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CONCEPTS AND METHODS OF HIGH-RESOLUTION EVENT STRATIGRAPHY

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INTRODUCTION

Modern geological analyses involving sedimentary rocks require a high-resolution system of dating, integrating, and correlating diverse stratigraphic, geochemical, and paleontological data that also takes into account the possibility that short-term phenomena (100 kyr or less) exercise a strong control on sedimentation. Such phenomena may be extraterrestrial, tectonic, volcanic, oceanographic, climatic, sedimentologic, and/or biologic in origin. Some reflect unpredictable perturbations of local to global scale. But most short-term phenomena are predictable and may be either autocyclic (locally regulated, with limited stratigraphic continuity) or allocyclic in nature (regionally to globally regulated, with extensive stratigraphic continuity) (Beerbower 1964). A stratigraphic system based on short-term phenomena would ideally be chronostratigraphic, involving the identification and regional tracing of "time lines" (isochronous surfaces or very thin event deposits), and easily integrated with refined, independently derived biostratigraphic and geochronologic systems.

An intensive search for such a new and revolutionary system of stratigraphy has been prompted in many parts of the Phanerozoic by attainment of "plateaus" in stratigraphic resolution utilizing the more standard tools of magnetostratigraphy, biostratigraphy, and geochronology: Most magnetic reversals have been identified; biostratigraphic systems can be no more refined than the maximum evolutionary rates of component taxa and their major structures (known for many favored groups); and geochronology is regulated by the analytical confidence limits of radiometric

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or other dating techniques. For the Cretaceous of North America, as an example, magnetostratigraphy is only useful for detailed correlation within the Berriasian-Hauterivian and Maastrichtian stages because of the long middle and early Late Cretaceous quiet interval. Average durations of Cretaceous intervals bounded by magnetostratigraphic "surfaces" are 1.6 Myr. The interval of polarity reversal in magnetostratigraphy is estimated at 4–5 kyr (Tarling 1983), but such reversal intervals are too widely spaced in the Cretaceous to be consistently useful in high-resolution correlation. Similarly, even with $^{39}Ar/^{40}Ar$ dating techniques, geochronology cannot consistently resolve Cretaceous ash or igneous rock dates to any higher resolution than 0.5 Myr; such dates can only be obtained from rocks that are relatively scattered through the stratigraphic column. Finally, biostratigraphic zonation in the Cretaceous of the Western Interior Basin of North America, whether utilizing ammonites (e.g. Cobban 1951, 1958, 1969, 1971, 1984, 1985), inoceramid bivalves (Kauffman 1975, 1976), or composite assemblage biozones (Kauffman 1970), has reached a limit of resolution of 0.1–0.5 Myr per biozone, depending upon the stage analyzed (Kauffman 1970, 1977).

As stratigraphic observation in field and subsurface data (aided by new logging techniques) has recently become more detailed and comprehensive, many stratigraphers have recognized that short-term to isochronous event deposits of millimeter to meter scale are far more common than predicted by prevalent uniformitarian philosophy in geology, based on today's highly variable, environmentally resilient, glacially influenced Earth that favors autocyclically dominated sedimentary systems. In fine-grained basinal facies, short-term event deposits may in fact dominate the stratigraphic record; most of them reflect widespread allocyclic forcing mechanisms such as rapid regional tectonic movements, tsunamis, explosive volcanism, extraterrestrial impact, rapid shifts in ocean currents and stratification, giant and prolonged storm events, influence of short-term climate cycles, major climate perturbations, and, among the global biota, mass extinctions and regional short-term evolutionary, migration, productivity, colonization, or mass mortality events. Many of these phenomena are regarded as "geologically instantaneous" in terms of their stratigraphic expression, i.e. they represent anywhere from a few hours to 100 kyr in time; they are essentially isochronous or near-isochronous deposits and, as such, comprise a working chronostratigraphy based on real data.

In the last few years, stratigraphic geologists and paleobiologists have become increasingly interested in the use of regionally distributed, short-term sedimentary "event deposits" as a new tool of refined regional and global correlation to supplement existing systems. The publication of *Cyclic and Event Stratification* (Einsele & Seilacher 1982) provided an important compendium of stratigraphic models for diverse event deposits. Widespread application of these data to development of a practical system of chronostratigraphy for sedimentary basins around the world is an important revolution in stratigraphic geology—termed *high-resolution event stratigraphy* (*HIRES*). In principle, HIRES proceeds where other systems of stratigraphy leave off in refinement, at the 100 kyr and less level of resolution and regional correlation. This concept, coupled with the recognition that many of the dynamic forces shaping basin history in marine systems operate primarily on a short-time basis, gives credence to attempts to develop a high-resolution event chronostratigraphy within and between sedimentary basins.

High-resolution event stratigraphy is rapidly evolving as the working tool of chronostratigraphy (North American Commission on Stratigraphic Nomenclature 1983). Its primary purpose is to provide an independent means of regional and interregional correlation based on isochronous to near-isochronous surfaces/strata. Proponents of HIRES predict that, given enough data, correlation based on such surfaces/strata can be consistently resolved to 100 kyr or less intervals of time. This has already been achieved in middle and Late Cretaceous sequences of the Western Interior Basin of North America, where over 1300 volcanic ash (bentonite) beds, hundreds of climate cycle beds, and many other event units allow division of the marine record into 40–50-kyr-long (average) event units (Kauffman 1986a, 1987, Kauffman et al 1987).

The evolution of HIRES as a concept and as a working tool of stratigraphy has been hindered by two historical factors: (*a*) The strict application of uniformitarian philosophy to the interpretation of geological processes and their stratigraphic reflection; and (*b*) the broadly held view, based on application of the modern Earth as a model for the geological past, that localized autocyclic processes dominate in the development of the stratigraphic record. Both concepts argue against an important role for regional to global unpredictable short-term events (perturbations) and the effects of predictable allocyclic forcing mechanisms (e.g. through eustatic sea-level changes, climate cycles, major impacting events, etc) in shaping the stratigraphic record. Uniformitarian concepts predict a stratigraphic record dominated by strata with restricted geographic extent, and thus limited correlation potential; this is the antithesis of HIRES, which depends largely upon allocyclically influenced sedimentation and major environmental perturbations to produce individual cyclic or event strata with significant regional extent. The key question to both uniformitarian and autocyclic arguments is whether or not the present is really the key to the past, or is it the other way around?

The uniformitarian concept of autocyclic dominance on sedimentation may in part be defensible from observation of the modern Earth, with its highly exaggerated diversity and resiliency of environments, high seasonality, comparatively low sea level, cool temperatures, and steep climatic and environmental gradients associated with extensive ice-bound poles. But today's pattern of environments and sedimentation does not make a good model for the 90% or more of geologic time that probably lacked permanent polar ice sheets. The great majority of geological history was characterized instead by significantly higher sea level (Vail et al 1977, Haq et al 1987), essentially ice-free polar areas, an absence of cold climatic zones, lower seasonality, and warmer, more equable, maritime-dominated global climates. Marine systems would have predictably been less variable in terms of temperature, chemistry, and circulation and more intensely stratified, with more sluggish circulation and lower dissolved oxygen levels than those systems of today. Such environments would result in broad expansion, equalization, and stabilization of global depositional environments and thus in more delicately balanced environmental and biological systems, especially in the marine realm. This, in turn, would diminish autocyclic effects on sedimentation.

Because of the less variable, more delicately balanced aspect of many environmental systems during most of geologic time, even moderate-level regional to global perturbations and allocyclic processes (related to, for example, rapid tectonic movements; explosive volcanism; monsoonal storm events; Milankovitch and other climate cycles; abrupt changes in sea level, ocean chemistry, circulation, or stratification; and diverse extraterrestrial phenomena) should have had a much enhanced and more obvious effect on sedimentation during these periods. This is especially true for shallow coastal and epicontinental seas. The net effect of "normal" Precambrian-Phanerozoic environmental conditions would therefore be to favor dominance of allocyclic, short-term sedimentary processes with regional extent over more localized, autocyclic processes. This, in turn, should enhance the possibility of developing high-resolution event-chronostratigraphic systems for much of the stratigraphic column.

Tests of this hypothesis, and of the feasibility of HIRES, have been made for the Cretaceous in the Western Interior Basin of North America, the site of one of the largest and most-studied epicontinental seas of the Phanerozoic [see Kauffman (1984b, 1985a, 1986a, 1987) and papers in Pratt et al (1985) and in Kauffman et al (1987)]. Examples are drawn from these works throughout this paper. In this Cretaceous setting, reflecting significantly higher sea level, warmer and more ameliorated, global, maritime-dominated climates, and ice-free polar areas, I estimate that between 75 and 80% of the bedding features in basinal settings, and up to 50% in nearshore settings, reflect short-term perturbations and allocyclic sedimentation processes. These event deposits are dominated by bentonites (volcanic ash falls), Milankovitch climatic cycle deposits (limestone-shale, chalk-marl, etc, bedding rhythms), anoxic to dysaerobic event deposits (dark, laminated organic-carbon-rich shales), concretion horizons, sediment bypass or starvation (lag) surfaces, regional giant storm deposits, and many other event strata. Event-bounded intervals average between 40–50 kyr for much of the section and have regional correlation of hundreds to thousands of square kilometers.

HIRES not only involves an understanding of the major differences between more equable, sensitive ancient environments and the more variable, resilient modern global environments (favoring allocyclic versus autocyclic controls on sedimentation, respectively), but also focuses on a different stratigraphic philosophy. This philosophy recognizes that the past is the key to the present, and that warm, stable, global environmental systems associated with eustatic highstand are much more typical of Earth history than are extensive glacial intervals ("ice ages"), including the present. Widespread, short-term dynamic changes in regional and global systems are more predictable during equable environmental periods. Thus event-stratigraphic units, from large eustatic cyclothems to millimeter-size volcanic, chemical, oceanographic, or biologic event strata, should characterize and even dominate ancient stratigraphic systems. This, in turn, dictates that observational resolution and data-collecting methods in the field should be far more detailed than in normal stratigraphic analyses, and it fosters a philosophy of collecting data—the expectation that one will commonly find regionally extensive, short-term event deposits in a stratigraphic sequence—that enhances development and application of high-resolution event stratigraphy to geological problem solving.

METHODOLOGY

Regional short-term event deposits are characteristically thin (a meter or less and commonly measured in centimeters or millimeters). This reflects both the short-term nature of the event and its sedimentary response and also the sedimentation rates characteristic of fine-grained shelf and basinal facies (0.5–4 cm kyr^{-1} before compaction), which dominate many parts of the Phanerozoic record. Consequently, high-resolution event stratigraphy depends upon observation and collection of key data at the centimeter-or-less scale in even the thickest stratigraphic sequences. It is at times a tedious process, but the rewards of discovery in terms of stratigraphic and paleobiologic phenomena, and the resolution achieved through this process in correlation, are well worth the efforts. To date, research designed to test high-resolution event stratigraphy has been mainly focused on

Mesozoic strata and linked to studies of mass extinction, climatic cycles, and eustatically influenced cyclothems or sequences (Haq et al 1987). In each case, HIRES analysis of numerous stratigraphic sections, cores, and logs within a sedimentary basin has led to definition of abundant, regionally correlative chronostratigraphic units of short (less than 100 kyr) duration.

At each section studied for HIRES data, the entire interval is trenched, with trenches up to a meter wide and as deep as necessary to consistently encounter fresh rock. A precisely machined, centimeter-scale version of the Jacob's staff with a sliding housing for a Brunton compass (the Elder staff, designed by W. P. Elder of the University of Colorado) is used to develop a 1-m flagged grid throughout the stratigraphic section; these flags serve as calibration points for high-resolution stratigraphic description of smaller units. The stratigraphic section is normally measured and described by two or more scientists to provide observational checks and balances. Each is responsible for collecting different data and samples, and ideally a physical stratigrapher, a paleontologist, and a sedimentary geochemist of sedimentologist work the sections simultaneously. Observations are made at the finest scale possible, but certainly at least at the centimeter scale (the average thickness of most bentonites). Individual stratigraphic units described and sampled during HIRES analysis may be as small as a few millimeters, or, if sedimentation has been monotonous and uninterrupted by events over a long interval, as large as several meters. There is no differentiation in technique made between basinal fine-grained rocks and basin margin shoreface and foreshore/delta or strand-plain facies; the latter naturally yield thicker individual descriptive units.

In each measured section, in addition to detailed lithologic description of major units, all potential event-stratigraphic units/surfaces are noted, sampled, and described in great detail. Each surface or unit so documented is regarded as a hypothetical isochronous to short-term event deposit to be tested through correlation (standard or graphic techniques) to numerous other sections. These potential event units fall into three basic categories, as diagramatically shown in Figure 1 within the context of a typical upward-fining transgressive hemicyclothem reflecting eustatic rise (modeled after the Cretaceous Greenhorn Cyclothem of Colorado; see papers in Pratt et al 1985).

Physcial event units (*PE*) include volcanic ash and bentonite deposits (the most trusted event units in concept and practice), volcanic flows and tuffs, regional channelization and scour events, giant storm beds, mass flow deposits, regional sediment bypass/starvation surfaces, rapidly formed transgressive disconformity surfaces (diachronous but regionally short term in many cases), and levels of meteorite impact debris; still to be tested are wind-blown silt deposits and synorogenic deposits (initial surface of deposition) resulting from rapid tectonic movement.

Chemical event units (*CE*) are determined from 10-cm to 1-m spot or channel sampling and analysis of such chemical components as C_{org}, C_{carb}, ^{18}O, and ^{13}C, and, less commonly, Sr and S isotopes, rare elements, and noble metals. Two kinds of chemostratigraphic events emerge from these analyses (see Figure 1, left side): (*a*) regionally correlative short-term excursions, or "spikes," of unusual magnitude in the chemical data [e.g. Pratt's (1985) correlation of the global ^{13}C and regional ^{18}O and C_{org} excursions across the Cenomanian-Turonian mass extinction boundary interval in the Western Interior Basin of North America]; and (*b*) bounding surfaces of longer, geochemically abnormal intervals (for example, anoxic or dysaerobic events that represent rapid regional stratification and destratification of the marine water column). Also included in chemostratigraphic events are chemical precipitate layers, primary chert layers resulting from the formation of silica gels on the seafloor, and similar deposits. I include under chemostratigraphic events various types of concretions and nodules formed early in diagenesis along specific isochronous or near-isochronous horizons, probably reflecting some unusual primary chemical or mineralogical character of specific buried sediment layers. In examples from the Cretaceous of the Western Interior Basin of North America, limestone and limestone-siderite concretion zones especially show remarkable parallelism to discrete bentonite beds when traced laterally. Septarian limestone concretions and siderite/limonite nodule zones are equally good in some cases.

Biological event units (*BE*) are deposits representing ecological, evolutionary, and extinction events, and are commonly discrete from biostratigraphic zones or zone boundaries. Thus, they may be represented by punctuated evolutionary events, by mass mortality surfaces resulting, for example, from rapid onset or overturn of anoxic watermasses, or by large volcanic ash falls. They may represent discrete steps in mass extinction (e.g. Elder & Kirkland 1986, Kauffman 1986a), rapid regional dispersal and colonization events reflecting oxygenation of a stagnant seafloor after a long interval of anoxia, and/or rapid changes in substrate characteristics. Immigration or emigration events associated with rapid watermass movements (Kauffman 1984b), population bursts, and productivity events producing a unique sedimentary deposit (e.g. a foraminiferal ooze) also comprise the kinds of data applied to bioevent stratigraphy (Kauffman 1986a).

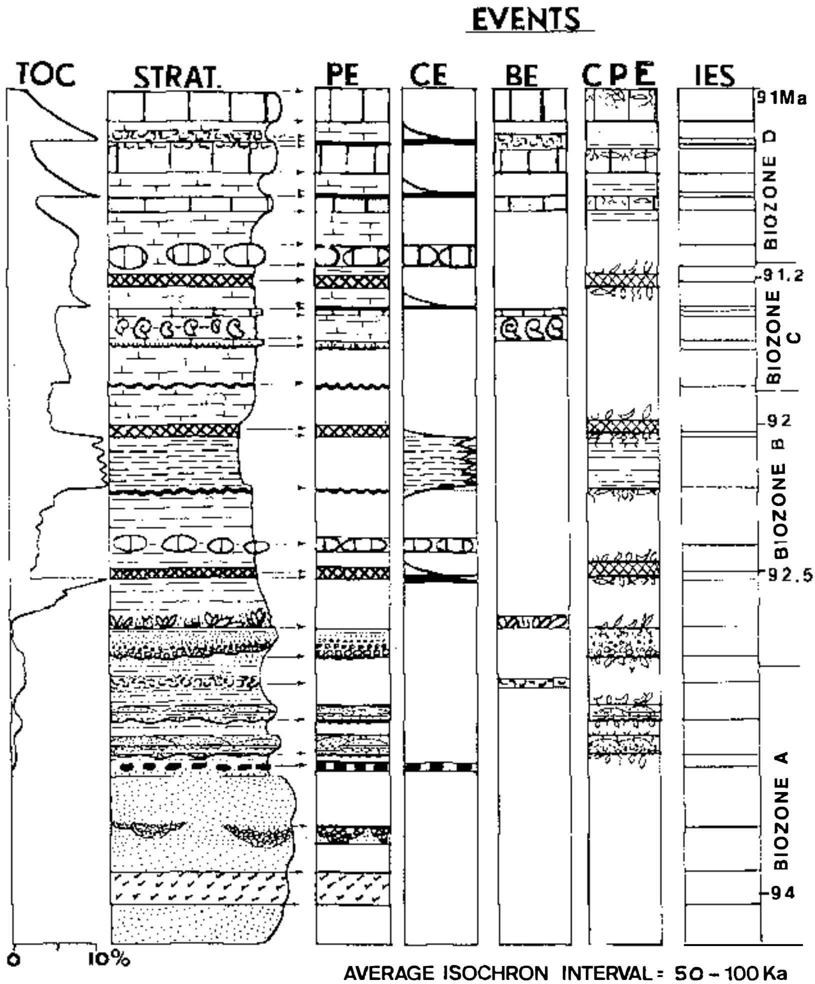
Not all event-stratigraphic units/surfaces fall directly into one of these three categories; some are clearly *composite event units* (*CPE*) combining physical, chemical, and/or biological event characteristics in their definition. Simple examples (Figure 4*A*) would be a major volcanic ash fall (physical event) that had a unique elemental composition or chemical effect on sediments and/or watermasses (chemical event), and that caused both a mass mortality below it (by suffocation) and a unique sediment surface for colonization above it due to a change in dominant grain size or the sealing off of toxic pore-water seepage at the sediment-water interface; either of these changes would produce widely traceable bioevents.

The most important composite event units (e.g. in the Cretaceous of the Western Interior Basin of North America), second only to volcanic ashes or bentonites in regional event correlation, are Milankovitch or similar climate cycle deposits (Figure 15). These bedding rhythms represent alternating dry (possibly warmer) and wet (possibly cooler) climates produced by variation in orbital parameters of the Earth-Sun system (Barron et al 1985, Fischer et al 1985, and references therein). Average Phanerozoic durations of these cycles and the sedimentary deposits influenced by them are calculated to be 20–25 kyr (variation in orbital eccentricity/precession), 40–50 kyr (variation in axial obliquity of the Earth), and 100–125 kyr ["bundles" of Fischer et al (1985), reflecting orbital eccentricity]. Fischer et al (1985) provide the most comprehensive assessment of the potential stratigraphic record of these allocycles and their sedimentary response. Barron et al (1985) present a detailed case history supporting climatic forcing of limestone-shale (or chalk-marl) cycles of sedimentation in the Cretaceous Greenhorn Formation of the Western Interior Basin; Kauffman (1986a) developed sedimentary models for the effects of Milankovitch

Figure 1 Schematic model for components and methods of high-resolution event stratigraphy (HIRES), plotted against an upward-fining transgressive (eustatic rise) stratigraphic sequence. Physical (PE), chemical (CE), biological (BE), and composite events (CPE) determined from centimeter-scale description of a stratigraphic column are composited to right into an integrated event stratigraphy (IES) with an average HIRES interval of 50–100 kyr at present. Key (left to right): TOC, total organic carbon (in weight percent) curve; STRAT, stratigraphic column; PE, physical events such as (down-column) Milankovitch climate cycle and/or productivity event limestones, volcanic ash or bentonite deposits (dark bands and X's), early diagenetic concretion zones, storm beds (thin sandstones), regional bypass surfaces or disconformities of short duration (wavy lines), mass flow deposits (graded beds), ferruginous and phosphatic nodule horizons (dark spheres), channelization events, paleosols, and volcanic flows; CE, chemical events from isotopic, carbon, and elemental analyses; BE, biological events such as mass mortalities, immigration and emigration events, colonization and productivity events, and mass extinctions; CPE, composite events such as Milankovitch climate cycle beds, ash falls (mass mortality, recolonization, physical and chemical events), storm beds (mass mortality, recolonization, physical events); IES, integrated event stratigraphy for each column and collectively for many columns in a basin as correlated by graphic techniques. IES can be integrated with both geochronologic and biostratigraphic data, as diagramatically shown on right. Based on actual data from papers in Pratt et al (1985).

climate cyclicity in various facies of an epicontinental seaway, using the Cretaceous of the Western Interior Basin of North America as an example.

Application of climate cycles to HIRES is based on the concept that broad regional climate changes producing alternating wet and dry intervals are amplified by delicately balanced Phanerozoic ocean-climate systems, especially during warm, equable eustatic highstand intervals. Such intervals are further characterized by increased potential for widespread giant



MODEL FOR HIGH RESOLUTION EVENT STRATIGRAPHY

storm or monsoon events. This exaggerated climate cyclicity should have had a profound effect on weathering, transport, and depositional rates of marine and terrestrial sediments derived from surrounding landmasses; on salinity in the surface waters of epicontinental seas (and thus stratification of watermasses and oxygen content of deeper benthic waters); on turbidity levels; and on the kind and level of biotic productivity in the photic part of the water column. Collectively, these factors should simultaneously affect sedimentation patterns in all facies, from marginal marine and shoreface to deep basinal settings (Figure 15*A*). This hypothesis has been successfully tested in a basin-to-margin transect of middle Cretaceous strata in the Western Interior Basin of North America (Elder, Gustason & Sageman, in Kauffman et al 1987), in which several individual ± 100 kyr Milankovitch climate cycles were traced relative to specific marker bentonites and biostratigraphic zone boundaries from limestone (dry)–calcareous shale (wet) bedding rhythms in the center of the basin, into marine shale (dry)–sandstone (wet) progradational units at the basin's western margin.

Detailed field documentation of short-term event deposits must be supplemented by laboratory analyses to reveal data on such things as small-scale sedimentologic and chemostratigraphic changes, impact events, and many biological event units/surfaces. This further requires a rigorous sampling program. Normally, bulk samples are taken either continuously or at very closely spaced intervals for laboratory analysis in each section. This is regulated by sedimentation rate and the nature of the events under study. Typically, 10–20 cm channel samples for micropaleontological and chemical analyses are taken at 0.5-m average intervals; $10–20 \times 50$-cm-thick block (bulk) samples are taken for macropaleontologic and sedimentary analyses, either continuously or at 50-cm intervals; and all unusual facies are sampled in great detail, as are any ash beds or bentonites that appear to be thick enough and rich enough in biotite, sanidine, and/or zircons for radiometric and fission-track dating. Subsequent laboratory analyses of these samples are added to the integrated event-stratigraphic data base initially developed in the field for each section.

For each stratigraphic sequence analyzed, high-resolution event-stratigraphic data are composited into an integrated event stratigraphy (IES; see Figure 1), and it is this composite set of chronostratigraphic surfaces and short-term event intervals that is applied to detailed correlation between sections, normally utilizing graphic correlation techniques (Edwards 1984). At present, for the Greenhorn and Niobrara eustatic cyclothems (late Albian–early Campanian) in the Cretaceous of the Western Interior Basin of North America, integrated event stratigraphy has attained levels of correlation between nearby sections averaging 40–50 kyr per event-bounded interval, and averaging 100 kyr or less for more distant correlations spanning hundreds to thousands of kilometers. The expectations for the system were exceeded in preliminary work in this basin, and this work promises higher precision of correlation in sedimentary basins elsewhere in the world and throughout the Phanerozoic. Many workers now recognize that event bedding is a common to dominant component of marine strata everywhere.

SELECTED CRETACEOUS EXAMPLES OF HIGH-RESOLUTION EVENT UNITS, WESTERN INTERIOR BASIN, NORTH AMERICA

During the middle and Late Cretaceous, the great Western Interior foreland basin of North America was broadly flooded by a shallow epicontinental sea, 1000 mi east-west and 3000 mi north-south in dimensions, connecting the cool temperate Circumboreal Ocean and its biotas to the north with an extension of the subtropical to warm temperate Caribbean Sea and Gulf of Mexico and its biotas to the south for over 36 Myr. The deposits of this epicontinental sea reflect highly diverse environmental settings (Figure 2). The tectonically active Cordilleran fold-and-thrust belt lay to the west. Eastward, the seaway covered five major tectonic belts: (*a*) a rapidly subsiding, coarse, siliciclastic-filled foredeep basin; (*b*) a north-south linear forebulge zone of active discontinuous uplifts and arches over which sediments were episodically eroded; (*c*) a broad, deep marine axial basin characterized by fine-grained shales and limestones and restricted marine circulation; (*d*) a tectonically active eastern hinge zone characterized by small, intermittently active uplifts and depressions; and (*e*) a broad, shallow eastern cratonic platform characterized by thin, disconformity-shortened sequences of fine-grained siliciclastic and carbonate rocks. Kauffman (1969, 1977, 1984b, 1985a, 1986a, and references therein) has summarized the tectonic, volcanic, sedimentary, and oceanographic history of this basin utilizing detailed studies of many workers.

The Cretaceous of the Western Interior Basin was affected, in its evolution, by episodic large-scale periods of tectonism and volcanism almost wholly correlated with intervals of eustatic rise and regional transgression, between which there were intervals of relatively low tectonic and volcanic activity associated with eustatic fall and regional regression. Major (second- and third-order) eustatic fluctuations caused large-scale changes in the size, shape, depth, and environments of the seaway every 5–10 Myr. The seaway was characteristically slightly brackish, as determined from faunal analyses, and somewhat dysaerobic during much of its history.

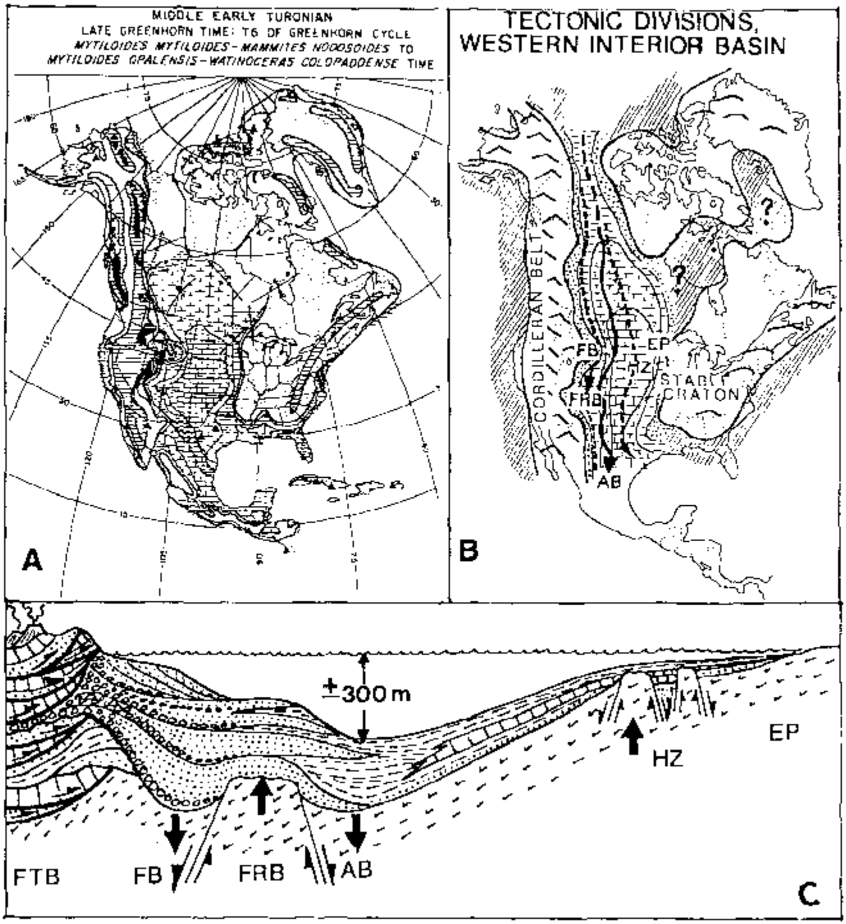


Figure 2 Distribution of facies and tectonic zones in the Cretaceous Western Interior Basin of North America (modified after Kauffman 1984b, 1985a). (*A*) Facies map of the Western Interior of North America at peak mid-lower Turonian eustatic highstand showing size and shape of seaway; HIRES techniques have been largely developed and tested in this area. (*B*) Generalized facies map during eustatic highstand showing active tectonic zones within the basin during the Cretaceous. Key to (*B*) and (*C*) as follows: FTB, Cordilleran fold-and-thrust belt; FB, foredeep basin; FRB, forebulge zone (in this basin a linear series of isolated Precambrian and Paleozoic tectonic blocks reelevated during the Cretaceous); AB, axial or central basin characterized by greatest water depths and fine-grained marine strata; HZ, hinge zone between the stable craton to the east (right) and the axial basin; EP, epicontinental or cratonic platform. Kauffman (1984b, 1986a; Figure 18 herein) has shown that most active tectonism and volcanism in these zones is correlated with eustatic rise events.

Normal marine salinity and circulation/oxygenation were achieved mainly during peak eustatic highstand intervals. Widespread dysaerobic and anaerobic events, reflecting long intervals of density stratification and sluggish basinal circulation of the seaway, were common (especially during eustatic rise and highstand intervals) and rapidly emplaced or broken down. Temperature ranged from subtropical (southern aperture) to cool temperate (northern basin), but this broad horizontal and vertical thermal gradient was frequently punctuated by rapid northward incursions of warm subtropical–warm temperate watermasses associated with mid- to peak eustatic rise, followed by rapid southern retreat of these watermasses during early eustatic fall. Kauffman (1969, 1977, 1984b, 1985a, 1986a) provides detailed analyses of the geological and oceanographic characteristics of the Western Interior Seaway during the Cretaceous.

The Western Interior Seaway of North America was thus large, persistent, environmentally diverse, open at both ends to allow mixing of watermasses, thermally equable and broadly graded. It was characterized by sluggish circulation, lower-than-normal oxygen levels, and frequent intervals of density (salinity, thermal) stratification. It was a delicately perched water body, developed during typical Phanerozoic conditions, that was highly sensitive to perturbations or cyclic environmental changes over broad areas (i.e. to allocyclic forcing of the sedimentary record within short time intervals), conditions favoring high-resolution event stratigraphy. The stratigraphic record of this seaway is probably better studied, with more precise data, than that for any similar epicontinental sea formed during the Phanerozoic. For these reasons, it has been a primary testing ground for concepts and methods of HIRES. In the following pages, examples are drawn from this region to demonstrate the nature and application of HIRES to geological problem solving.

PHYSICAL EVENTS

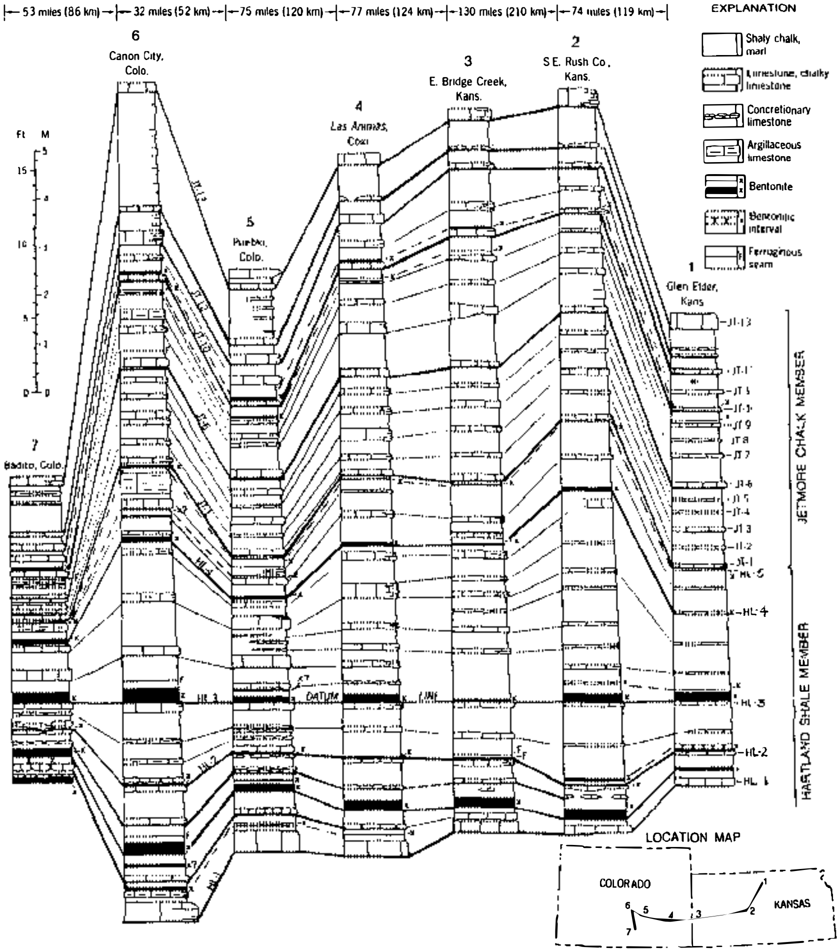
Volcanic Ash and Bentonite Deposits (Figure 4)

Explosive volcanism associated with major intervals of tectonic deformation in the Western Interior Basin was intermittently very common; bentonite forms 2–10% or more of the marine basinal sedimentary record after compaction (Kauffman 1985a; E. G. Kauffman & D. Beeson, in preparation), and 85% of all volcanic ash/bentonite deposits are associated with tectonically active intervals of basin history (Kauffman 1984b, 1985a), especially along the western Cordilleran fold-and-thrust belt. Over 750 discrete bentonite layers have been described and traced over at least 100 km in the late Albian Kiowa–Skull Creek Cyclothem, the latest Albian–

middle Turonian Greenhorn Cyclothem, and in the late Turonian–early Campanian Niobrara Cyclothem (18 Myr, average of 41.7 persistent ashes Myr^{-1}). Up to 1300 bentonites are projected for the entire Cretaceous marine section once it is studied through HIRES. This suggests a potential regional HIRES correlation interval averaging between 23.8 and 26.5 kyr based on volcanic ash events alone, the most trusted of event markers, for the Western Interior Basin. Ashes and bentonites are essentially isochronous surfaces from which a working chronostratigraphy and an initial graphic axis of real time can be best developed in correlation.

The major problem in HIRES bentonite/ash correlation is the proof of absolute equivalency of each ash from section to section. The ash record of the Cretaceous sequence of the Western Interior Basin was sourced from several places (Idaho-Montana, Arizona–New Mexico, Texas, and possibly the Pacific island arc, the Caribbean island arc, and the Sierra Nevadas). Each area probably had different chemical phases of volcanism. Therefore, sequential elemental analyses of ashes in each stratigraphic sequence would seem to be the primary means of ensuring accurate correlation. But this is an expensive, time-consuming process, and test runs are only now beginning. More normal means of regional ash correlation include unusual color and lithology as determined in the field; recognition of persistent composite ashes with multiple heavy mineral zones; the geometry of bentonite associations or bundles [i.e. persistent doublets, triplets, or larger stratigraphic bundles between which ashes are sparse (Figure 4*B*)]; the persistent occurrence of certain bentonite beds with other easily recognized event markers or with widespread biostratigraphic zone boundaries (Figure 3); and through graphic correlation (see the subsequent discussion).

Within the Western Interior Basin, an initial focus on larger, easily recognized, more regionally persistent bentonite deposits has provided an important set of event-stratigraphic units against which smaller ashes, other event units, and biostratigraphic data can be compared. Some large beds, like the X-Bentonite marker bed (Hattin 1975, Kauffman 1985b) and the Clayspur Bentonite (Knechtel & Patterson 1962) marking the lower-middle Cenomanian and the Albian-Cenomanian boundary intervals, respectively, extend over thousands of square miles within the Western Interior Basin. Most significant bentonites with thicknesses of at least 1–2 cm have distributions of at least a thousand square miles. Recent examples of high-resolution ash/bentonite correlations are those of Sageman (1985) for the Hartland Shale Member between Arizona and Kansas (680 mi), and of Elder (1985) and Hattin (1985) for the Cenomanian-Turonian boundary interval over the same transect. Figure 3 shows Hattin's (1985) data for the regional correlation of regionally persistent Cen-



HIRES CORRELATION OF BRIDGE CREEK LIMESTONE, COLORADO TO KANSAS

(MODIFIED FROM D. HATTIN, 1985)

Figure 3 Regional correlation of HIRES units (volcanic ashes/bentonites: bold dark lines and X's) (probable Milankovitch climate cycle beds, especially persistent limestone and limestone concretion units), Hartland and Jetmore members, Greenhorn Limestone, from central Colorado (left) to central Kansas (right; see index map). Figure from work of Hattin (1985; see locality details), as modified to show not only Hattin's marker horizons (HL-1–4, JT-1–13) in bold dark lines, but also probable correlations of other units over this 700+ km transect (thin lines). Average event-bounded interval is about 40 kyr. This is a typical example of the quality and refinement of HIRES correlation in the Cretaceous sequence of the Western Interior Basin of North America, using standard correlation techniques.

omanian-Turonian (Bridge Creek Limestone and equivalents) bentonites vs cyclically bedded limestone-shale bedding couplets (Milankovitch cycles; see Barron et al 1985). Average bentonite event-bounded intervals in this example, compared against the radiometric scale of Kauffman (1977; revised in 1985a, Figure 4), are about 225 kyr, and the average resolution for all event marker beds within this same interval is about 66 kyr, *before* consideration of chemostratigraphic and bioevent units. Large ashfalls may also have a prominent chemostratigraphic and bioevent signature (mass mortality and colonization surfaces), and these falls become composite event units (CPE), as shown in Figure 4*A*.

Storm Beds

Eustatic highstand and global climate amelioration during the Cretaceous and other warm, equable Phanerozoic intervals probably caused more widespread northward and southward migration, and enhancement, of tropical storm belts and monsoonal tracks (Barron & Washington 1984). Seasonally, this would have brought these storms belts over the Western Interior Basin. These factors, as well as the delicately balanced nature of Cretaceous climate/ocean systems, would have combined to enhance the size, regional extent, and sedimentary reflection of storms. Many authors have noted a strong dominance of storm-related sedimentation in Western Interior Basin shoreface and proximal offshore facies belts (Figure 5); field stratigraphers have been able to use storm beds that have not been subsequently destroyed through heavy bioturbation as event marker units across many miles of continuously exposed outcrop. The regional along- and offshore extent of these Cretaceous storm units seems to exceed the predictions based on modern hurricane deposits along the Atlantic Coast, for example. The only real test of storm units for high-resolution event correlation over significant distances, however, is the unpublished work of Glenister (1985), who used graphic correlation to show the regional time equivalency of certain middle Turonian Codell Sandstone Member storm beds (examples in Glenister & Kauffman 1985) for nearly 70 mi along the northern Colorado Front Range in lower shoreface deposits. New data are summarized in Figure 6. Figure 5 illustrates sedimentary structures of a typical Cretaceous storm bed and its effect on the biota.

Regional Bypass and Disconformity Surfaces

Many transgressive disconformities characterize the Cretaceous cyclothems of the Western Interior Basin, especially in shoreface sequences and as a result of ravinement (migrating erosional surface cut at normal wave base) processes during early transgression. Except for those formed during exceptionally rapid sea-level rise and/or regional subsidence, most of these

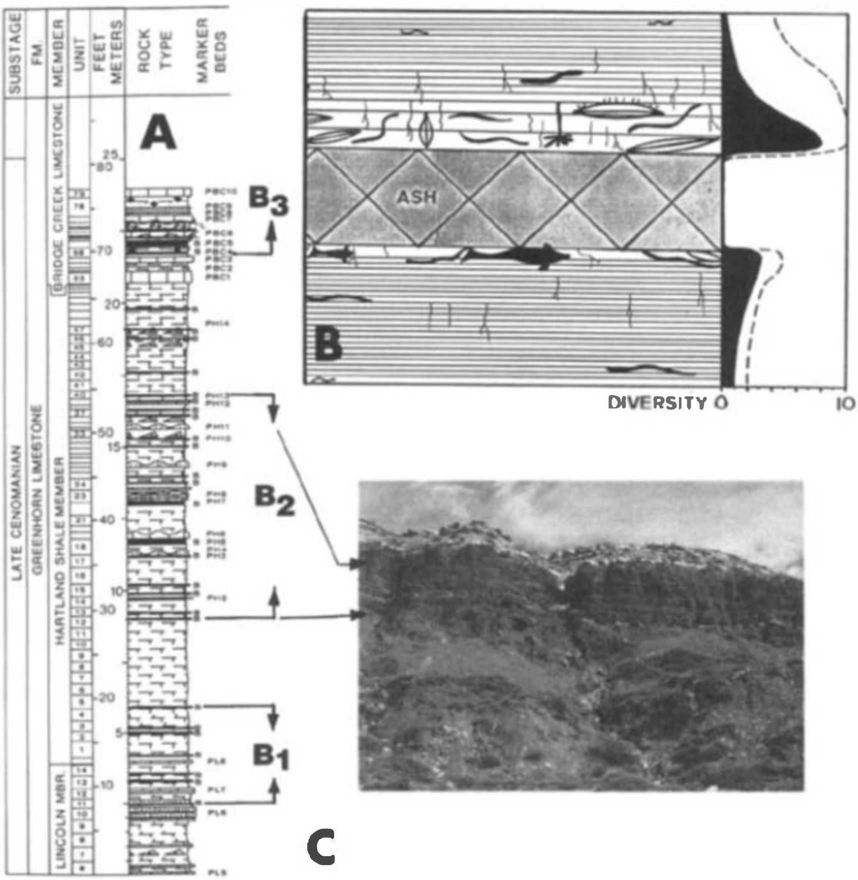


Figure 4 Volcanic ash/bentonite deposits as high-resolution event stratigraphic units in the Cretaceous of the Western Interior Basin of North America. (*A*) Stratigraphic column of the Cenomanian Lincoln, Hartland, and basal Bridge Creek Limestone members, Greenhorn Formation, at Rock Canyon Anticline west of Pueblo, Colorado (after Sageman 1985). Dark bold lines with "B" to right are bentonite deposits arranged in three major clusters, or "swarms" (B_1, B_2, B_3), reflecting intense volcanic activity, with sparser intermediate marker units. These swarms are the first level of regional HIRES correlation, followed by individual ash correlations. (*B*) Model of a single bentonite bed from (*A*) (gray, with X's) showing composite nature of this event having mass mortality bioevent at base (through suffocation), forming prominent physical and chemical event bed (the bentonite), and having regional colonization surface on top as a result of bentonite sealing off toxic interstitial pore-water seepage to sediment-water interface. Diversity reflects benthonic foraminifer species (black) and molluscs (dashed). (*C*) Photograph of (*A*) section, with prominent bentonite swarm represented by white lines across outcrop and bracketed with arrows.

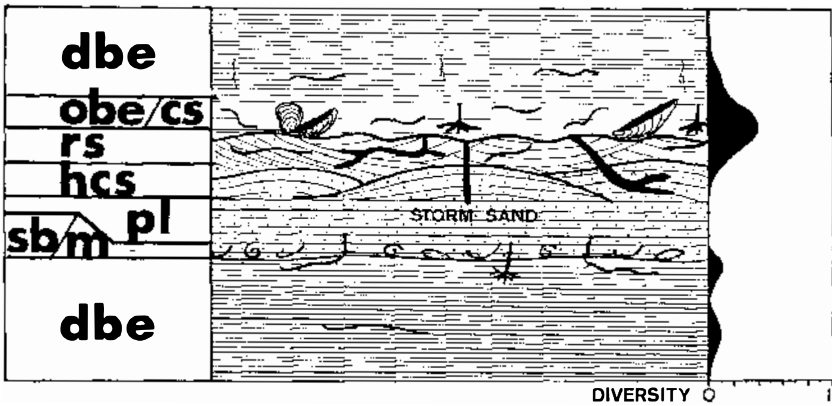


Figure 5 Model of a regional storm bed (lower shoreface expression), taken from the Codell Sandstone near Pueblo, Colorado (middle Turonian) (Kauffman, 1986a), showing the composite event nature of the bed. Note mass mortality surface among burrowing organisms and storm-transported molluscs at base, storm bed as a physical event unit, and colonization surface with increased macrofossil diversity on top (in oxygenated water) before return to laminated shales and dysaerobic benthic conditions (line pattern). Key (base to top): dbe, dysaerobic benthic environment (dark laminated shales); m, mass mortality surface at base of storm bed; sb, basal scour bed of unit; pl, planar laminated, high-flow regime beds of storm unit; hcs, hummocky cross-stratified beds; rs, ripple-laminated beds on upper surface of storm bed; obe/cs, oxygenated benthic environment with colonization surface.

disconformities are regionally diachronous and therefore not suited for high-resolution event stratigraphy. But disconformities and paraconformities that characterize offshore basinal sequences, especially those around eustatic highstands, seem to form regionally within very narrow time intervals and thus to represent bypass and condensation intervals of short duration reflecting sediment starvation. One of the best global examples of this phenomenon is the bypass/starvation/condensation surface associated with peak mid-lower Turonian eustatic highstand (*Watinoceras* and lower *Mammites nodosoides* biozones) in many parts of the world, and as seen in much of the Deep Sea Drilling Project (DSDP) data. In the Western Interior Basin, these strata are partially or completely missing over large parts of the central axial basin, and in western Europe across many somewhat elevated, older massifs. This disconformity surface lies within a 1.0 Myr interval; the diachroneity of bounding depositional surfaces is regionally very slight, probably within 100 kyr from initial tests.

Impact Event Beds

The impact of large extraterrestrial objects on continents and shallow marine shelf areas would predictably throw great quantities of dust-size

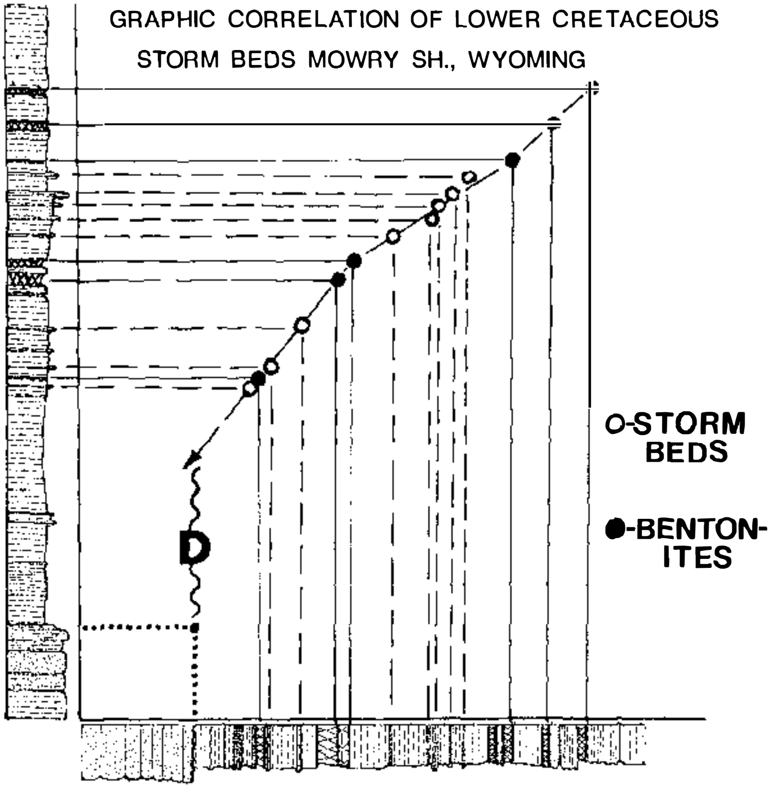
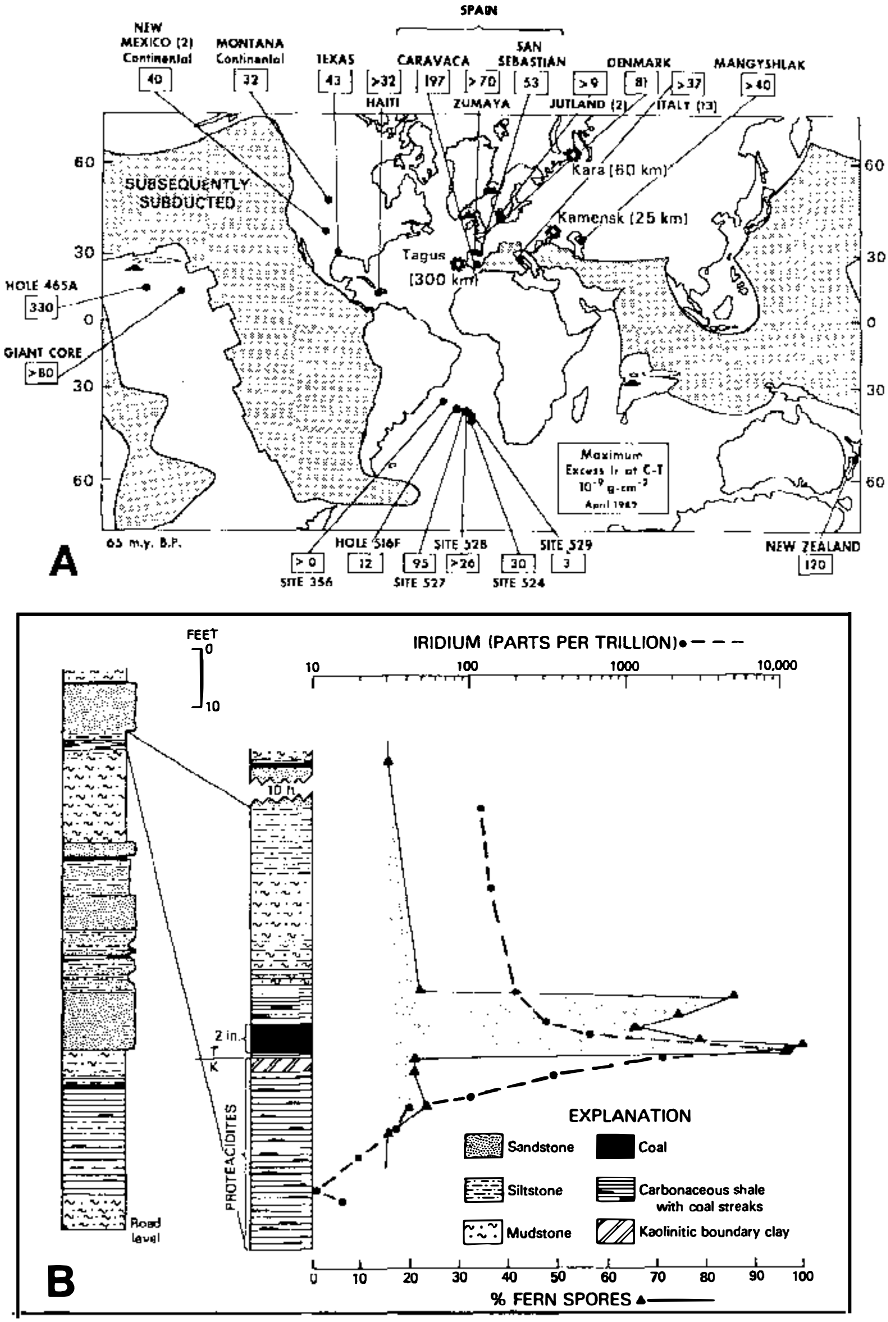


Figure 6 Storm beds as regional event correlation surfaces, as proven by graphic correlation. Graphic plot of two stratigraphic sections of the lower Shell Creek–Mowry Shale units in the western Powder River Basin (Kaycee, Arminto), Wyoming, showing line of isochron correlation drawn through intersection points of same bentonites in two sections (dark dots) and the relationship of distal toes of storm beds (open circles) to this time line between sections. Key: D, major transgressive disconformity on top of Albian Muddy Sandstone, which omits large portion of lower shale section in vertical column.

and larger impact debris into the atmosphere. This would ultimately settle out over the surface of the Earth as a thin, chemically and physically unique deposit within a few years to tens of years. Such a deposit would not only contain a unique mineral/element suite of mixed origin (bolide and target area) but also might contain shock-metamorphic mineral grains, microtekites, ash fragments, and unique concentrations of iridium and other rare elements. The Cretaceous-Tertiary boundary clay, worldwide, represents such a deposit and is the best example of a short-term impact event unit in the Phanerozoic (Alvarez et al 1980, 1984; Figure 7*A* herein).


SPAIN
NEW MEXICO (2) Continental
40
MONTANA Continental
32
TEXAS
43
>32
HAITI
CARAVACA
197
>70
ZUMAYA
SAN SEBASTIAN
53
>9
JUTLAND (2)
DENMARK
81
>37
ITALY (13)
MANGYSHLAK
>40
SUBSEQUENTLY SUBDUCTED
Kara (60 km)
Kamensk (25 km)
Tagus (300 km)
HOLE 465A
330
GIANT CORE
>80
Maximum Excess Ir at C-T 10^{-9} g-cm^{-2} April 1982
65 m.y. B.P.
>0
SITE 356
HOLE 516F
12
95
SITE 527
SITE 528
>26
30
SITE 524
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3
NEW ZEALAND
120
A
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IRIDIUM (PARTS PER TRILLION)
10
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1000
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2 in.
T
K
PROTEACIDITES
Road level
EXPLANATION
Sandstone
Coal
Siltstone
Carbonaceous shale with coal streaks
Mudstone
Kaolinitic boundary clay
0 10 20 30 40 50 60 70 80 90 100
% FERN SPORES
B

This globally distributed boundary clay is present in the San Juan Basin of New Mexico (Figure 7*B*) at numerous localities (Orth et al 1981, Bohor et al 1984) and contains the iridium-rich chemical signal, shocked quartz and feldspar grains, and chemically unique clay minerals. Recent discovery of two or more iridium peaks just below the Cenomanian-Turonian mass extinction boundary near Pueblo, Colorado (Orth et al 1987), suggests that other "impactites" may be present in the Western Interior Basin as HIRES correlation horizons.

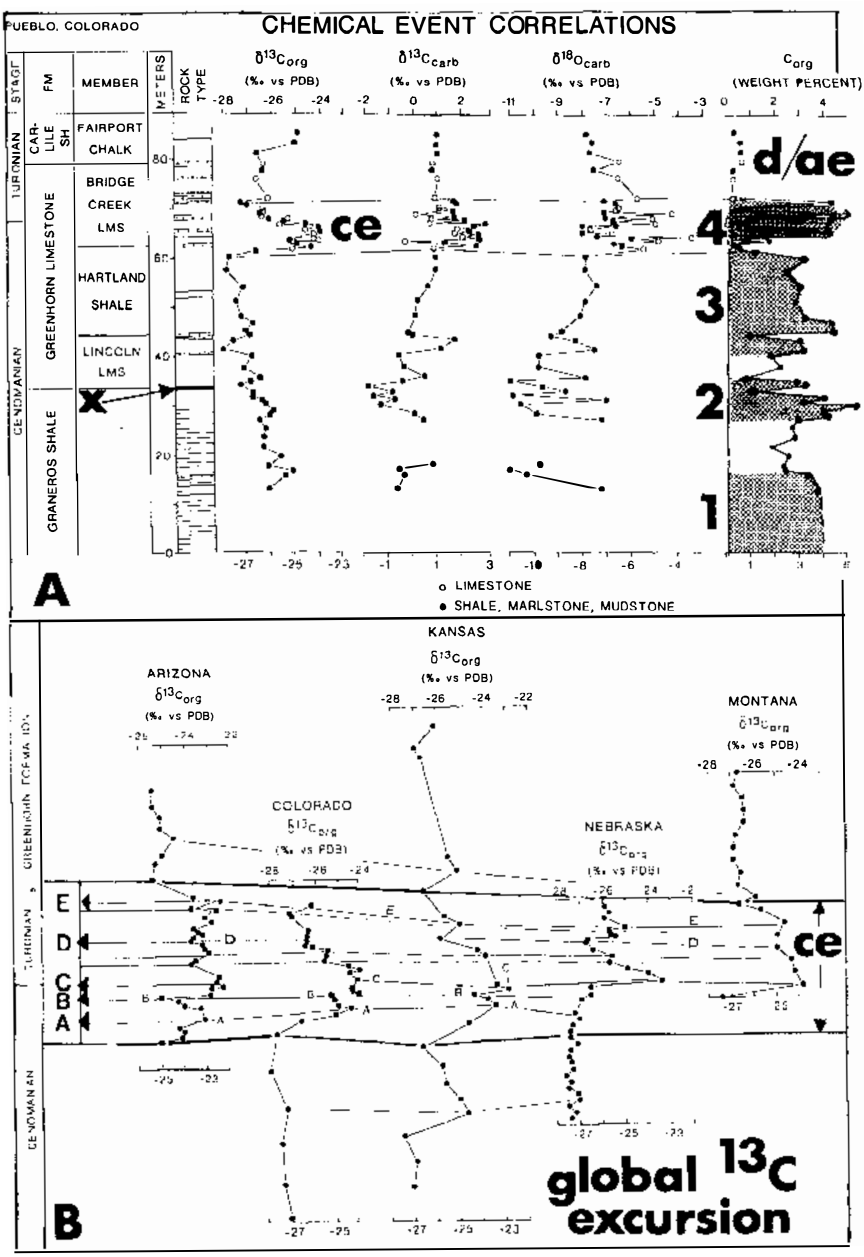
CHEMICAL EVENTS

Closely spaced analyses for organic and carbonate carbon, ^{18}O and ^{13}C isotopic values, and other elements are a normal part of high-resolution stratigraphic research. Major excursions ("spikes") of extraordinary magnitude and short duration (100 kyr or less), or longer intervals characterized by unusual geochemical values (i.e. widespread anoxic or dysaerobic events, especially their boundaries) are the tools of regional Cretaceous chemostratigraphy. The best published examples of these phenomena in the Western Interior Basin of North America are associated with the Cenomanian-Turonian boundary interval (Figure 4); Pratt (1985) has provided the most comprehensive geochemical data. Zelt (1985) has also shown that natural gamma-ray spectrometry can yield data on short-term Th/U spikes that are regionally correlative.

Light-Stable Isotope Chemostratigraphic Events

Pratt (1985) has published an excellent example of light stable isotope event chemostratigraphy in the Western Interior Basin, based on detailed analysis of ^{13}C and ^{18}O values through the latest Albian–middle Turonian Greenhorn Cyclothem. Figure 8*A* shows typical detailed chemostratigraphic data from near Pueblo, Colorado, associated with the Bonarelli global oceanic anoxic event. This major ^{13}C excursion (Figure 8*A*) is a global HIRES chemostratigraphic signal also found widely in DSDP core analyses at the same level (Pratt 1985); in North America, it is precisely correlative with regional ^{18}O and C_{org} excursions (Figure 8). Within this

Figure 7 Global event marker bed reflecting chemical and physical fallout from a large meteorite impact at the Cretaceous-Tertiary boundary. (*A*) World map showing dispersion of impact fallout debris (boundary clay) bearing iridium (values for each locality; Alvarez et al 1982). (*B*) Stratigraphic sections of the Cretaceous-Tertiary boundary (K-T) showing kaolinitic boundary clay, iridium spike, and peak in fern spores (ecological generalists and forest floor dwellers in low light situations) reflecting filtered sunlight after impact due to atmospheric dust/debris/smoke cloud (Pilmore & Flores 1987).


PUEBLO, COLORADO
CHEMICAL EVENT CORRELATIONS
STAGE
FM
MEMBER
METERS
ROCK TYPE
TURONIAN
CENOMANIAN
CARLILE SH
FAIRPORT CHALK
GREENHORN LIMESTONE
BRIDGE CREEK LMS
HARTLAND SHALE
LINCOLN LMS
GRANEROS SHALE
δ13Corg (‰ vs PDB)
δ13Ccarb (‰ vs PDB)
δ18Ocarb (‰ vs PDB)
Corg (WEIGHT PERCENT)
d/ae
ce
4
3
2
1
x
A
o LIMESTONE
• SHALE, MARLSTONE, MUDSTONE
KANSAS
ARIZONA
COLORADO
NEBRASKA
MONTANA
E
D
C
B
A
ce
global 13C excursion
B

global ^{13}C chemoevent marker, at least two regionally correlative positive spikes separated by a short negative excursion (Figure 8*B*) can be defined across the Western Interior Basin. A smaller pair of negative and positive excursions just below and above the Graneros Shale–Lincoln Limestone boundary may be regionally important but remain to be tested. The smaller-scale excursions in these data are of 100 kyr or less magnitude, based on an average radiometric scale (Kauffman 1977, 1985a).

There also exist in these data prominent short-term (50–100 kyr) fluctuations in the $^{18}O_{carb}$ values. The most prominent excursion spans the Cenomanian-Turonian boundary interval, where at least two major positive spikes and one negative short-term ^{18}O spike can be defined regionally as chemoevent units (Pratt 1985). In addition, a rapid set of ^{18}O fluctuations in the upper Graneros Shale and the Lincoln Limestone Member of the Greenhorn Formation (Figure 8*A*) may be of value in HIRES, but these fluctuations remain to be tested regionally.

Organic Carbon Chemostratigraphic Events

Short (25–100 kyr) and long-term density stratification events in the Western Interior Seaway, as well as episodic incursions of oceanic oxygen-minima zones, produced widespread anoxic and dysaerobic intervals that resulted in deposition of regionally correlative, organic-carbon-rich strata. Closely spaced analyses of C_{org} reveal these intervals, which are of particular interest because of their potential as petroleum source rocks.

There are two major aspects of C_{org} chemostratigraphy that are useful in HIRES. The first is short-term spikes in the data representing less than 100 kyr of time and having regional expression. [Figure 8*A* (after Pratt 1985) shows typical data.] Kauffman (1986a) proposed a model whereby many of these could represent the wet phase of wet-dry and possibly cool-warm Milankovitch climate cycles (Figure 15). The effect of this phase (high rainfall and salinity stratification of the seaway, limiting downward mixing of oxygen) would be exaggerated during eustatic highstand, broad

Figure 8 High-resolution chemoevent stratigraphy and regional correlation, as shown by organic carbon, ^{13}C, and ^{18}O analyses of the Cenomanian-Turonian boundary interval from Arizona to Montana, and from Colorado to Nebraska (after Pratt 1985). (*A*) Major interval of carbon and stable-isotope disruption around the Cenomanian-Turonian extinction boundary at Pueblo, Colorado. Note position of X-bentonite marker bed (Texas-to-Alberta event bed) (X), major global chemical event interval (ce), and the development of four regionally correlative anoxic/dysaerobic events in the basin (see Figure 10), labeled 1–4 and shaded, as depicted by high C_{org} levels. (*B*) Details of the zone of chemical disruption (ce) shown in (*A*), with data from points throughout the Western Interior Basin. Note regional correlation potential of small-scale isotopic fluctuations (^{13}C) represented by fine lines, with most prominent lines of correlation regionally labeled A–E (modified from Pratt 1985).

global warming, climate amelioration, and sluggish ocean circulation (Figures 10, 15). Second, longer-term anoxic or dysaerobic intervals are represented by relatively thick, regionally correlative, organic-carbon-rich stratigraphic sequences. The apparent rapidity with which these density stratification events became established or broke down, however, as represented in rapid shifts (100 kyr or less) from high to low C_{org} values in strata, indicates that the boundaries of these events may be regionally useful in HIRES. For example, Kauffman (1985b), Sageman (1985), Pratt (1985), and Elder (1985) noted five regionally persistent intervals of high (3% or greater) C_{org} in the latest Albian–early Turonian transgressive phase of the Greenhorn Cyclothem throughout the Western Interior Basin. Four of these are shown by Pratt's (1985) data from Pueblo, Colorado (Figure 8*A*). When traced regionally relative to individual bentonite or ash beds, C_{org}-enriched intervals appear to consistently occur at the same stratigraphic levels. Their relative synchroneity strongly suggests that the density stratification of the seaway associated with anoxic and dysaerobic intervals became established and broke down very rapidly, usually within 100-kyr intervals or less of strata. L. K. Barlow (in Pratt & Barlow 1985) provided an excellent example of a rapid shift in C_{org}, and in bioturbation levels, associated with onset and breakdown of a major oxygen depletion event during deposition of the Coniacian lower shale unit, Smoky Hill Member, Niobrara Formation, along the Colorado Front Range (Figure 9). Organic carbon levels climb from 1.2 to 5% by weight, and bioturbation levels drop from "severely bioturbated" to "nonbioturbated," within less than 1 m of strata, probably less than 100 kyr in time. After 0.4–0.5 Myr, C_{org} drops from 3.2 to 1.0% and bioturbation abruptly becomes intense again within less than 100 kyr. Both contacts of this regional oxygen depletion event, when traced relative to other event markers (e.g. bentonites), are abrupt and near-isochronous over a wide area in both C_{org} levels and bioturbation. Both contacts are therefore important regional HIRES chemistratigraphic events.

Such sharp changes in benthic and midwater oxygen levels suggest abrupt stratification and destratification of the Western Interior Seaway over wide areas; Kauffman (1986a; Figure 10) has suggested circulation models for these events in which rapid changes in stratification history may be a result of intermittent desalination events during high rainfall and accelerated interior drainage of freshwater runoff; of thermal stratification resulting from overlap of northern and southern watermasses; of rapid incursion of warm tropical/subtropical watermasses from the south as sea level rose sufficiently to breach the southern silled aperture to the Western Interior Basin; and of rapid incursion of oxygen minima zones across the

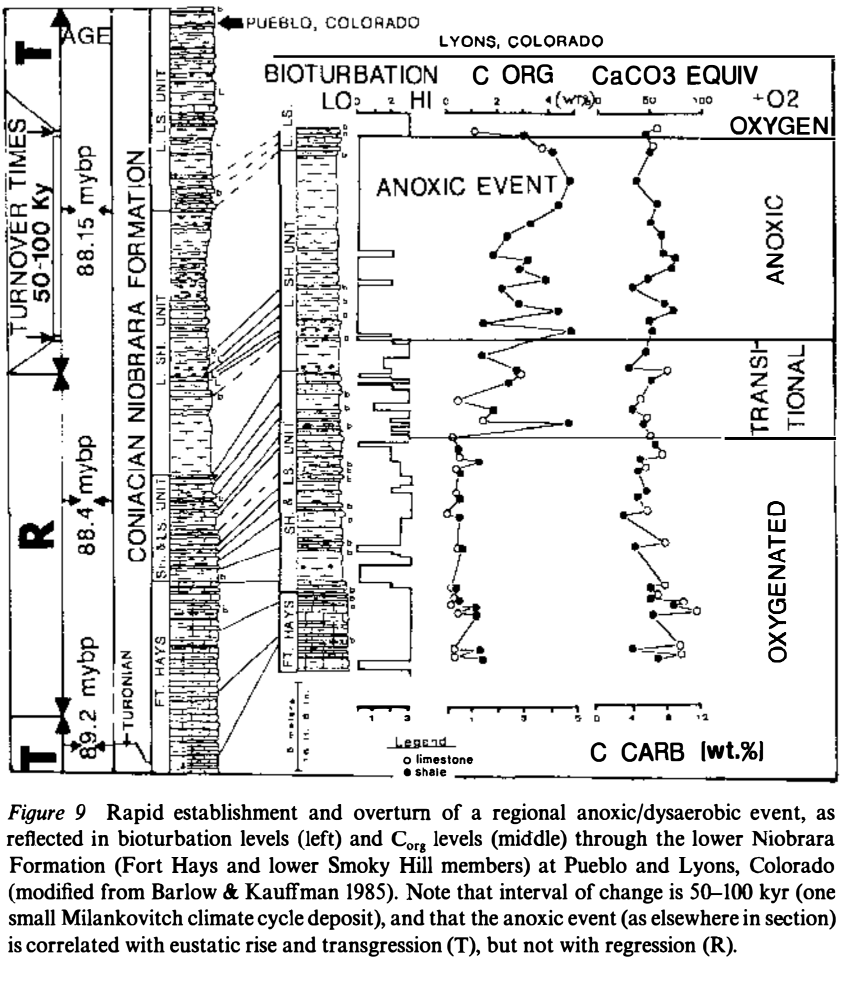
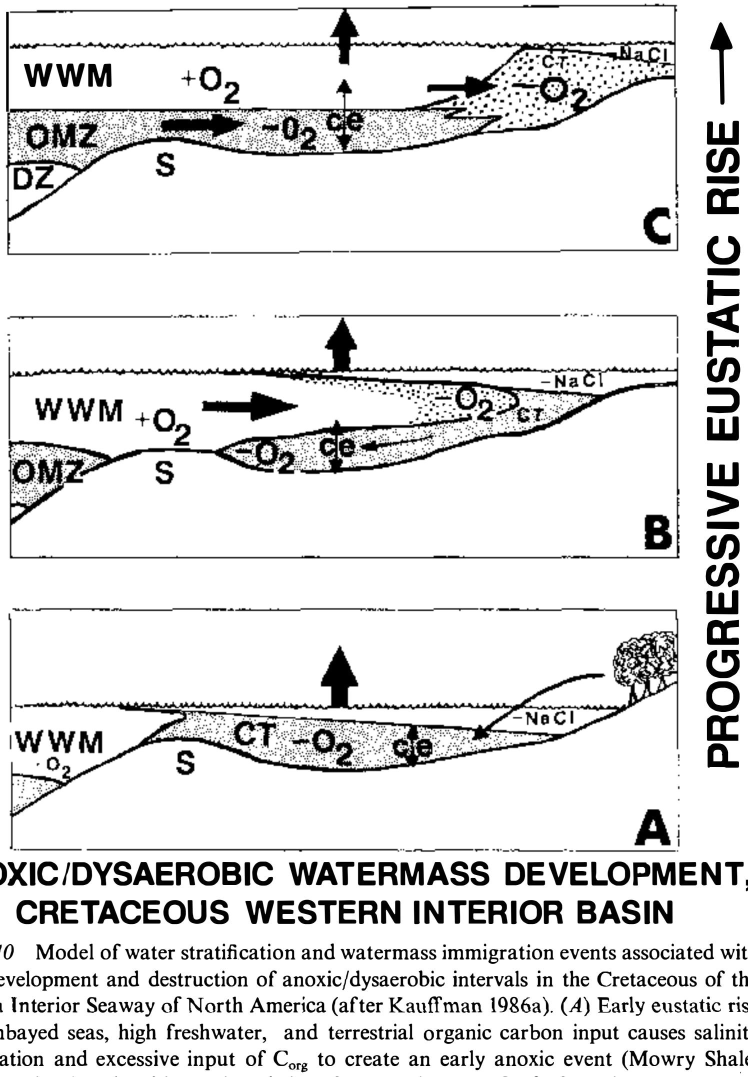


Figure 9 Rapid establishment and overturn of a regional anoxic/dysaerobic event, as reflected in bioturbation levels (left) and C_{org} levels (middle) through the lower Niobrara Formation (Fort Hays and lower Smoky Hill members) at Pueblo and Lyons, Colorado (modified from Barlow & Kauffman 1985). Note that interval of change is 50–100 kyr (one small Milankovitch climate cycle deposit), and that the anoxic event (as elsewhere in section) is correlated with eustatic rise and transgression (T), but not with regression (R).

benthic zone with rising sea level and expanding oceanic oxygen depletion. Figure 10 outlines these models.

Concretion Zones

It has been widely documented that persistent zones of limestone, limestone-siderite, siderite, dolomite, and even limonitic concretion and nodular zones regionally retain their relative stratigraphic position when compared with persistent bentonite beds. This suggests, therefore, a primary regional (allocyclic) short-term depositional control on their formation.



ANOXIC/DYSAEROBIC WATERMASS DEVELOPMENT, CRETACEOUS WESTERN INTERIOR BASIN

Figure 10 Model of water stratification and watermass immigration events associated with rapid development and destruction of anoxic/dysaerobic intervals in the Cretaceous of the Western Interior Seaway of North America (after Kauffman 1986a). (*A*) Early eustatic rise with embayed seas, high freshwater, and terrestrial organic carbon input causes salinity stratification and excessive input of C_{org} to create an early anoxic event (Mowry Shale, Graneros Shale); (*B*) With continued rise of sea level, warm Gulf of Mexico watermasses breach the southern sill of the Western Interior Basin and wedge over cooler, denser northern waters, and below an episodically emplaced subnormal saline wedge, to again stratify the water column and cause anoxic benthic conditions (Hartland Shale, Smoky Hill Shale); (*C*) Near peak transgression, expansion of oceanic oxygen minimum zones causes their incursion into epicontinental seas, already devoid of oxygen (Bridge Creek limestone event, Bonarelli global oceanic anoxic event). Key: WWM, warm water Gulf of Mexico watermass; C-T, cool temperate dense watermass; OMZ, oxygen minimum zone; DZ, dysaerobic deep-ocean watermass; ce, fluctuations of density stratification boundary reflecting Milankovitch climate cycle control.

Many limestone concretion zones laterally grade into persistent limestone beds representing the dry phases of Milankovitch climate cycles. Figure 3 (Hattin 1985) shows this phenomenon with regard to beds of the lower Bridge Creek Limestone Member, Greenhorn Formation, from Kansas to Colorado; Kauffman et al (1987) provide stratigraphic correlation of the same beds to Utah. Similar regional correlations of septarian limestone concretion zones of the upper Blue Hill and lower Codell Members, Carlile Shale, have been noted by Glenister & Kauffman (1985) along the Colorado Front Range outcrop belt. Inasmuch as most concretions seem to represent early diagenetic phenomena rather than primary deposits, it is probable that persistent, near-isochronous concretion zones form in response to some primary regional sedimentary control. Possibly concretions form where there was a concentration of biogenic carbonate or organic material along certain bedding planes, which was then remobilized in such a way as to initiate accretionary carbonate deposition early in diagenesis.

BIOLOGICAL EVENTS

The role of biological events (bioevents) in high-resolution event stratigraphy has recently been discussed in the review by Kauffman (1986a), from which the following synthesis is made. Bioevents include episodes of punctuated evolution, mass mortalities, steps and catastrophes during mass extinction, rapid immigration and emigration events, productivity events and population bursts (acmezones), rapid regional benthic colonization events, and other ecostratigraphic phenomena. In some cases, bioevents mark biostratigraphic boundaries, but the two systems of stratigraphy are not interdependent. Bioevents occur at three scales: local (extending less than 100 mi), regional (basinwide), and intercontinental to global in aspect. The last two are important in HIRES. Many of these types of bioevents are common in the Cretaceous of the Western Interior Basin of North America, from which examples are taken, as well as in other Phanerozoic basins.

Punctuated Evolutionary Events

The rapid origin of new subspecies and species through mechanisms inherent in punctuated evolutionary theory (Eldredge & Gould 1972, and subsequent papers), coupled with rapid, widespread marine dispersal of newly derived taxa through planktotrophic larvae or mobile adult stages (see Kauffman 1975), produces "geologically instantaneous," geographically widespread first appearances of these taxa. These levels comprise not only important biostratigraphic boundaries, but also evolutionary bioevent marker horizons. Kauffman (1986a) gives examples from the Western Interior Basin. The abrupt regional first appearances of new taxa of scaphitid and baculitid ammonites (Cobban 1951, 1962, and other papers) and of inoceramid bivalves (Kauffman 1975, and other papers), within existing lineages of biostratigraphically important Cretaceous molluscs, probably represents to a large degree punctuated evolution coupled with rapid marine dispersal of new taxa. For example, the biostratigraphic zone boundaries associated with the sections shown in Figure 3 are based on the first occurrences of new ammonite and/or inoceramid bivalve species, the abrupt appearance of which, throughout the Western Interior Basin, strongly suggests punctuational evolutionary events. Regionally, these particular zonal boundaries are essentially isochronous, maintaining a nearly constant stratigraphic position relative to bentonite beds and climate cycle-related limestone units (Figure 3). A regional test of this apparent synchroneity, utilizing graphic correlation of zonal ammonite first-appearance data to a line of isochronous correlation (LOIC) constructed from bentonites (Figure 17), shows that first appearances are near-isochronous between sections (punctuational?), whereas last appearances of the same taxa are diachronous (differential extinction rates among subpopulations).

Population Bursts

The onset of favorable environmental conditions for certain taxa may be regionally rapid in delicately balanced, slowly circulating epicontinental seas like that of the Cretaceous Western Interior Basin. Short-lived regional population bursts may result, especially among plankton, leaving a sedimentary bioevent signal. Coccolith-rich varves at 1 cm or less intervals and planktonic foraminifer-rich calcarenites or pelagic limestones are common Cretaceous examples from the Western Interior Basin. A benthic example is the regional (Wyoming to Texas) colonization of strata directly overlying the Cenomanian X-bentonite marker bed (Figure 8*A*) by abundant calcareous benthic foraminifera and beds or biostromes of the otherwise moderately rare oyster *Ostrea beloiti*. Population bursts among biostratigraphically important ammonite and foraminifer species have been used to define acmezones (epiboles) in the Cretaceous. The persistent short-term (less than 100 kyr) population explosion of several species of calcareous benthic and planktonic foraminifera and diverse molluscs, within a meter of strata encompassing the early middle Cenomanian Thatcher Limestone Member, Graneros Shale (Figure 14), is a regional bioevent marker extending from central Colorado to New Mexico. This interval reflects a short-term immigration event of warm oxygenated water from the Gulf of Mexico region.

Productivity Events

Like population bursts, productivity events represent a short interval of highly favorable conditions for biotic proliferation, but in this case the conditions extend to diverse organisms or whole paleocommunities. In some cases, productivity events are measured by planktonic rain and rates of benthic accumulation of tests; these productivity events commonly produce a major change in lithology toward more calcareous (or siliceous) strata, in contrast to clay-dominated sedimentation in marine basins. In limestone-shale or chalk-marl bedding rhythms associated with Milankovitch climate cycles (Barron et al 1985; Figures 3, 15), the carbonate-enriched portion of the cycle is in part diagenetic, and in part due to increasing primary productivity among calcareous plankton associated with normalization of surface water conditions in the seaway during the dry and potentially warmer climatic intervals (Figure 15). These pelagic biogenic limestones form regional event marker beds second only to volcanic ash/bentonite horizons for regional HIRES correlation across the Cretaceous Western Interior Basin (Hattin 1985, Elder 1985, and references therein).

Ecostratigraphic Events

These represent abrupt widespread changes in community structure as a result of regional (allocyclic) changes in environment (climate, oceanography, paleobathymetry, water chemistry, etc). Detailed bed-by-bed examination of all biotic components in high-resolution stratigraphic analysis is required to see these rapid changes [see Figure 12 for typical data (from Elder 1985)], which maintain their stratigraphic position relative to bentonites and other chronostratigraphic event markers over great distances in the Western Interior Basin. Typical examples are (*a*) the great diversification of warm-water taxa associated with rapid incursion of subtropical watermasses into the Western Interior Seaway during eustatic rise and breaching of the silled southern aperture of the basin (Kauffman 1984b, Elder 1985); the abrupt regional appearance of subtropical and warm temperate molluscan elements of the *Sciponoceras gracile* biozone fauna (Figures 11, 13) represents this event. The previously cited Thatcher Limestone bioevent (Figure 14) is a similar and shorter-term event. (*b*) Rapid changes in benthic faunas associated with the onset and overturn of regional oxygen depletion events, from depauperate inoceramid bivalve–dominated low-oxygen communities to more diverse benthic molluscan communities, has been well documented for the Hartland oxygen depletion event by Sageman (1985, Figures 2, 3), for the recovery from the Cenomanian-Turonian Bonarelli oceanic anoxic event by Elder (1985; and

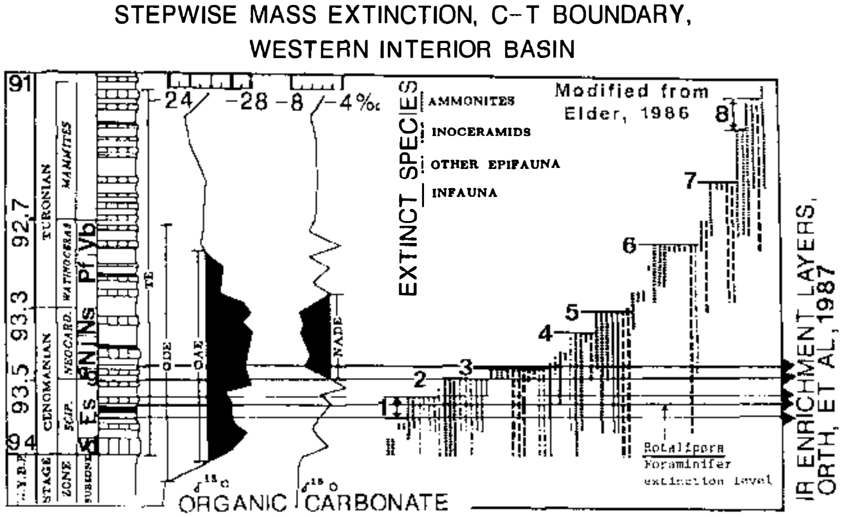


Figure 11 Stepwise mass extinction bioevents in the Cenomanian-Turonian mass extinction interval (modified after Elder 1986). All data compiled here collected at 1–10 cm HIRES intervals. Note stepwise nature of molluscan extinctions, each within 50 kyr or less time (extinction bioevents), the inclusion of most mass extinction events within an interval of global stable isotope (climate, ocean) disruption (ce in Figure 8), and the correlation of lower stepwise extinction events with an interval of iridium enrichment (five small spikes, or chemoevents, marked by thin lines) at Pueblo, Colorado (Orth et al 1987). Letters in column 4 from left refer to ammonite subzones (see Elder 1986). Key: ODE oceanic disruption interval; OAE, oceanic anoxic event (Bonarelli event); NADE, North American desalination event (as indicated by rapid negative excursions of ^{18}O).

Figure 11 herein) and Kauffman (1984a), and for the ichnofauna of the lower Niobrara (lower shale unit) oxygen depletion event by Barlow (in Pratt & Barlow 1985) (Figure 9) in the Cretaceous sequence of the Western Interior Basin.

Immigration-Emigration Bioevents

The silled nature of the southern aperture of the Western Interior Basin, blocked by the central Texas uplift and choked by impinging Precambrian and Paleozoic ranges to the east and west, inhibited influx of warm subtropical waters into the seaway until middle to late stages of eustatic rise during the Cretaceous. Breaching of this sill during eustatic highstand resulted in rapid immigration (and, with lowering sea level, emigration) of subtropical faunal elements into the basin. Kauffman (1984b) documented these rapid changes and estimated their timing as under 0.5 Myr, and in some cases within 100 kyr, over hundreds to thousands of square miles.

ECOSTRATIGRAPHY OF CENOMANIAN-TURONIAN BOUNDARY INTERVAL

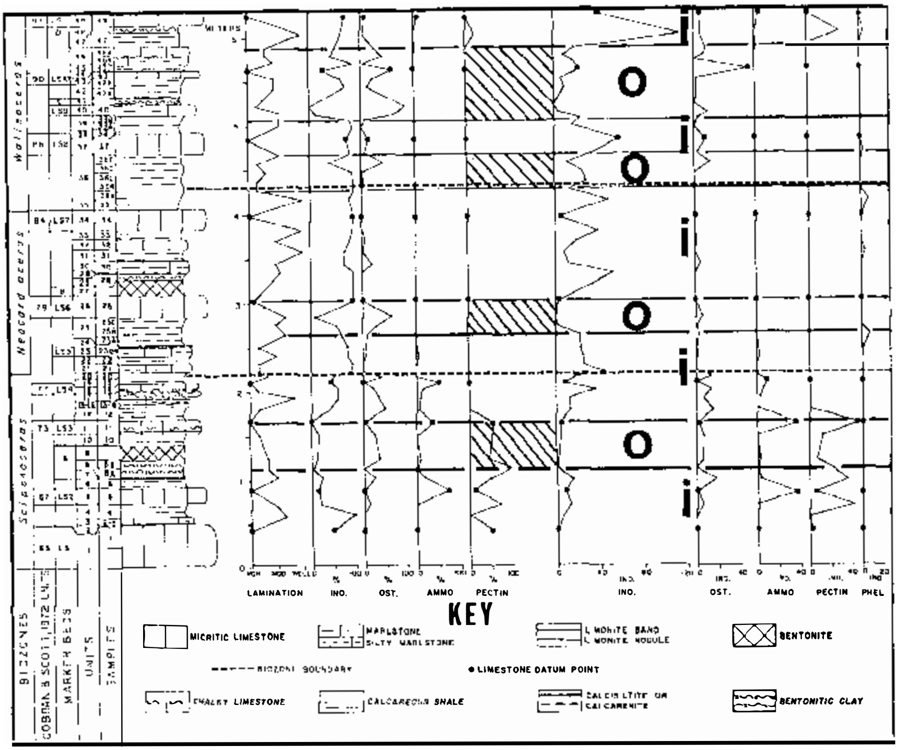
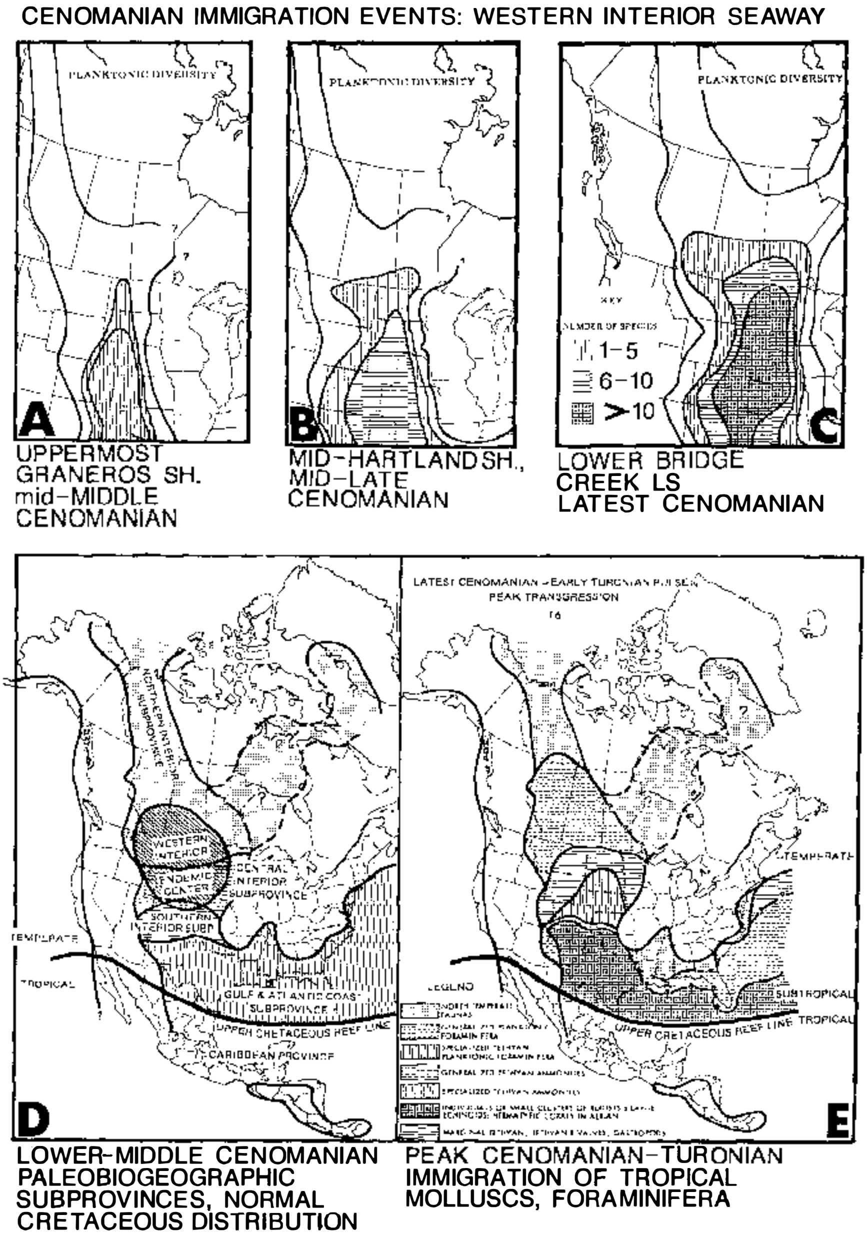


Figure 12 Ecostratigraphy of the Cenomanian-Turonian boundary interval at Pueblo, Colorado (after Elder 1985). Graphs show absolute and relative abundance of major macrofossils; horizontal lines bound taxonomically consistent communities (o, *Ostrea*-dominated; i, *Inoceramus*-dominated) with regional correlation potential (striped lines accentuate *Ostrea* community). Note rapid turnover from one community to another.

The Cenomanian Thatcher Limestone event (Figure 14) lasted about 100 kyr and was characterized by a dramatic change from totally arenaceous to calcareous benthic and planktonic foraminiferal assemblages and by a major increase in molluscan diversity (4 to 36 species, including rudistid bivalves, within 50 cm of rock). This represents an early pulse of an immigration-emigration event associated with a warm-water incursion. The most dramatic of these events in the Western Interior Basin is that associated with the Cenomanian-Turonian boundary interval (Figure 11; Elder 1985, Elder & Kirkland 1986, Kauffman 1984b). Figure 13*A* shows


CENOMANIAN IMMIGRATION EVENTS: WESTERN INTERIOR SEAWAY
PLANKTONIC DIVERSITY
A
UPPERMOST GRANEROS SH. mid-MIDDLE CENOMANIAN
PLANKTONIC DIVERSITY
B
MID-HARTLAND SH., MID-LATE CENOMANIAN
PLANKTONIC DIVERSITY
KEY
NUMBER OF SPECIES
1-5
6-10
>10
C
LOWER BRIDGE CREEK LS LATEST CENOMANIAN
NORTHERN INTERIOR SUBPROVINCE
WESTERN INTERIOR
ENDEMIC CENTER
CENTRAL INTERIOR SUBPROVINCE
SOUTHERN INTERIOR SUBP.
TEMPERATE
TROPICAL
GULF & ATLANTIC COAST SUBPROVINCE
UPPER CRETACEOUS REEF LINE
CARIBBEAN PROVINCE
D
LOWER-MIDDLE CENOMANIAN PALEOBIOGEOGRAPHIC SUBPROVINCES, NORMAL CRETACEOUS DISTRIBUTION
PEAK TRANSGRESSION
TEMPERATE
SUBTROPICAL
UPPER CRETACEOUS REEF LINE
TROPICAL
LEGEND
E
PEAK CENOMANIAN-TURONIAN IMMIGRATION OF TROPICAL MOLLUSCS, FORAMINIFERA

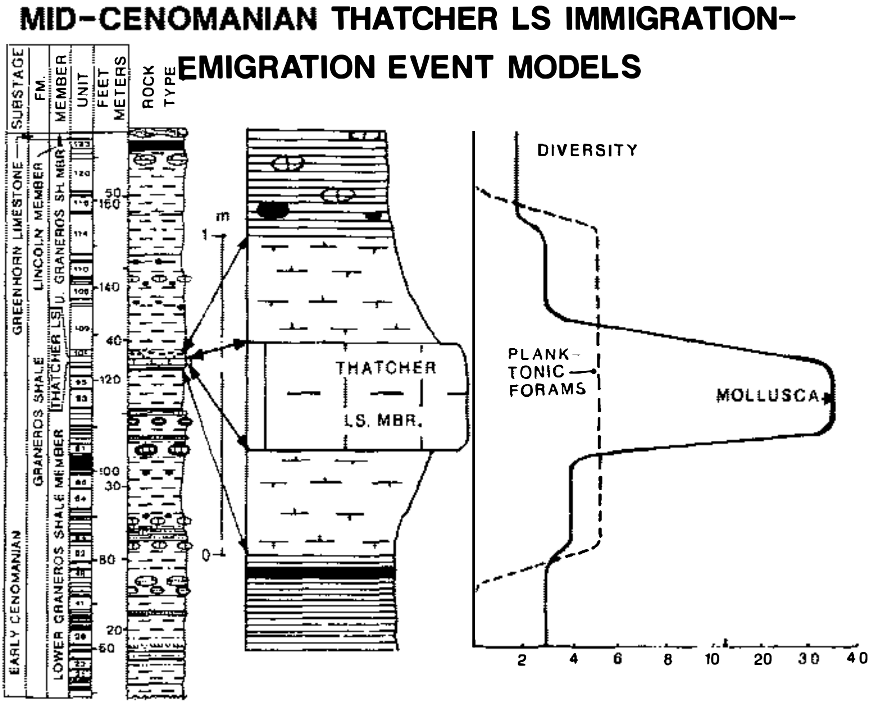


Figure 14 Rapid immigration-emigration event of subtropical molluscs and planktonic foraminifera into the Western Interior Seaway of North America during Thatcher Limestone (middle Cenomanian) time (100 kyr), middle Graneros Shale (Kauffman 1986a). Note rapid increase in carbonate planktonic foraminifers and molluscs within approximately 20 kyr, the short diversity peak, and the equally rapid emigration with a short watermass migration. Background strata are dark organic-carbon-rich clay with mild temperate, low-diversity molluscan communities.

the average paleobiogeographic distribution of temperate subprovinces in the Western Interior Seaway prior to the rapid northward immigration of subtropical and southern warm temperate taxa (Figure 13*B*) during a series of northward pulses of warm watermasses approaching the Cenomanian-

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Figure 13 Rapid immigration event of tropical-subtropical molluscs and foraminifers into the Western Interior Seaway of North America near the Cenomanian-Turonian boundary, marking peak eustatic rise and transgression. (*A–C*) Maps showing planktonic foraminifer diversity and aerial extent during this 1–2 Myr interval (from Eicher & Diner 1985). (*D*, *E*) Average paleobiogeographic distribution of Mollusca (predominantly temperate) and (in *E*) distribution of tropical-subtropical faunal elements into the Western Interior Seaway during eustatic highstand (different patterns represent different groups; from Kauffman 1984b). Major immigration time is estimated between 100–500 kyr.

Turonian eustatic high-stand [see Kauffman (1984b) for examples and Kauffman (1986a) for detailed discussion].

Mass Mortality Events

Short-term (100 kyr or less) deterioration of environmental conditions in the Western Interior Seaway linked to mainly allocyclic (oceanographic, climatic) phenomena produced many regional mass mortality surfaces that are useful in high-resolution event stratigraphy. The "fish-scale marker bed" at the Albian-Cenomanian boundary represents one such marker that can be traced from Alberta to Colorado as a single surface or closely spaced series of mass mortalities, probably associated with overturn of the anoxic bottom waters characterizing the upper Albian Mowry Sea (Kauffman 1986a). Sageman (1985) documented similar mass mortalities associated with oxygen depletion events in the upper Cenomanian Hartland Shale Member, Greenhorn Formation, and Barlow (in Pratt & Barlow 1985) (Figure 9) documented onset of one of several Niobrara Formation (Coniacian-Santonian) anoxic events, almost totally decimating the benthic trace and shelly fossil biota, within a meter of strata (100 kyr or less).

The most common type of mass mortality surfaces in the Western Interior Basin are associated with short-term dynamic fluctuations of benthic oxygen within long-term oxygen depletion events. Oxygenated intervals of a few months or years permit settling and initial growth of benthic molluscan larvae, but the entire spat or juvenile crop is abruptly killed off, in situ, during more anoxic intervals. Cretaceous examples are *Entolium* and *Inoceramus* mass mortality surfaces found throughout the upper Cenomanian Hartland Shale Member (Sageman 1985) in the Western Interior Basin. Kauffman (1978, 1981) detailed similar mass mortality surfaces among *Inoceramus*, *Bositra*, and *Ostrea* in the Jurassic Posidonenschiefer and Solnhofen/Nusplingen formations of southern Germany.

Large bentonite falls should suffocate larger organisms and produce regional mass mortality surfaces at their bases (Figure 4, showing a model based on several analyses of the middle Cenomanian Graneros Shale), but initial research shows variable and inconclusive evidence for this from ash to ash. Similarly, some but not all large storm beds have mass mortality surfaces, especially among larger-shelled benthos and trace-making organisms, at their base (Figure 5), as do modern storm deposits spread over a few hundred square miles of sea floor.

Mass Extinction Bioevents

Episodic mass extinctions have broadly affected global biotas and are well documented in the Cretaceous sequence of the Western Interior Basin, e.g.

the Cenomanian-Turonian (C-T) and Cretaceous-Tertiary (K-T) extinctions. The K-T boundary impact-extinction event is already regarded as a global event marker of unusual proportions (Alvarez et al 1984). The C-T extinction is one of the best documented in the Phanerozoic (Kauffman 1984a, 1986a, Elder 1985, Elder & Kirkland 1986) and provides an excellent example of mass extinction bioevent stratigraphy (Kauffman 1986a). In both the K-T and C-T boundary intervals, mass extinction was found to proceed through a series of discrete steps of accelerated to catastrophic extinction among certain ecologically related taxa sets, each step being very short lived (100 kyr or less) and forming a regional to global bioevent surface for correlation [see Elder & Kirkland (1986) and Kauffman (1986a) for summaries]. Individual steps commonly reflect rapid changes in the oceanography (chemistry, stratification) and the climate (temperature, storm cycles) of the basin. These may be expressed as extraordinarily rapid, large-scale shifts in stable isotopes of ^{13}C and ^{18}O (see Pratt 1985; Figure 8 herein), and a single extinction step may be linked to an individual 50–100 kyr geochemical excursion. Apparently, the rate and magnitude of each large oceanographic fluctuation exceeded the adaptive ranges and evolutionary potential of diverse taxa (Kauffman 1986a). The C-T mass extinction data (Elder & Kirkland 1986; Figure 11 herein) show six to seven short-term to near-isochronous steps of molluscan extinction that Elder has traced as short-term events throughout much of the Western Interior Basin, plotting their position against bentonite (ash) marker horizons. New data on iridium enrichment levels (Orth et al 1987) further show low to moderate Ir-enrichment peaks, some of which may indicate meteorite or comet impacts, precisely correlative with the lower four of Elder's molluscan extinction steps and with the large planktonic foraminifer extinction (*Rotalipora* extinction; Eicher & Diner 1985, Leckie 1985) beginning between molluscan steps 1A and 1B. A chronostratigraphic relationship between impact, climate/ocean disruptions, and mass extinction steps is implied across the C-T boundary interval.

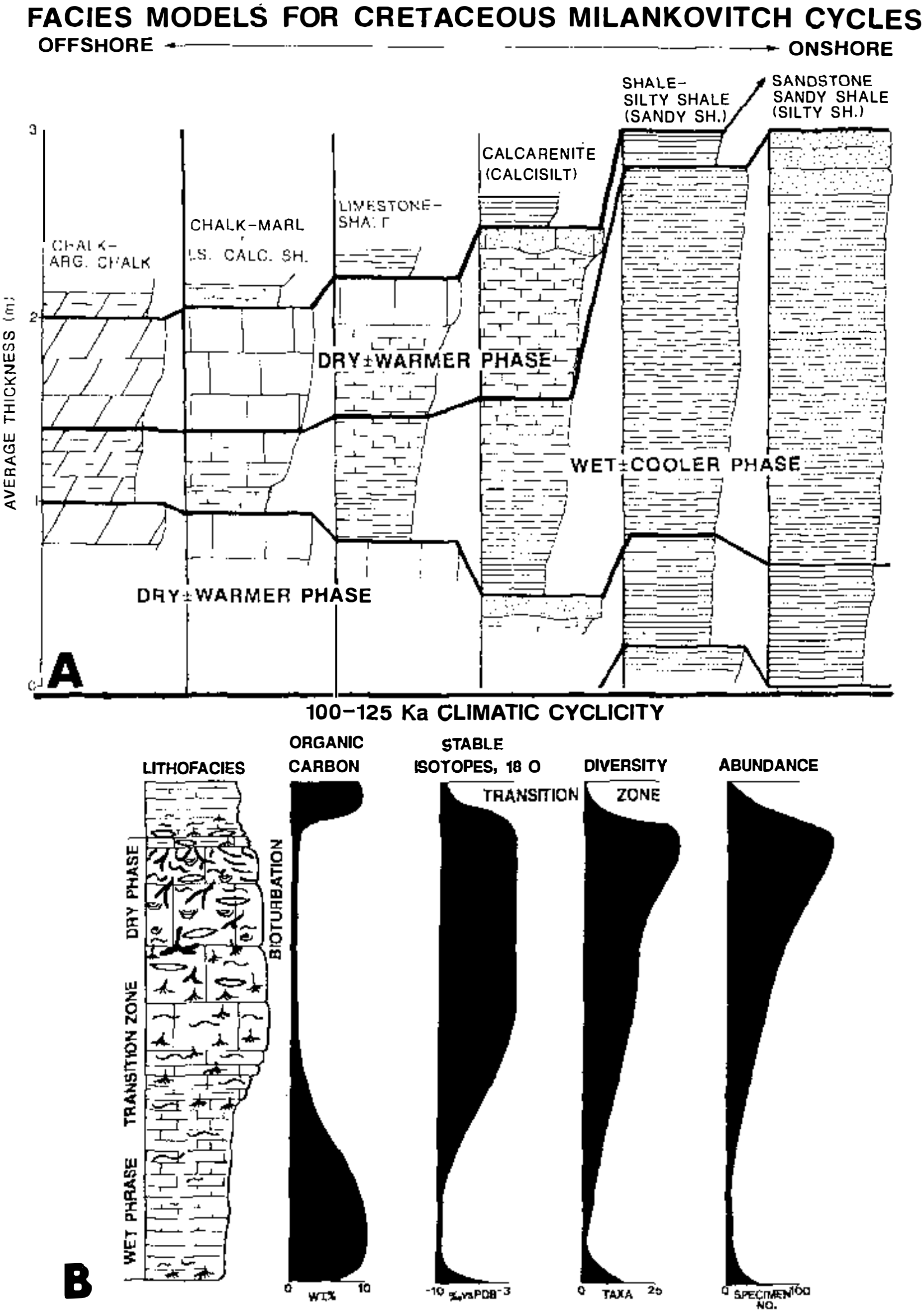
COMPOSITE EVENTS

Milankovitch Climate Cycle (M-Cycle) Deposits

Of the diverse kinds of composite event units previously discussed, those representing Milankovitch or similar climate cycle deposits are of particular value in HIRES correlation of Cretaceous strata in the Western Interior Basin; they are second only to ash/bentonite beds in regional correlation potential. Facies interpreted as representing Milankovitch cycles are varied. Kauffman (1986a) proposed facies models for the North American Cretaceous (Figure 15*A*), involving asymmetrical bedding couplets, or "rhythms," with varying lithologic composition depending upon the depositional setting. Strata representing the wet (possibly cooler) phase of the cycles lie at the base of each couplet model, and different lithologies representing the dry (possibly warmer) phase lie at the top (Figure 15*A*). The end-member lithotypes may grade or appear to change abruptly (mainly in carbonate facies where the cyclicity has been enhanced by diagenesis; Ricken 1986). In offshore facies of the Western Interior Basin these cycles, normally a meter or less in thickness, are thus expressed as marl (wet; basal)–chalk (dry; top), calcareous shale/shaley chalk–pelagic limestone, clay shale–calcareous shale, and silty clay shale (wet; basal)–clay shale (dry; top) bedding couplets with slight to broad facies gradations between depositional end members. In nearshore facies, Kauffman (1986a) proposed that these cycles might be represented by sandy shale (wet; basal)–silty shale (dry; top) couplets, by bundled distal storm bed (wet)–sandy and silty shale (dry) couplets in distal lower shoreface sequences, and by progradational shoreface sandstone (wet)–silty marine shale (dry) couplets attaining 10 m or more in thickness. Facies are normally graded between dry to wet end members in nearshore settings.

In these Cretaceous models (Kauffman 1986a; Figure 15*A* herein), variations in basinal M-Cycle couplets were generally attributed to a combination of fluctuations in calcareous plankton productivity (highest during normal marine dry periods, producing pelagic limestone, chalk, and calcareous shale) and/or offshore transport potential of terrigenous clay (highest during wet climate phases as a result of increased erosion and current velocities, coupled with temporary development of a brackish water lens across parts of the seaway that partially restricted calcareous plankton populations). Variations in more nearshore facies were attributed solely to the increased erosion, supply, and fluvial-coastal-offshore transport of relatively coarser siliciclastic material during prolonged wet phases of Milankovitch cycles. This caused near-synchronous, small-scale coastal progradation (a few miles seaward at the most) of strand and delta plains over more normal, marine clay-dominated facies representing dry phases.

Figure 15 (*A*) Depositional models for Milankovitch climate cycles from the center (left) to the margins of the Cretaceous of the Western Interior Basin of North America (modified from Kauffman 1986a), taken from actual examples in the Cenomanian-Turonian Greenhorn Cyclothem. (*B*) Generalized model, from several Cenomanian-Coniacian data sets, of a Milankovitch climate cycle deposit in the carbonate facies of the axial basin, Western Interior Seaway (from Kauffman 1986a), showing high organic carbon (reflecting low oxygen), negative ^{18}O values [reflecting subsaline lenses on the Interior seaway during wet seasons causing density stratification (and thus low benthic oxygen)], and low molluscan and trace fossil diversity during wet climate phases, as compared with low carbon preservation in the benthic zone, normal ^{18}O values, and high diveristy during normal warm dry climatic phases. [See Kauffman (1986a) for details].



FACIES MODELS FOR CRETACEOUS MILANKOVITCH CYCLES
OFFSHORE
ONSHORE
SHALE-
SILTY SHALE
(SANDY SH.)
SANDSTONE
SANDY SHALE
(SILTY SH.)
CALCARENITE
(CALCISILT)
CHALK-MARL
LS. CALC. SH.
CHALK-
ARG. CHALK
DRY±WARMER PHASE
WET±COOLER PHASE
DRY±WARMER PHASE
AVERAGE THICKNESS (m)
3
2
1
0
A
100–125 Ka CLIMATIC CYCLICITY
LITHOFACIES
ORGANIC
CARBON
STABLE
ISOTOPES, 18 O
DIVERSITY
ABUNDANCE
TRANSITION
ZONE
DRY PHASE
TRANSITION ZONE
WET PHRASE
BIOTURBATION
0
WT%
10
-10
-3
0
TAXA
25
0
SPECIMEN
NO.
100
B

Three tests of these facies models to prove their origins through Milankovitch climate forcing are necessary: (*a*) They must have durations and stratigraphic repetition compatible with M-cycle periodicity; (*b*) they must be internally consistent with the predictions of Milankovitch climate effects on sedimentation in terms of their physical, chemical, and biological characteristics; and (*c*) they must be simultaneously developed in different depositional settings, among different facies suites, as a result of regional to global climate forcing. Preliminary testing of these three criteria in the Cretaceous of the Western Interior Basin of North America has strongly supported the concept of Milankovitch climate forcing for these cycles, as follows:

1. Utilizing K-Ar radiometric dates (average values) clustered around basinal limestone–calcareous shale cycles of the Greenhorn and Niobrara formations of the Western Interior Basin, Kauffman (1977) roughly calculated periodicities of 40–60 kyr for Niobrara bedding rhythms and 60–80 kyr for the most obvious Greenhorn bedding rhythms, both well within the predicted range of M-cycles. Lack of attention to the more subtle carbonate cycles in these sequences, formed during predictable intervals when the dry (warm?) Milankovitch effect might have been damped, or due to diagenetic remobilization of carbonates within them, prevented these early calculations from being more precise. Fischer et al (1985), however, summarized data from more detailed calculations to suggest that these sequences, and similar Mesozoic cycles in Europe, did locally demonstrate a 21-kyr, probable 41-kyr, and 100+-kyr cyclicity compatible with the Milankovitch forcing hypothesis.

2. Selected basinal marl-chalk, shale-limestone, and calcareous shale–clay shale couplets from the Greenhorn Formation (Cenomanian–lower Turonian) of the Western Interior Basin have been tested in detail (centimeter-scale) for physical, chemical, and biological evidence pertaining to the M-cycle hypothesis. Barron et al (1985) and Kauffman (1986a) collectively showed the following changes upsection (from wet to dry phases) in calcareous shale–limestone and marl-chalk bedding couplets of the Bridge Creek Limestone Member, Greenhorn Formation: (*a*) decreasing clay content; (*b*) increasing pelagic carbonate content; (*c*) decreasing organic carbon content, from 3–10% to less than 1% by weight; (*d*) normalization of ^{18}O values, from abnormally negative at the base (-6 to -11 $^0/_{00}$ vs the PDB standard; a brackish water signal) to -2 or -3 $^0/_{00}$ vs PDB at the top (normal Cretaceous marine values); (*e*) increasing numbers, generations, and diversity of trace fossils upsection, with a correlative change from predominantly detritus-feeding infaunal forms at the base (*Chondrites*, *Planolites*) to mixed detritus- and suspension-feeding

groups at the top; and (*f*) few or rare epifaunal body fossils in the lower part to larger, more numerous and diverse body fossils (predominantly bivalves) at the top.

Collectively these observations support the hypothesis of Milankovitch climate forcing for these bedding cycles. Wet (basal) phases of sedimentation were characterized by increased rainfall and internal drainage into the basin, producing a brackish water lens on top of the seaway, diminishing calcareous plankton production, establishing a density stratification in the water column, and preventing extensive downward mixing of oxygen to the sea floor. This, in turn, resulted in dysaerobic to anaerobic benthic conditions, preservation of large amounts of C_{org}, and greatly diminished benthic habitation by molluscs and trace-making organisms. Wet cycles were also characterized by increased rainfall, erosion, runoff velocities, and siliciclastic sediment availability to the basin, producing a predominance of clay sedimentation. Dry periods (tops of cycles) were characterized by normal marine surface waters, high calcareous plankton production, breakdown of salinity stratification in the water column, and benthic oxygenation. This resulted in diverse benthic faunas and low levels of C_{org} preservation due to aerobic bacterial decay, organism recycling, and oxygenation of organic carbon. Low rainfall, reduced runoff, and siliciclastic sediment supply also characterized dry phases, allowing pelagic carbonate to dominate over clay sedimentation.

3. Finally, Elder, Gustason & Sageman (in Kauffman et al 1987) carefully documented and traced the largest limestone beds of the Bridge Creek Limestone Member, Greenhorn Formation (late Cenomanian–early Turonian) throughout the central Western Interior Basin (Kansas, Colorado), i.e. those representing the ± 100 kyr Milankovitch cyclicity as defined by Barron et al (1985) and Fischer et al (1985). These events could be identified westward to the shoreline in Utah when traced relative to well-defined regional bentonite (chronostratigraphic) marker horizons. In this transect, they found that the same cycles characterized by calcareous shale (wet)–pelagic limestone (dry), or marl (wet)–chalk (dry) bedding cycles in the central basin, were represented in proximal offshore settings by alternating cycles of clay shale (wet)–limestone concretion horizons (dry) and clay to silty clay shale (wet)–lag calcarenites or shell coquinas (dry). In shoreface settings the M-cycles were represented by progradational sandstone sequences (wet) alternating with silty and sandy clay shale sequences with a basal shell lag (dry) that disconformably overlay the shoreface sandstones. Recognition of Milankovitch effects in shoreface sedimentation and strand plain–delta plain progradation is of great importance to basin analysis inasmuch as many of these progradational events were considered to represent small-scale eustatic

changes. In either case, they are important event units in nearshore correlation.

The most dramatic example of regional HIRES correlation of Milankovitch climate cycle deposits (composite event units) is the regional tracing of individual limestone or chalk beds (dry phase) as isochronous to near-isochronous event deposits retaining a constant position relative to bentonite/ash marker horizons, from central Kansas to central Colorado (Hattin 1971, 1985), into northeastern Arizona [Black Mesa area (Elder & Kirkland 1985)] and south-central Utah (Elder, Gustason & Kirkland in Kauffman et el 1987). Figure 3 shows part of this correlation; compare the relative positions of limestones and volcanic ash deposits across this 440-mi transect.

CORRELATION

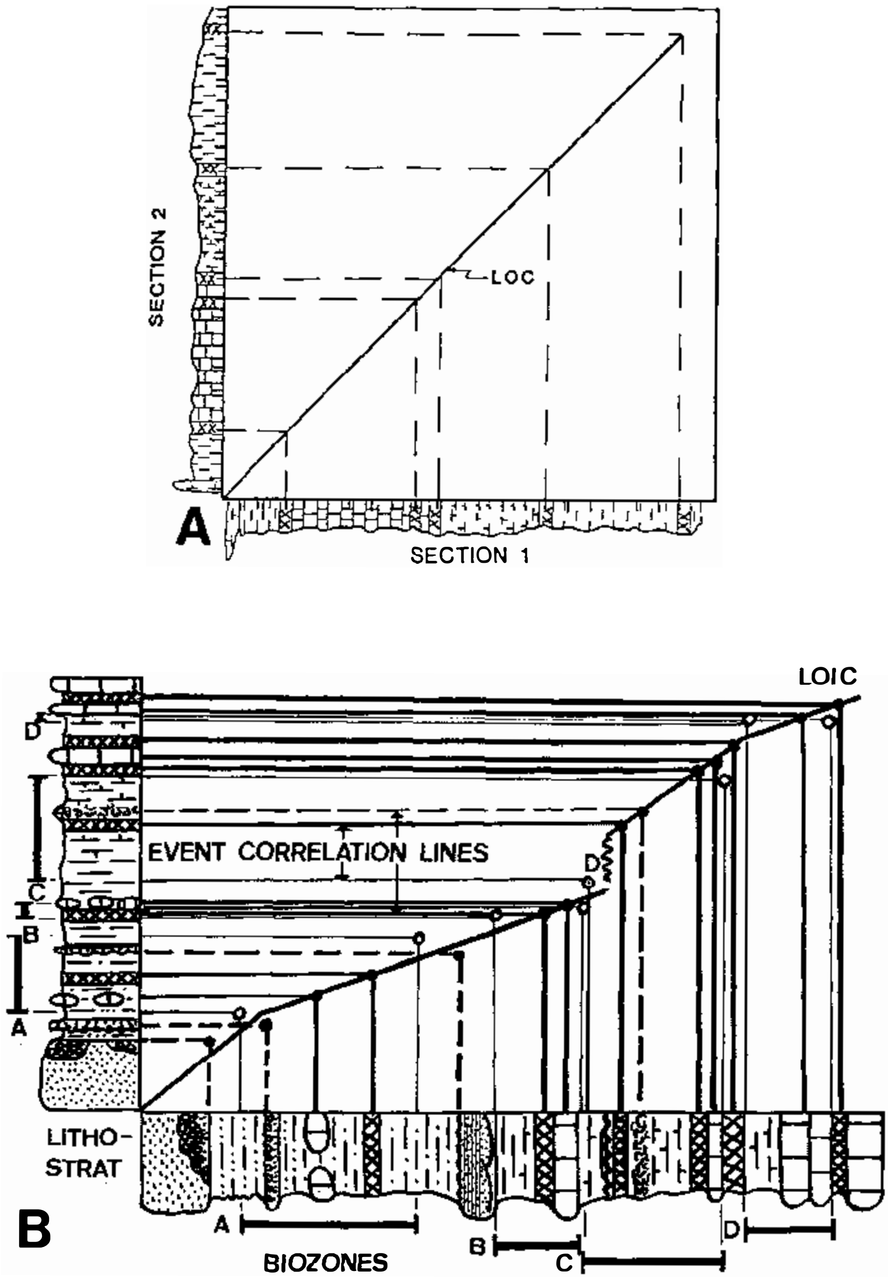
Definition and detailed description of potential physical, chemical, and biological event units in individual measured sections of a traverse are only the first steps in HIRES. Each such unit must subsequently be tested and proven to be representative of a short-term isochronous regional event before it can be incorporated into a high-resolution event chronostratigraphy. The proof we seek is our ability to precisely correlate such units among numerous stratigraphic sections within a study area, with each event unit maintaining a relatively constant position in comparison to adjacent event units, some of which must be indisputable chronostratigraphic surfaces, i.e. volcanic ash/bentonite horizons.

Correlation is accomplished by two methods: (*a*) Standard visual section matching, which may or may not involve lateral tracing of individual beds over essentially continuous outcrop belts between sections; and (*b*) graphic correlation techniques (Miller 1977, Edwards 1984).

Standard correlation techniques (Figure 3) rely heavily upon the initial recognition of lithologically unique event-marker beds and, independently, upon detailed biostratigraphy to establish a coarse but secure correlation between two sections; this correlation then moves to the examination of smaller-scale event-stratigraphic units and their correlation between sections. The process proceeds from the section with the most data toward the nearest satellite section, and from there toward the next nearest section, and so on. As seen in Figure 3, correlations can be made using this method, relying primarily on event-stratigraphic units, to a high level of resolution (100 kyr or less per event-bounded interval).

Graphic correlation provides an even more detailed and objective means of correlating event units and more dissimilar, distantly spaced sections. Edwards (1984) provides the most up-to-date and easily understood review of the technique. In standard graphic correlation, as normally practiced prior to the development of HIRES, two stratigraphic sections plotted to the same scale are laid out along the *X*- and *Y*-axes of the graphic plot (see Figures 16, 17) and adjusted so that some known correlation surface(s) or biozone(s) common to both would produce lines of intersection near the center of the graphic field. First and last occurrences of key biostratigraphic indices in both sections are then plotted as separately marked intersects in the field, and when all such data are plotted, a line of graphic correlation is plotted by eye or (more commonly) by regression analysis. With this line in place, variations in slope of the line across the field of correlation are taken to indicate differences in sedimentation rates between the sections, and breaks in the line are taken to indicate missing sections (i.e. disconformities or faults) on one or both axes. Intervals of the stratigraphic sequence in both sections, and the historical events they represent, are considered to be essentially coeval if their points of intersection in the field of correlation fall on or within a standard deviation of the line of (biostratigraphic) correlation (LOC). After correlation of the first two sections (commonly the most complete available), data from both are composited on the vertical axis, calibrated, and a third section is placed on the horizontal axis for correlation to the composite standard data set [see Edwards (1984) and Miller (1977) for technique]. Figure 17 shows two examples from the Cretaceous of the Western Interior Basin of biostratigraphic vs event-stratigraphic correlations between (*A*) two Coniacian, lower Niobrara Formation sections (Barlow 1985), and (*B*) two Cenomanian–lower Turonian Greenhorn cycle transgressions in the Western Interior Basin. In this standard type of graphic system, regional correlation is wholly based on biostratigraphy without consideration of the relative value of first vs last taxa occurrences in the section (although these can be sorted out, and first occurrences give more consistent correlation). Only recently have the users of standard graphic correlation begun to integrate available magnetostratigraphic, geochronologic, and chronostratigraphic data into older, biostratigraphically based systems.

High-resolution event stratigraphy (HIRES) makes possible a new dimension in graphic correlation. It develops both the line of correlation between two sections and the composite standard, based primarily on isochronous or short-term event deposits. The resultant line of correlation becomes a line of isochronous correlation (LOIC), and any two points or intervals that intersect it, or come within a standard deviation of the line, are considered to have occurred at the same absolute point or interval of time. The line can further be calibrated to real time by tying it to trusted radiometric dating. The advantages of this system are (*a*) it can be based on many more points (event-stratigraphic units); (*b*) it does not have



HIRES MODELS FOR GRAPHIC CORRELATION

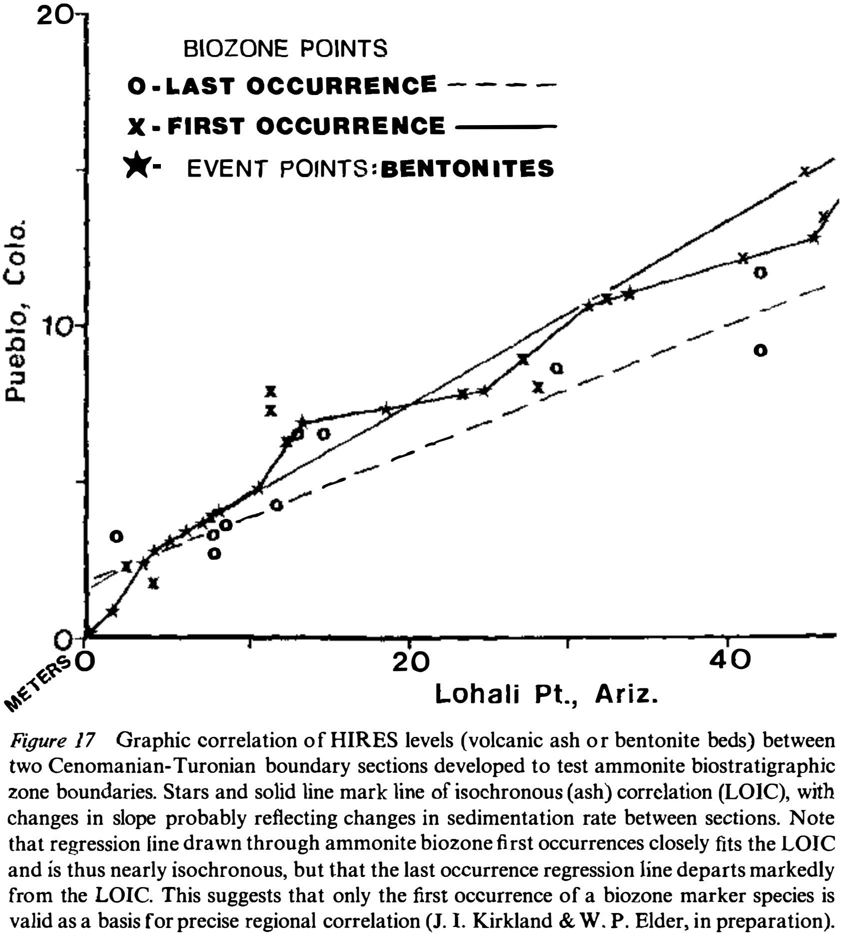


Figure 17 Graphic correlation of HIRES levels (volcanic ash or bentonite beds) between two Cenomanian-Turonian boundary sections developed to test ammonite biostratigraphic zone boundaries. Stars and solid line mark line of isochronous (ash) correlation (LOIC), with changes in slope probably reflecting changes in sedimentation rate between sections. Note that regression line drawn through ammonite biozone first occurrences closely fits the LOIC and is thus nearly isochronous, but that the last occurrence regression line departs markedly from the LOIC. This suggests that only the first occurrence of a biozone marker species is valid as a basis for precise regional correlation (J. I. Kirkland & W. P. Elder, in preparation).

the same potential for error as biostratigraphic correlations in which ecological, evolutionary, and preservational controls can severely distort or modify the field data for any section, and thus the correlations; (*c*) it provides a real time matrix for basin analysis and for looking at the short-

Figure 16 (*A*) Simple model of graphic correlation to develop an isochron event correlation line from volcanic ash beds in two sections [X's and dashed lines; LOC is solid diagonal line (from Barlow 1985)]. (*B*) Detailed model for graphic correlation of high-resolution event stratigraphic data from two sections (after Kauffman 1986) showing development of line of isochron correlation (LOIC) from event units (ash layers and climate cycle beds), near-correlation of mass flow deposits to this line, and position of biozone first and last occurrence points (open circles), which are close but not isochronous.

term dynamics of any system; and (*d*) if the event units are carefully chosen, this system has a more regional, facies-wide potential for correlation than biostratigraphy, where even the best organisms may be subjected to subtle ecological (habitat) controls on occurrence.

Further, the HIRES graphic correlation system can provide an independent check on the accuracy of biostratigraphic, geochronologic, and magnetostratigraphic data and correlations based on them; yet the system is open ended enough to incorporate any type of data for testing or compositing. Figure 16*B* shows a model of the HIRES graphic correlation system, based on a set of a actual correlations between two complex Cretaceous sequences in Arizona and Colorado. Clearly, ash/bentonite correlation units form the basis for construction of the HIRES graphic correlation system, with Milankovitch climate cycle deposits and concretion horizons running a close second in utility.

Figure 17 shows a Cenomanian-Turonian correlation matrix of HIRES event units (volcanic ashes/bentonites) in the Western Interior Basin against which are plotted the first and last occurrence points of key ammonite biostratigraphic indices. Note that the first occurrences of ammonite taxa fall very close to LOIC, but that last occurrences (local population extinctions) in some cases fall considerably beyond the LOIC; this, in turn, suggests that first occurrences of index taxa in biostratigraphy are the most trustworthy in correlation, and, in addition, that dispersal of newly evolved or immigrant taxa can be very rapid and geographically widespread (data from J. I. Kirkland & W. P. Elder, in preparation).

APPLICATIONS OF HIRES

High-resolution event stratigraphy, especially when correlated through graphic correlation, forms a powerful new tool of stratigraphy and basin analysis. It achieves, for the Cretaceous of the Western Interior Basin of North America as an example, a resolution averaging about 50 kyr per HIRES event-bounded interval for basinal settings, and about 100–150 kyr for marginal facies in the basin. At the coarsest level, HIRES equals the finest level of biostratigraphic zonation developed for the basin; HIRES thus creates a new and more precise dimension in regional correlation. As such, and especially when integrated with a large radiometric data set, HIRES is well suited for looking at the rates and patterns of geological, biological, oceanographic, and climatic evolution within sedimentary basins, and for integrating diverse data in basin analysis. Some basic examples of the interpretive potential of HIRES within the Western Interior Basin are given by Kauffman (1987), who demonstrated the following applications (Figure 18):

HIRES REGIONAL CORRELATION OF MARINE AND TECTONIC EVENTS

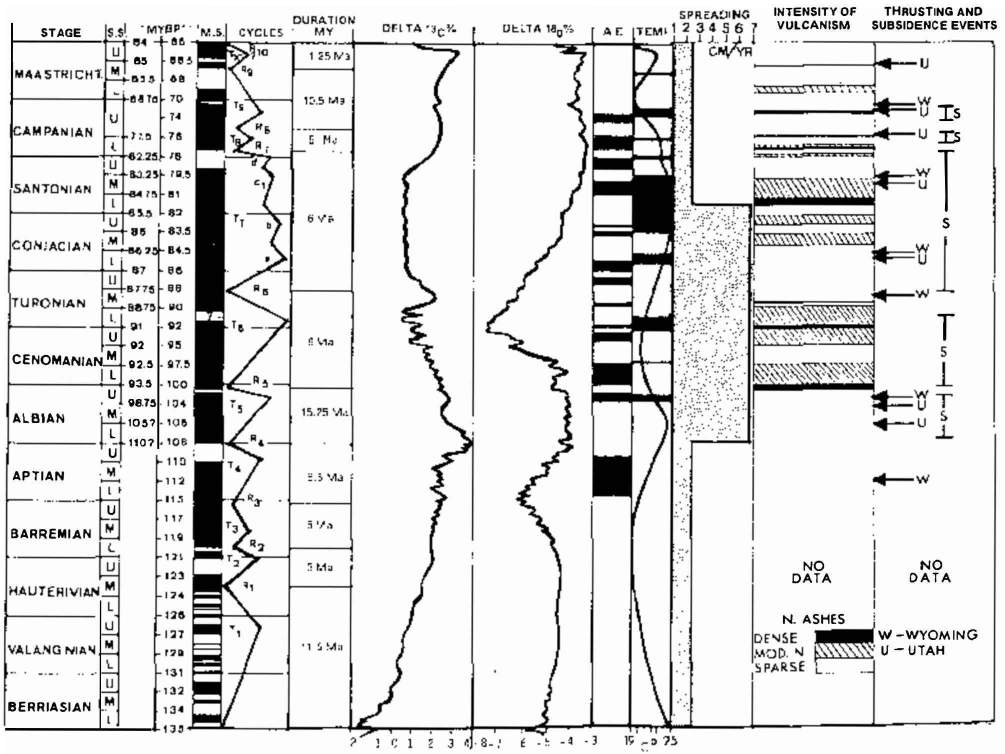


Figure 18 Summary diagram of tectonic and oceanic events for the Cretaceous of the Western Interior Basin of North America (from Kauffman 1984), with correlations calibrated by high-resolution event stratigraphy. Note close correlation of tectonic and volcanic events to global sea-level rise and transgression into epicontinental seas (right-sloping line and T numbers on left side), and correlation of tectonic quiescence with regression and sea-level fall (left-sloping lines), suggesting a dominant plate-tectonic control on both eustatic history and continental tectonic history. Note also correlation of anoxic events (AE) with eustatic rise (CYCLES) and with warm temperature shifts (dark shading under TEMP).

1. Calculation of the timing, volume, and magnitude of volcanism, based on bentonite (ash) volume and distribution within the basin and mapping of the source and distribution of single ash beds within narrow time intervals. From the latter, paleowind directions can be calculated. Most volcanic ash was derived from northern (Idaho, Montana) and southwestern (Arizona, New Mexico, Texas) source areas; 80–85% of explosive volcanism was correlated with active thrusting and tectonic movement in the Cordilleran region and with eustatic rise, suggesting a connection to increased spreading and subduction rates along the Pacific margin of North America.

2. Calculation of the timing and relative magnitude of tectonic movement within the basin, including thrusting, normal faulting, subsidence, rebound, and regional movement on tectonic blocks. It was concluded that most active tectonism in this region was associated with eustatic rise events, reflecting accelerated Pacific spreading and subduction rates; that tectonic activity was episodic and commonly short term; and that intervals of tectonic and volcanic quiescence were largely associated with eustatic fall intervals and with slowing of rates of ocean spreading and subduction. From this, a two-phase model of tectonics within the basin was developed (Kauffman 1985a, 1986a), linked to plate movements and sea level, and it was determined that active subduction drove regional Cordilleran and basin tectonics without significant time lag.

3. The rates and magnitude of paleoceanographic phenomena were documented in great detail. Second through sixth-order absolute and relative sea-level changes (Kauffman 1985a) were calibrated and correlated within very narrow time intervals to global standards of eustatic history and sequence stratigraphy (e.g. to those in Haq et al 1987). Anoxic and dysaerobic events were identified throughout the Cretaceous and linked in time to eustatic rise and highstand intervals, and rarely to early regression and eustatic fall. It was determined that these events resulted from very rapid (100 kyr or less) stratification and destratification within the marine water column. The effects of Milankovitch climate cycles on stratification and on salinity and oxygen levels within the basin were documented to within at least 40–50 kyr intervals involving cyclic stratification and deoxygenation events (wet phase), followed by normalization of marine chemistry and circulation (dry phase). Major changes in watermass characteristics (temperature, circulation, chemistry) were shown to be closely related to rapid immigration of warm watermasses from the Gulf of Mexico (Kauffman 1984b); these pulses have been calibrated (intervals of rapid immigration or emigration take under 100 kyr regionally) and correlated to peak eustatic rise events. Biological response to these diverse

oceanographic changes could be documented within 100-kyr intervals or less.

4. Sedimentation rates can be calibrated within 50 kyr stratigraphic intervals for all facies within the basin (see Elder & Kirkland 1985), and thus short-term changes in these rates due to tectonic movement, sediment supply, or biological productivity can easily be plotted. Tracing of individual ash beds across the basin relative to sediment thickness between them allows detailed calibration and identification of bypass and disconformity surfaces associated with eustatic highstand, ravinement development, regional submarine uplift, and sediment starvation in the central basin.

5. HIRES provides a powerful tool in the interpretation of biological events within the basin: rates and patterns of evolution; dispersal rates and patterns; the nature and biogeography of population bursts, productivity events, community and species dispersion, and both population and ecological structure. Biostratigraphic zone boundaries, and individual taxa used in biostratigraphy, can be calibrated and evaluated against HIRES matrices, especially by utilizing graphic correlation. Most biostratigraphic indices for the basin correlate closely to graphic axes of event stratigraphy, suggesting near- (but not absolute) isochronous boundaries. First appearances of biostratigraphically useful taxa fall closer to "time lines" than do last appearances.

SUMMARY

High-resolution event stratigraphy is a new and powerful tool of regional stratigraphy. It can be used to precisely correlate stratigraphic sections and develop theory and tests for basin analysis, paleoceanography, paleoclimatology, evolution, and biostratigraphy. In the Western Interior Basin of North America, the Cretaceous marine sequence is dominantly composed of allocyclic and perturbational event units that are isochronous or short term (100 kyr or shorter) in aspect. These have allowed a very detailed HIRES to be developed, with resolution in correlation between 50 and 100 kyr, and less for some intervals. This exceeds the resolution of any other system of stratigraphy. HIRES has many applications, and it is still in the development and testing stage.

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