitivity of bottom life to changes in oxygen availability (commonly much more restricted in the Past than now) has left cyclic patterns related to orbital forcing. These systems are further attractive because (1) they tend to offer depositional continuity, and (2) presence of abundant microfossils yields close ties to geochronology. A tantalizing possibility that stratigraphy may yield a record of orbital signals unrelated to climate has turned up in magnetic studies of our Cretaceous core. Magnetic secular

variations here carry a strong 39 ka periodicity, corresponding to the theoretical obliquity period of that time - Does the obliquity cycle perhaps have some direct influence on the magnetic field?

I consider the following lines of research to be particularly important:

- (1) Studies of stratigraphic sequences in which Milankovitch cyclicity is particularly apparent, and in which the record appears to be unbroken and extends for time spans in the 10^6 - 10^7 Ma range. This includes such sequences as the Newark Series (Olsen), the pelagic Cretaceous of Italy which we have been studying, and the Eocene of Angola (Fig. 5).

- (2) Extending such studies to the tracking of magnetic secular variation, which may turn out to provide a record of orbital variations independent of climate.

- (3) Exploring the geographic dimension, by global mapping of the distribution of cycle styles for given time-slices. How do cycle patterns change with latitude, from hemisphere to hemisphere, from ocean to ocean? Only such studies will bring cyclostratigraphic studies to bear on the problems of climatic change. ALBICORE is a start in that direction.

- (4) Extending cyclostratigraphic research into the Paleozoic. Milankovitch patterns, in particular the 1;5;20 ratio of precession to the eccentricity cycles, have now been established back to the Triassic Period, but Paleozoic stratigraphic patterns do not seem to fit this scheme. Were the orbital periods, or the Earth's response to them, different in Paleozoic times?

1 Orbital Variations

Quasi-rhythmical orbital variations have affected the Earth since its inception. The current patterns of such rhythms with periods of up to 400,000 years, are well defined from astronomical observations. Not so clear is how the major orbital parameters and their minor variations have changed through time. The length of the day, for example, is lengthening with transfer of angular momentum to the moon, and the current rate of change has been well established, but it seems highly unlikely that the change has been linear, and the existing data on this from historical geology are unsatisfactory. Other orbital variations such as the obliquity cycle and the precession are linked to the rotation rate, so that they too have changed with time, in ways that remain undefined.Astronomers are interested in the patterns of change for obvious reasons, but so are geologists and climatologists. If the orbital variations of the past have left a record in the rocks - specifically, in the sequentially accumulated layers of sedimentary and volcanic rocks that form an incomplete envelope of the crust - they may provide a geochronology (Gilbert, 1895) and a means for refining the crude time scale provided by radiochemistry. But furthermore, the orbital variations influence

the latitudinal and seasonal distribution of insolation, and thereby atmospheric climate and oceanic dynamics, and thus come to be agents in "Global Change." While the major Icehouse and Greenhouse modes of the outer Earth have probably been driven by internal cycles (mantle convection - Wilson cycle of plate tectonics: Fischer, 1984). The orbital variations have modulated oceanic an climatic behavior within these major modes. Such modulations may be thought of as experiments, and if they can be reconstructed from the historical record they will bring light to the range of climatic-oceanic behavior that lies beyond the realm of human experience.

2 The Quaternary Record

The case for such orbital forcing has now been compellingly made for the Pleistocene. It was first suggested nearly 150 years ago by Adhemar, and the theory was further developed and improved by Croll (for a summary, see Imbrie & Imbrie, 1979), but its quantitative footing - that the orbital variations vary insolation substantially - was the life-work of M. Milankovitch (1941), subsequently improved by Berger (1980, 1988) and others. The tie of the glacial record to orbital variations did not become definitive until Imbrie and others discovered that the isotopic record in the foraminifera of Pleistocene stratigraphic sequences retrieved from the ocean floor provided a proxy of ice volume, and found that the fluctuations in ice volume not only showed the same hierarchical frequencies of the orbital variations, but also historical coherence between these different phenomena (Imbrie, 1982).

3 Pre-Quaternary Record of Orbital Variations

But many climatologists and geologists remained dubious about the existence of an orbital record during non-glacial times. Duff, Hallam and Walton (1967) suggested that whereas the relatively small changes in insolation values during glacial times became greatly amplified by the positive feedback of a greatly increased Earth albedo due to the spread of glaciers and pack ice, the absence of such feed-back during non-glacial times made a record of orbital variations unlikely. Stratigraphers working in the gap- riddled record of the epicontinental regions saw little hope of recovering a record of persistent rhythmicity.Yet, some stratigraphers found rhythmic patterns in the stratigraphic record that seemed best explained as products of orbital forcing. Thus G.K. Gilbert (1895) interpreted the rhythmic spacing of limestones in the Late Cretaceous of Colorado as the expression of the precessional cycle, W. Bradley (1929) viewed the rhythmical alternations of oil shales and dolomite beds in the lacustrine Green River Formation (Eocene) of the Rocky Mountain region in the same manner, and W. Schwarzacher (1947) viewed the alternations of massive and laminated

carbonates in the Late Triassic Dachstein platform of the Alps as precessional, and their grouping into bundles of 5 as an expression of the 100 ka eccentricity cycle. As geological attention has shifted from purely local or regional concerns to global patterns, the number of these stratigraphers has grown (e.g., ROCC group, 1986; Fischer, 1986; Fischer et al., 1990; Fischer, 1991; Fischer and Bottjer, 1991).

4 Oscillations Recorded in Older Stratigraphy

The pragmatic facts are that the stratigraphic record is replete with repetitive features - some visible to the eye, (Fig. 5), others (such as the Pleistocene isotope curve) only retrievable by instrumental studies. Some reflect only the stochastically recurring alternations between the several modes of a depositional system, such as the alternation of channel and overbank deposits in alluvial systems, and were designated as "autocyclic." But others seem to have been "allocyclic," driven by forces outside the regional setting, and candidates for the rhythmic climatic- oceanographic changes to be expected from global forcing. These oscillations are of many sorts, of which the following have been recognized to date:

- 1. Cryogenic cycles. Changes in global ice volume, reflected in

    - (a) variations in the isotopic composition of sea water. Best recorded in foraminiferal tests of pelagic sediments retrieved from the deep-sea floor (isotopic cycles) (Imbrie, 1982)

    - (b) oscillations in sea level, on the scale of 10^{-1}- 10^2 m, best recorded in subtidal-intertidal alternations and emergence cycles of carbonate platforms (emergence cycles), (e.g. Schwarzacher 1947, Fischer 1964, Goldhammer et al. 1987, Hinnov and Goldhammer 1991), (Fig. 1).

- 2. Carbonate production cycles. Oscillations in productivity of pelagic carbonate producing organisms (mainly coccolithophorids) are best recorded in pelagic chalk and marl sequences (Herbert and Fischer, 1987; Herbert and d'Hondt, 1990; Fischer et al. 1991) (Figs. 2, 5).

- 3. Dilution cycles. Oscillations in the flux of detrital mud are best recorded in hemipelagic sediments of continental margins (Roof et al., 1991).

- 4. Dissolution cycles. Oscillations in the depth and intensity of the lysocline - the level at which oceanic carbonate accumulation gives way to carbonate dissolution, best recorded in relatively deep (2-5 km) pelagic sequences.

- 5. Desiccation cycles. Oscillations in the regional precipitation-evaporation ratio are best recorded in

- (a) marginal marine evaporite sequences, where annual varving permits an approach to net evaporation as recorded in annual sulfate precipitation (Anderson, 1982, 1984).

- (b) alternations of lake and playa conditions in lacustrine systems (Fig. 1) (Olsen 1987, Fischer and Roberts 1991).

● 6. Redox cycles. Oscillations in the aeration of bottom waters best recorded in pelagic systems by

- (a) retention of organic carbon (Figs. 2, 5), and

- (b) shifts in the spectrum of bottom-dwelling animals, best reflected in their burrowing patterns (ichnofabric) (Fischer et al., 1991).

● 7. Magnetic cycles. Oscillations in magnetic parameters may be significant in sediments which acquired a remnant magnetism during or soon after deposition, and in which this signature has not been irretrievably lost by subsequent/magnetic overprints. The remnant magnetism thus developed depends (a) on the presence and character of suitable magnetic carrier phases (such as the mineral magnetite), and (b) on the strength and direction of the then-prevailing magnetic field.

Inasmuch as the carrier phase is linked to lithology, which responds to climate and oceanic change, oscillations in the carrier phase may be expected to reflect orbital (as well as other) sorts of lithic forcing. Hence it is not surprising that the detailed magnetic investigations of the Piobbico core (Napoleone et al., 1991, 1992) find the 100 ka eccentricity cycle, dominant in Fourier spectra of lithic variation, to be present in the magnetic intensity spectrum as well (Fig. 4). It is not so easy to explain why it should also appear in the inclination and declination spectra. It is even more difficult to understand why a 39 ka periodicity - that of the obliquity cycle - should dominate the magnetic intensity spectra and should also appear in the inclination and declination spectra, when it appears as only a very weak component of the various spectra related to lithology. There would thus appear to be a possibility that the magnetic field is affected by orbital variations - a suggestion that has been made previously, but has never been taken very seriously by the paleomagnetic community. If it were to be true, then paleomagnetic studies might provide a record of orbital cycles that is independent of transmission through climatic and oceanic dynamics - a possibility worth pursuing.

Paleontological criteria play a large role in the recognition of these cycles (1a, 1b, 2, 4, 6) - which should not be surprising, considering the great sensitivity of organic communities to climatic and oceanographic change.

5 Theoretical Considerations

Complications arise from the following factors:

- 1. The cycles may be overprinted and swamped out by grosser lithic changes in response to tectonic-geomorphic events. This is particularly the case in marine settings near major sources of detrital sediments, and is minimized in carbonate platforms and pelagic settings.

- 2. Cycles may be only partially preserved or totally lost owing to interruptions in deposition and continual reshuffling of sediments such as occurs in the "tempestite regime." This implies that many stratigraphic facies are never likely to lend themselves to the establishment of a "cyclostratigraphy."

- 3. Cycles of the higher frequencies may be largely or entirely destroyed by the burrowing activities of organisms (bioturbation). This is likely to be the case in slowly deposited facies, such as the "red clay" of the very deep ocean floor, accumulated at mean rates of $1mm/10^3 = 1m/10^6 years$.

- 4. Cycle patterns are hierarchical and therefore complex (Figs. 2, 4, 5). The earliest workers sought to identify stratigraphic cycles with only one forcing period, such as that of the precession. Subsequent studies such as those by Schwarzacher (1947), Van Houten (1964), Herbert and Fischer (1987) found hierarchical patterns. The hierarchy most commonly encountered is the grouping of ca 5 bedding couplets into sets (bundles, Figs. 2, 5), which may in turn be grouped into superbundles of 4 (Fig. 2). On the other hand, the patterns can become complicated when members of the hierarchy shift phase relative to the others, and vary in strength of expression.

- 5. The different orbital forcing functions affect climate and oceanic behavior in quite different ways, and impinge upon a specific depositional setting via different pathways. The northern and southern hemispheres, for example, respond to the obliquity cycle in phase, but to the precessional cycle 180° out of phase. When this complication is combined with the observation that the climatic-oceanographic forcing of any given depositional setting contains both globally averaged effects such as sea level and locally imposed effects such as variations in the amount and timing of insolation, the likelihood of a wide range of possible combinations and variations emerges. When these effects take different pathways that impose different lag times (such as global oceanic turnover), further complications may result. On the one hand this may be daunting for a first recognition of cycle patterns, but on the other such complexities, once resolved, provide a wealth of additional information.

6 Identification of Specific Cycles

Vital to development of a cyclostratigraphy is the identification of oscillations observed in the stratigraphic record with specific cyclic forcing functions. This revolves largely around timing the cycle period. The following approaches have been used.

6.1 Varving.

The varve method, employed by Bradley (1929), Fischer and Roberts (1991), Ripepe, Roberts and Fischer (1991), and Anderson (1982, 1984). Some sedimentary sequences - in particular those of deep-water evaporites and those of meromictic lakes - retain a fine lamination which can with reasonable probability be assigned to the annual cycle, (varving). Continuous varving permitted Anderson to plot variations in sulfate precipitation for a 200,000 year record, which provided a remarkable record of the precession in late Permian time. Episodic varving in lake sediments, extrapolated to the non-varved intervals, permitted Bradley to recognize the precession in lacustrine Eocene sediments of the Rocky Mountain region (see also Fischer and Roberts, 1991; Ripepe, Roberts and Fischer, 1991). Varved sediments are, however, rare, and generally do not form time-series long enough to be useful in timing cycles in the Milankovitch frequency band.

6.2 Radiometry

Radiometric approaches are fairly accurate in the radiocarbon range (the last 30 ka, possibly extendable to 100 ka), and are applicable to many sediments, but for the vast bulk of geological time (Harland et al., 1990) radiometry depends on the dating of specific geological events, such as the emplacement of an ash layer or an intrusion, which are then extrapolated to the stratigraphy at large. Stratigraphical stage-boundaries dated in this manner generally have confidence limits of one or two million years for the last 100 Ma or so, but beyond this the uncertainties increase toward the 10 Ma level, and, in Cambrian time, beyond that. The durations of Mesozoic stages, averaging 3-10 Ma long, have errors in the range of 1-5 Ma. Rhythmic time series studied to date generally occupy fractions of such a stage, and extrapolating the assumed stage duration down to the level of the time-series in question involves further errors depending on accuracy of stratigraphic correlations and uniformity of sedimentation rate. As a result, such calculations are approximations with confidence limits in the range of a factor of 1.5 to 2. This generally serves to ascertain whether a given rhythm falls within the confines of the Milankovitch frequency band, but generally does not identify it definitively with one of the specific orbital variations.

6.3 Magnetic reversal stratigraphy

Magnetic reversals since the Late Jurassic have now been identified on the sea-floor, and can be recognized in many stratigraphic sequences. Through biostratigraphy these reversals have been tied to the radiometric scale. The width of the corresponding magnetic anomalies on the deep- sea floor provides a means of refining the radiometric time- scale, assuming relatively constant sea-floor spreading rates. At times of frequent reversals, the polarity zones are only a few million years long, commonly shorter than stages, and may thus afford a better basis for estimating the periods of cycles. Whereas much of our work has been in the "Cretaceous long normal" polarity chron which lacks the requisite reversals, work in the Tertiary (Schwarzacher, 1987; Herbert and d'Hondt, 1990) have used reversal stratigraphy to good effect in dating cycles.

6.4 Ratios

As pointed out above, stratigraphic cycles commonly occur in hierarchies. A grouping of ca 5 bedding couplets into bundles, in Triassic platform emergence cycles has now been well documented (Schwarzacher, 1947; Goldhammer et al., 1987; Hinnov and Goldhammer, 1991). It has been found in Triassic-Jurassic lacustrine sequences (Van Houten, 1964; Olsen, 1986), and occurs in Eocene (Fig. 5) and Cretaceous (Fig. 1, 2) pelagic sequences (Fischer et al., 1990). Furthermore, the Triassic-Jurassic lacustrine beds and the Cretaceous pelagic sequence of the Scisti a Fucoidi show a grouping of the 100 ka bundles into 400 ka superbundles.The geochronology based on radiometric data shows that these examples all lie within the Milankovitch frequency band, and thus the case of identifying bedding couplets with the ca, 20 ka precession, the bundles with the ca 100 ka eccentricity cycle, and the superbundles with the ca 400 ka eccentricity cycle becomes compelling.The ratios between cycle levels in the hierarchy thus emerge as an important clue to cycle identity. It is noteworthy, however, that to date no such good ratios have been found in the Paleozoic. Such studies are as yet in their infancy, but the 5;1 ratios, commonly visually striking in the Cenozoic and Mesozoic, have not emerged (cf. Boardman and Heckel, 1989; Goldhammer et al., 1991).

7 Present Status of Global Cyclostratigraphy

At this stage, the case for a pre-Quaternary record of orbital variations has been made in principle. The main stratigraphic facies showing heirarchical periodicities of the orbital variations are:

- (1) Deep-water evaporites (Permian, Anderson 1982, 1984). Their varving, offers the best age control. They suffer from (a) being too short to

apprehend the longer cycles, (b) from difficulties in tying them chronologically to other facies, and (c) in being scarce. Nevertheless, work on these sequences should be pursued. In particular, it now becomes essential to restudy the Castile sequence by means of instrumental scans. Studies should also be carried on to other sequences of this type, such as the varved anhydrites of the Zechstein Formation of Germany.

- (2) Lacustrine facies: Primarily the Triassic-Jurassic Newark Group sequences studied by Van Houten (1964) and Olsen (1986). Lakes as closed systems provide continuity of deposits and a record responding mainly and sensitively to local/regional climatic change (wet vs. dry). The disadvantages of lacustrine studies lie mainly in poor ties to the marine record and global geochronology. The most significant work being carried on at this time is that of Paul Olsen (Lamont). Other large and persistent lake systems of this sort include an unstudied Devonian complex in Nova Scotia, which would perhaps provide entry to the presently enigmatic Middle and Lower Paleozoic.

- (3) Biogenic pelagic facies such as those explored in the Piobbico Core (Fischer et al., 1991) in deep-sea cores (Herbert and co-workers). The not-so-deep pelagic sediments appear to have recorded (a) changes in the aeration state of the bottom waters, and (b) carbonate productivity in the surface waters. These parameters presumably reflect changes in circulation and in the general productivity patterns of the oceans, and a combination of local and global effects. Deep pelagic facies are complicated by the superposition of dissolution events, and by the effects of bioturbation on slowly accumulated muds.

- (4) Carbonate platform facies such as those studied by Schwarzacher (1947), Fischer (1964), Goldhammer et al., (1987), and Hinnov and Goldhammer (1991). Such facies monitor small-scale sea-level fluctuations - a globally integrated signal in contrast to lacustrine cycles. Whereas Milankovitch cyclicity has been well substantiated, uncertainties about the origin of sea-level oscillations pose a problem (I lean toward small-scale glacial effects). Also, like the evaporite and lacustrine records the platform rocks generally lack the means of close correlation into the global stratigraphy, based mainly on pelagic fossils.

8 My Own Researches

8.1 Piobbico Core

I have been working primarily with orbital cyclicity in the pelagic facies - and in recent years mainly with the Piobbico core, cut by an Italo-American consortium

(Premoli Silva-Fischer-Napoleone) in the mid-Cretaceous Scisti a Fucoidi of the central Apennines. We have used this core as a means of exploring various techniques of extracting continuous time-series data of various parameters from rocks. Figs. 2-4 are a summary of the work to date. We are continuing work on this core.

8.2   Eocene of Angola

Some of my Italian colleagues, working in Angola, have discovered there what appears to be a truly extraordinary Milankovitch sequence in Eocene chalks, in which the shale-chalk couplets appear even better defined than in the Albian of Italy, as is their bundling into sets of ca 5 (Fig. 5). We hope to make a detailed photographic record of these exposures in 1992, and to sample the sequence in more detail.

The regional setting of this sequence - between the extremely nutrient- rich upwelling belt of southwest Africa and the tropical waters of the Gulf of Guinea - may well have provided an ideal site for recording lateral displacements of the boundary, of the sort that might be driven by orbital cycles.

The Eocene, like the Mid-Cretaceous, was a time of Greenhouse Climate, and this could well turn out to be the most dramatic expression of orbital/Milankovitch cyclicity in greenhouse times. We do not presently have support for this study. Eocene time contains numerous magnetic reversals, well tied into the planktonic fossil record, and if Angolan sequence retains its original remnant magnetism then it should be possible to define the cycle periods with a higher degree or precision than has theretofore been achieved.

8.3   Project Albicore

It is one thing to establish the effects and a record of orbital forcing in principle, in isolated sequences. Such work may indeed help to define the relative changes in cycle periods through time. But they will not shed light on geological problems by providing refined chronologies, nor will they illuminate the problems of ancient climates. For this it will be necessary to study cyclicity globally and for restricted time-slices, which will provide a general view of changes in cycle patterns as related to latitude, continent-ocean distribution etc.

Toward this end I hope to generate a global attack on the pelagic facies of one time-slice - the Ticinella praeticinesis subzone of the Albian, about 100 million years ago, at about the peak of the Cretaceous greenhouse. We chose this zone because (1), it shows such striking cyclicity in Italy (Fig. 2, 3, 4), (2) it is readily recognized by foraminifera and nannofossils, and (3) it stems from a time when high sea- levels left a widely distributed record of pelagic sediment. We expect to find such sediments in about 15-20 countries. My plan is to carry on studies modelled somewhat (with improvements) on those we have developed in Italy (Piobbico core), which will produce comparable data. The

work in individual countries would be financed and carried out by groups of concerned scientists, advised and aided by an international steering committee.

Our first step in this direction will be an international workshop, organized by Premoli Silva, Fischer and Napoleone, to be held on October 4-9, 1992, in Perugia, Italy. The reason for choosing that locale is that it lies within striking distance of the outcrops in which our model - the cyclicity in the Scista a Fucoidi - can be displayed.

This workshop will be largely combined with another, the APTICORE conference of Larson and Erba. This will attempt to organize a parallel project to focus on the slightly earlier (early Aptian) events - the eruption of enormous quantities of basalt in the mid-Pacific region, and the widespread development of oil shales the Selli Bed - which is also very well displayed there. A vital part of the participants - that of the world's Mid- Cretaceous stratigraphers - will be equally involved in both workshops.

The aim of the ALBICORE workshop will include (a) alerting the Mid-Cretaceous stratigraphers to the opportunities provided by these approaches, which provide a focus very different from the conventional one, (b) educating them in the general background, in the need for extended interdisciplinary approaches, (c) providing a general forum of exchange on these matters, (d) organizing some international "action groups" who would set out to undertake such studies at specific locales, and (e) organizing a supporting organization that would provide advice, and support such as providing laboratory facilities for specific types of analyses.

We expect 50-75 people for the combined workshops. Larson has asked NSF Ocean Sciences for support, through JOIDES, and this may help to cover travel expenses for the 15 or so US participants, but is limited to supporting US workers. Our dependence on other nations, many of whose scientists do not have travel money, makes it imperative to find funds no thus restricted. I hope that the NSF Global Change program will allow for this, but we are likely to fall short of support for non-US participants.

9   References

ANDERSON, R.Y., 1982, A Long Geoclimatic Record From the Permian, Journal of Geophysical Research, v. 87, p. 7285- 7294.

BERGER, A., 1980, Milankovitch Astronomical Theory of Paleoclimates: A Modern Review, Vistas in Astronomy, v. 24, p. 103-122.

BERGER, A., 1988, Milankovitch Theory and Climate, Reviews of Geophysics, v. 26, p. 624-657.

BERGER, A., LOUTRE, M.F., AND DEHANT, V., 1989, Influence of the Changing Lunar Orbit on the Astronomical Frequencies of Pre-Quaternary Insolation Patterns, Paleoceanography, v. 4, p. 555-564.

BOARDMAN, D.R. II, AND HECKEL, P.H., 1989, Glacial-Eustatic Sea-Level Curve for Early Late Pennsylvanian Sequence in North-Central Texas and Biostratigraphic Correlation With Curve for Midcontinent North America, Geology, v. 17, p. 802-805.

BRADLEY, W.B., 1929, The Varves and Climate of the Green River Epoch, U.S. Geological Survey Professional Paper, 158, p. 87-110.

DUFF, P.M., HALLAM, A. AND WALTON, E.K., 1967, Cyclic Sedimentation, Elsevier, 280 pp.

FISCHER, A.G., 1964, The Lofer Cyclothems of the Alpine Triassic, Kansas Geological Survey Bull., v. 169, p. 107- 149.

FISCHER, A.G., 1984, The Two Phanerozoic Supercycles: in Berggren, W., and Van Couvering, J., eds., Princeton Univ. Press pp. 29-150.

FISCHER, A.G., 1986, Climatic Rhythms Recorded in Strata, Ann. Rev. Earth & Planet. Sci., 14, 351-376.

FISCHER, A.G., deBOER, P., & PREMOLI SILVA, I., 1990, Cyclostratigraphy, In Ginsburg, R.N., & Beaudoin, B., eds., Cretaceous Resources, Events and Rhythms, Dordrecht-Boston-London, Kluwer Publ., p. 139-172.

FISCHER, A.G., HERBERT, T.D., PREMOLI SILVA, I., NAPOLEONE, G., & RIPEPE, M., 1991, Albian Pelagic Rhythms (Piobbico core), Jour. Sedimentary Petrology, v. 61, No. 7, (in press).

FISCHER, A.G., & ROBERTS, L., 1991, Cyclicity in the Green River Formation (Lacustrine Eocene), Wyoming, 1991, Jour. Sediment, Petrol., v. 61, No. 7, (in press).

GILBERT, G.K., 1895, Sedimentary Measurement of Geological Time, Journal of Geology, v. 3, p. 121-125.

GOLDHAMMER, R.K., DUNN, P.A., AND HARDIE, L.A., 1987, High-Frequency Glacioeustatic Oscillations With Milankovitch Characteristics Recorded in Middle Triassic Platform Carbonates in Northern Italy, Amer. Jour. Sci., 287, 853- 892.

GOLDHAMMER, R.K., OSWALD, E.J., AND DUNN, P.A., 1991, in Franseen, E.K., Watney, W.L., Kendall, C. St. C., and Ross, W.C., (eds.), Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition, Kansas Geological Survey, in press.

HARLAND, W.B., ARMSTRONG, R.L., COX, A.V., CRAIG, L.E., SMITH, A.G., AND SMITH, D.G., A Geologic Time Scale 1989, 1990, Cambridge University Press, 280 pp.

HAYS, J.D., IMBRIE, J., AND SHACKLETON, N.J., 1967, Variations in the Earth's Orbit: Pacemaker of the Ice Ages, Science, v. 194, p. 1121-1132.

HERBERT, T.D., AND FISCHER, A.G., 1986, Milankovitch Climatic Origin of Mid-Cretaceous Black Shale Rhythms in Central Italy, Nature, 321, 739-743.

IMBRIE, J., 1985, A Theoretical Framework for the Pleistocene Ice Ages, Jour. Geol. Soc., London, 142, 417- 432.

IMBRIE, J., AND IMBRIE, K., Ice Ages: Solving the Mystery, Harvard Univ. Press, 224 pp.

MILANKOVITCH, M., 1941, Kanon der Erdbestrahlung und Seine Anwendung auf das Eiszeitenproblem, Serbian Academy of Science, v. 133, 633 pp.

NAPOLEONE, G., & RIPEPE, M., 1990, Cyclic GeomagneticChanges in Mid-Cretaceous Rhythmites, Italy, Terra Nova, 1, 437-442.

NAPOLEONE, G., RIPEPE, M., ALBIANELLI, A., LANDI, S., AND POMPEO, R., 1992, Variazioni Cicliche del Campo Magnetico Terrestre ne'll Albiano Superiore della Seria Umbra, Bol. Societa Geol. Ital., in press.

OLSEN, P., 1986, A 40-million Year Lake Record of Early Mesozoic Orbital Forcing, Science, v. 234, p. 842-848.

RIPEPE, M., ROBERTS, L., AND FISCHER, A.G., 1991, ENSO and Sunspot Cycles in Eocene Oil Shales: An Image Analysis Study, in Franseen, E.K., Watney, W.L., Kendall, C. St. C., and Ross, W.C., (eds.), Sedimentary Modeling: Computer Simulations and Methods for Improved Parameter Definition, Kansas Geological Survey, in press.

ROCC GROUP, 1986, Rhythmi Bedding in Upper Cretaceous Pelagic Carbonate Sequences: Varying Sedimentary Response to Orbital Forcing, Geology, 14, 153-159.

SAVRDA, C.E., AND BOTTJER, D.J., 1989, Trace-fossil Model for Reconstructing Oxygenation Histories of Ancient Marine Bottom Waters: Application to Upper Cretaceous Niobrara Formation, Colorado, Paleogeography, Paleoclimatology, and Paleoecology, v. 74, p. 49-74.

SCHWARZACHER, W., 1947, Ueber die Sedimentaere Rhythmik des Dachsteinkalkes von Lofer, Geologische Bundesanstalt, Wien, Verhandlungen, 1947, No. 10-12, p. 175-188. SCHWARZACHER, W., 1987, Astronomically Controlled Cycles in the Lower Tertiary of Gubbio, Earth & Planet. Sci., Letters, 84, 22-26.

SCHWARZACHER, W., 1990, Milankovitch Cycles and the Measurement of Time, Terra Nova, 1, 405-408.

VAN HOUTEN, F.B., 1964, Cyclic Lacustrine Sedimentation, Upper Triassic Lockatong Formation, Central New Jersey and adjacent Pennsylvania, Kansas Geological Survey, Bulletin, v. 169, p. 497-531.
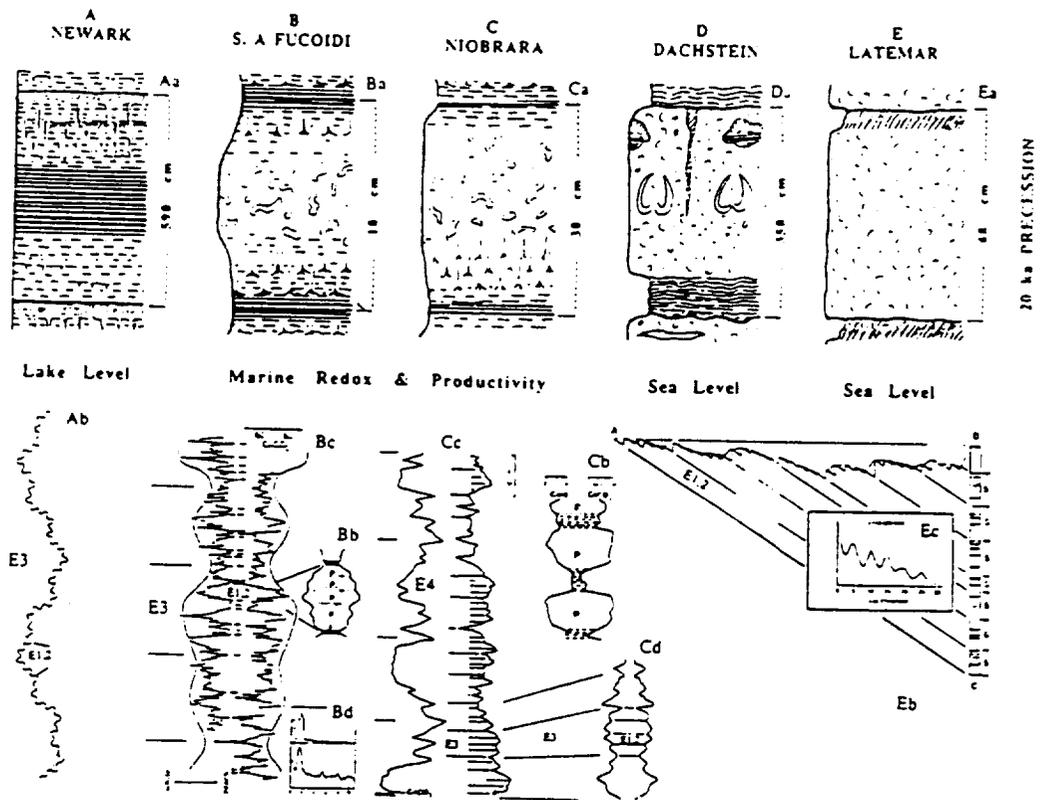
Five stratigraphic sequences showing hierarchical rhythmicity identified with orbital cycles. *Upper tier* comparison of precessional cycles. Note variations in scale. *Lower tier* eccentricity cycles. A Lacustrine facies, Triassic-Jurassic Newark Supergroup, eastern North America. Aa Precessional cycle lake-shore mudstones etc., followed by lacustrine fish-bearing shale (commonly black), succeeded by playa mudstones a lake-level cycle. Ab Eccentricity cycles. E1,2 cycle: fluctuations in carbonate and analcime content, attributed to degree of basin flushing by periodic attainment of overflow E3 cycle is a modulation in oxidation level, resulting in alternation of drab and red colors. B Pelagic, Albian Scisti a Fucoidi, Italy. Ba Precessional cycle black, more or less laminated shale (anaerobic) succeeded by Chondrites marls (dysaerobic) followed by Planolites-bearing limestone (aerobic). Cycle attributed to fluctuations in planktonic carbonate productivity linked to degree of bottom aeration. Bb An E1,2 bundle of precessional cycles expressed in calcium carbonate values (*mirror plot*) and in occurrence of black shales. Piobbico core, Bc Instrumental profiles of 8 m (1600 ka) of Piobbico core, showing darkness curve (*left*) and calcium carbonate curve (*right*). Black shales in center. High-frequency signal is that of precessional couplets; these are grouped into E1,2 bundles, and these into E3 superbundles. (After Herbert and Fischer 1986). Bd multitaper spectra of darkness curve and calcium carbonate curve, showing the E1,2 peak (Park and Herbert 1987). C Hemipelagic Coniacian-Campanian Niobrara Formation. Colorado, USA. Ca Precessional signal: shale, dark, nonbioturbated, anaerobic?, followed by Chondrites chalk (dysaerobic), succeeded by Planolites-bearing chalk (aerobic). Cb Precessional couplets defined by detailed calcium carbonate profiles and organic carbon content. Berthoud No. 1 State. (Pratt et al. 1990). Cc Entire Niobrara Formation, Berthoud No. 1 State. *Left* calcium carbonate curve, general; *right* gamma ray log. Precessional cycles not resolved. E1,2 cycles, at lower limit of resolution, are grouped into E3 superbundles in sets of 4, and these into a yet longer cycle which may represent E4 or a still longer (1600 ka) cycle. (After Pratt et al. 1990). Cd Fort Hays Member. Adobe Oil & Gas Co. Johnson Taylor 11-22, mirror plot of resistivity laterolog. Precessional cycles not resolved. E1,2 cycles grouped into E3 "superbundles". (After Laferriere et al. 1987). D Platform facies, Late Triassic Dachstein Limestone, Northern Alps. Precessional signal: massive neritic limestone containing large clams etc. alternates with peritidal algal laminites. Evidence that a eustatic oscillation commonly led to full emergence of platform is furnished by occasional presence of relic soils (clayey red to greenmudstones) and common mudstone-filled

1.6 Ma

60 – 80
CaCO₃

0

c.
b
a
d
c
IV
b
a
d
1.0
c
III
b
a
d
c
II
b
a
d
c

2

5
4
3
2
1

C

4

6

E1,2   D

E1,2   E

8 m

white ←→ black

A   B

0 2 4 6 8 10

0
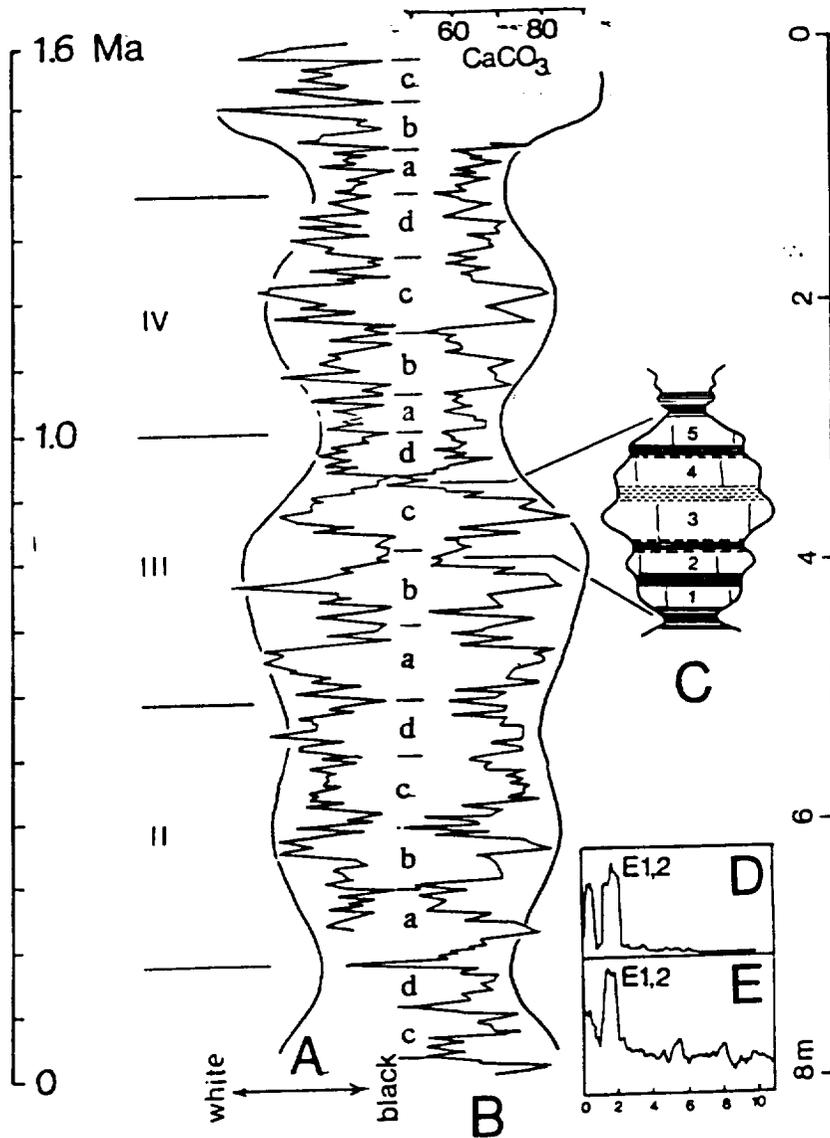
Fig. 2--Quantitative expression of hierarchical Milankovitch cyclicity patterns in the pelagic Mid-Cretaceous (Scisti a Fucoidi) of Italy (Fig. 1). Left curve: variations of gray-scale darkness, by microdensitometry of diapositives; right curve: calcium-carbonate values. High-frequency dark-light (low-carbonate/high-carbonate) bedding couplets (a,b,c,d,e) represent the precessional cycle (productivity and redox cycles combined). A baseline variation in carbonate content (and thickness of carbonate beds) groups these couplets into sets of ca. 5, representing the ca. 100-ka eccentricity cycles (1,2,3,4). The enveloping trace shows the grouping of bundles into sets of 4, representing the ca. 400-ka eccentricity cycle (A,B,C,...). From Fischer et al., 1991.
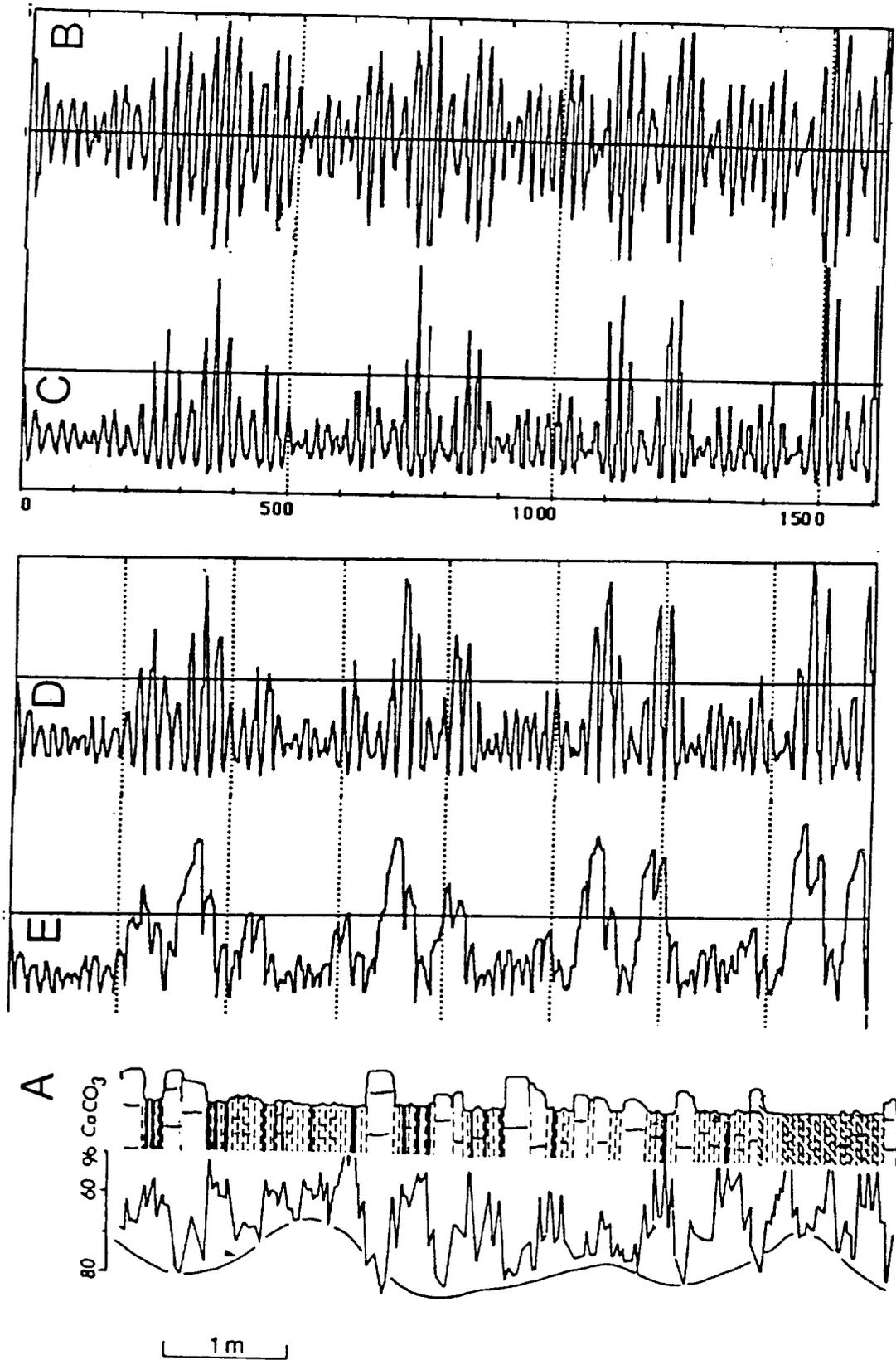
Fig. 3
(A), calcium carbonate profile in m 9-16 of Cretaceous
    Piobbico core, compared to outcrop expression at Erma,
    800 m distant. Time represented ca. 1,400 ka.
(B-E), successive steps in computer simulation of 1,600 ka:
(B), precession index calculated for 1450 ka BP- 150 ka AP.
(C), biogenic rock accumulation rate, obtained by varying

skeletal production as a logistic function of B.
D), curve C converted to stratigraphy by converting time-axis
    to stratigraphic thickness according to accumulation rate.
(E), burrow-mixing to depths varying from 0 to 12 cm as a
    logistic function of B.
    For Fourier spectra, see Fig. 4.
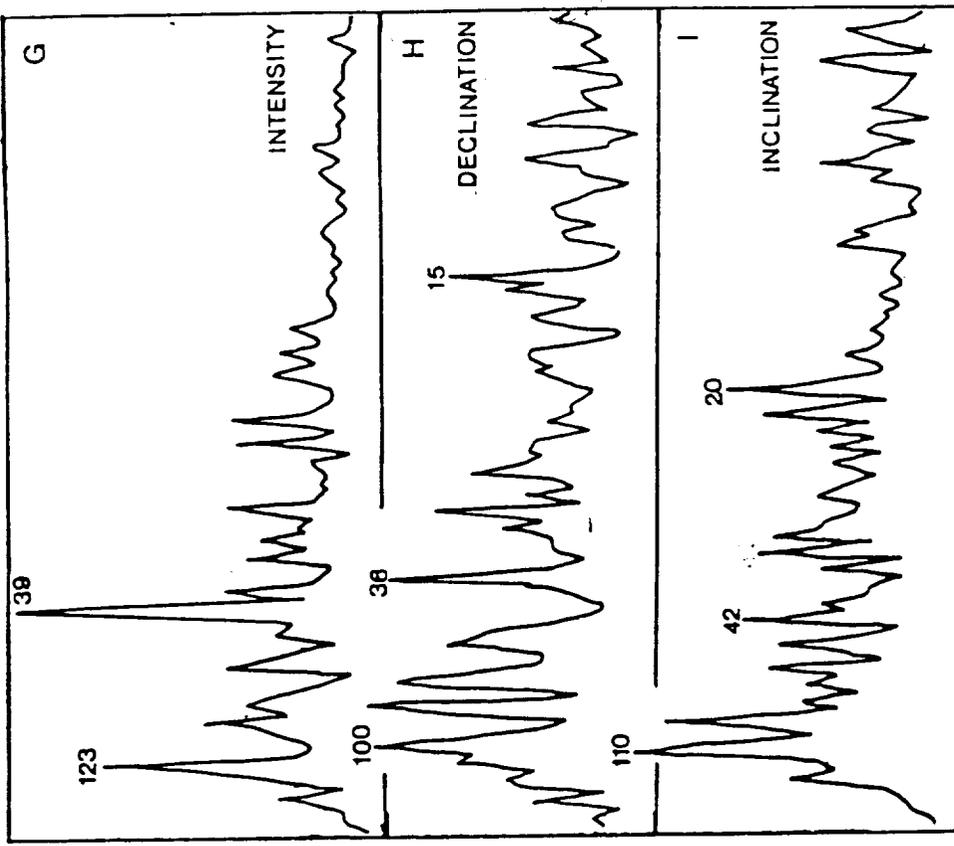
Fig. 4.- Fourier (FFT) spectra. (A), precession index (Fig. 3 B);
(B), first step in simulation (Fig. 3C); (C), second step in
simulation (Fig. 3D);
(D), Synthetic stratigraphy (Fig. 3 E);
(E), actual sequence in Piobbico core (calcium carbonate, Fig. 3A).
(F), spectrum of foraminiferal abundance. Piobbico core
m 10.3-14.2.
(G)-(I) magnetic parameters, core m 10.4-12.7, sample spacing
2.5 cm, demagnetized at 200 °C. From various sources.
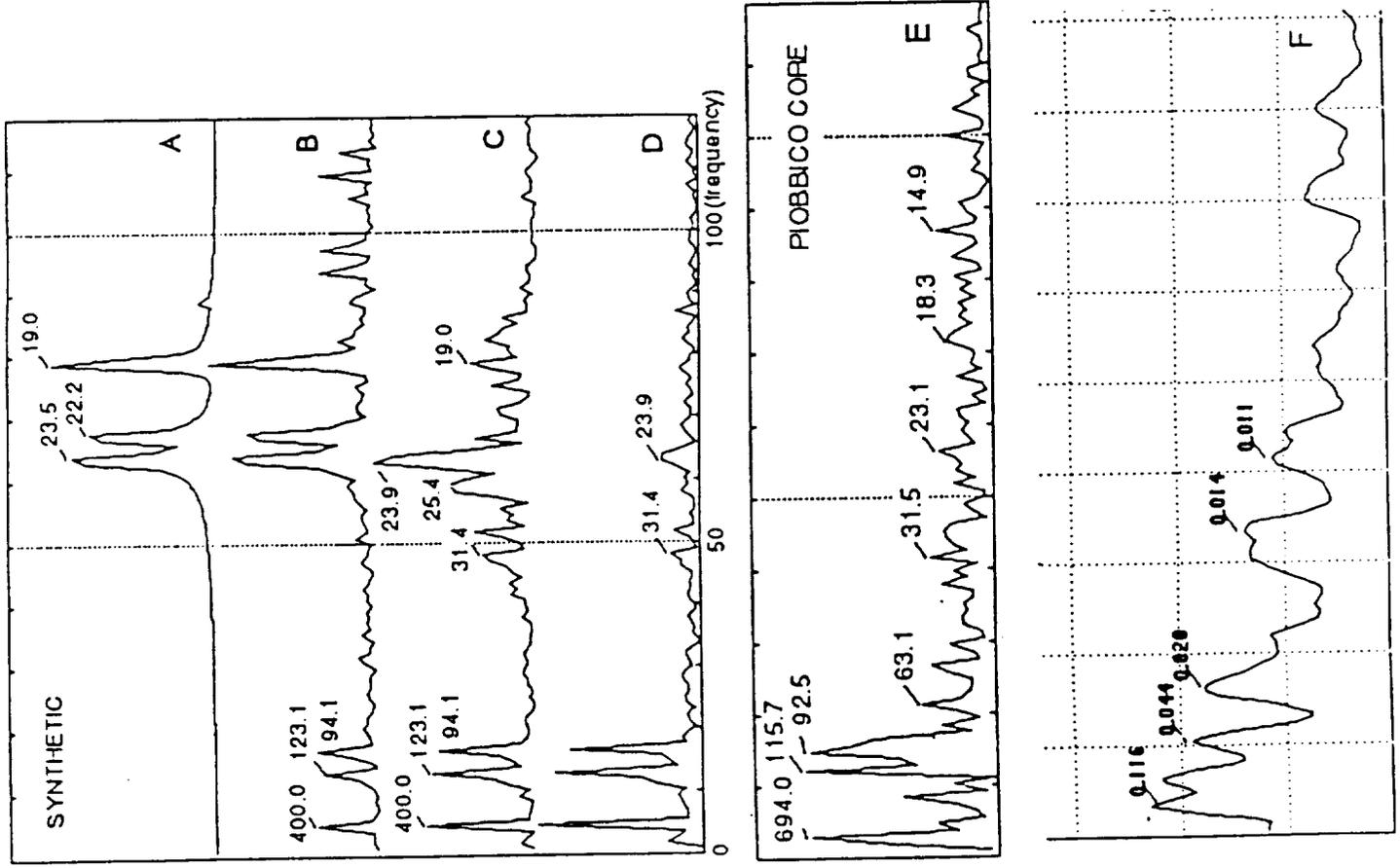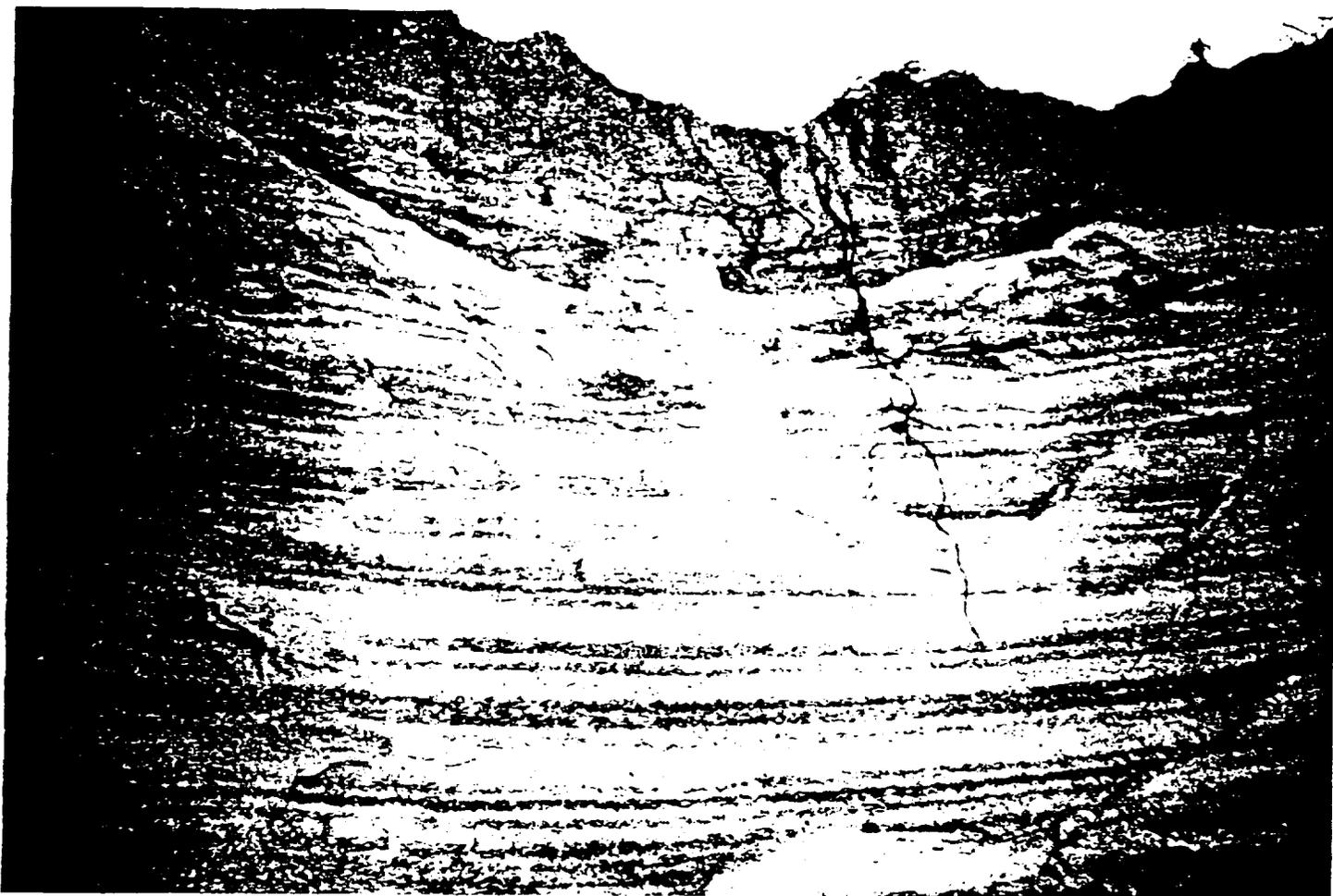
Fig. 5--Pelagic chalk-marl sequence in Eocene of Angola. This is the most dramatic visual stratigraphic record of Milankovitch cyclicity known to me, but has yet to be studied. By analogy with the Scisti a Fucoidi cycles (Figs. 1, 2 and 3), I would interpret the high-frequency chalk-marl bedding couplets as alternations of (a) calcareous plankton blooms combined with bottom aeration, and (b) reduction of carbonate productivity combined with bottom stagnation. This appears to be a record of the precession. They are bundled in sets of ca. 5 into what would have to be the ca. 100-ka eccentricity cycle. The number of bundles in the 20-km strip of coastal cliffs is estimated at ca. 100, which implies a 10-million-year record of Milankovitch cyclicity. Study is being planned.