Controls on carbonate and siliciclastic sediment deposition on a mixed carbonate-siliciclastic shelf (Pennsylvanian Eastern Shelf of north Texas)

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Abstract Patterns and trends of carbonate and siliciclastic lithologies in late Paleozoic cyclothems are used as the basis for identifying the factors controlling deposition in mixed carbonate-siliciclastic systems. The cyclothems examined in detail occur on the Eastern Shelf of the Midland basin in north Texas. Cyclothems are products of deposition in shelfwide mixed carbonate-siliciclastic systems and contain an intermediate water depth carbonate zone positioned between a shallow nearshore zone of siliciclastic deposition and a deep-water outer shelf zone of siliciclastic deposition. Carbonate sedimentation was largely depth controlled, because carbonate sediment production was primarily from microbes, multicellular algae, or other light-controlled benthic organisms. Siliciclastic sedimentation in the noncarbonate outer shelf environments resulted from pulses of fine-grained siliciclastic sediment traversing the carbonate zone in storm-generated suspension clouds. Increased siliciclastic sediment input narrowed the carbonate zone on the shelf but did not greatly shift its central position. Cyclothem deposition corresponds to a limited range of conditions covered in a general model of mixed carbonate-siliciclastic deposition on shelf surfaces. The major variables in this model are the quantity and composition of siliciclastic sediment delivered to the shoreline and carried onto the shelf, the depth of the lower limit of the photic zone as it intersects the shelf surface, the gradient of the depositional surface, and the proportion of benthic production to planktic production of carbonate sediment. In systems where carbonate sediment is predominantly benthic in origin (Paleozoic and Triassic oceans), the first three variables are dominant and result in outer shelf siliciclastic deposition beyond a carbonate zone. In systems where planktic production of carbonate occurs (Jurassic to modern warm-water oceans), planktic production of carbonate tends to overwhelm benthic production and produces carbonate deposition on outer shelf surfaces. General patterns of sedimentation are set by the benthic/planktic production ratio and the gradient of the depositional surface, whereas specific patterns are produced by the amounts of siliciclastic sediment transported onto the shelf and the manner in which the photic zone intersects the shelf.

Understanding the nature of controls on sediment deposition in settings with concurrent carbonate and siliciclastic deposition is usually difficult. These are areas where processes of siliciclastic and carbonate sedimentation interact and produce a depositional regime dissimilar to that present in the more familiar carbonate or siliciclastic systems. The depositional controls that dominate in this regime are poorly known, and what is known is too general to describe trends in carbonate-siliciclastic composition or to specify the spatial context of different types of sediments deposited there. Only recently have settings with mixed carbonate-siliciclastic deposits received much attention, and attempts to model these settings are limited. This can be improved, and current work with Carboniferous cyclothem deposits has indicated better ways to model mixed carbonate-siliciclastic systems and to identify depositional controls.

Mixed carbonate-siliciclastic deposition is usually described within the context of a simplistic framework in which siliciclastic sediments occur in shoreward areas and carbonate sediments occur outward on a shelf or platform surface (fig. 1). In this system carbonate and siliciclastic sediments are separated by a boundary zone whose position on the shelf varies like the front between warring factions on a battlefield; mixtures of carbonate and siliciclastic sediment are confined to transitional mixing zones between the carbonate and siliciclastic fields (Mount, 1984; Doyle and Roberts, 1988). The rest of the area in this system is examined with the use of depositional models pertaining to completely carbonate sedimentation or completely siliciclastic sedimentation. The simplicity of this concept makes it easy to apply, so the concept is widely used to interpret ancient sedimentary deposits.

In many cases, however, the depositional patterns of carbonates and siliciclastics do not fit this pattern. There is much evidence for reversed placement of carbonate and siliciclastic zones, with siliciclastic deposits outboard (i.e., in a position farther away from shore) from carbonates, on shelf surfaces in Carboniferous depositional systems. Reversed sediment placement is not a part of conventional models covering mixed depositional systems, even though the pattern could be produced locally where the boundary zone between siliciclastics and carbonates is highly irregular. Reversed sediment placement in Carboniferous depositional systems occurs on middle to outer shelf areas, beyond

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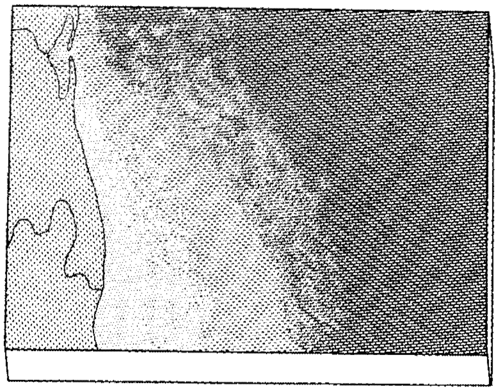

Figure 1. Carbonate-siliciclastic depositional system with inner shelf siliciclastic deposition and outer shelf carbonate deposition. This is a commonly used model for mixed carbonate-siliciclastic deposition and is a variant of the more general model described here.

nearshore areas with siliciclastic sediments. A reasonable conclusion to draw from these observations is that a nearshore siliciclastic–outboard carbonate relationship applies only to the inner part of shelves and not to depositional trends seen across a complete shelf transect.

These depositional relationships are better examined with more inclusive models that encompass large-scale mixed carbonate-siliciclastic depositional systems and are shelfwide in scope. Models of this type have not yet been developed, so here a general mixed carbonate-siliciclastic model is developed in which variations in depositional controls produce predictable variation in depositional patterns. This model provides a better understanding of the details of depositional trends in transitional mixing zones between carbonates and siliciclastics and leads to a better understanding of shelf-scale processes of sediment transport and deposition.

Depositional trends in Carboniferous cyclothems

Depositional trends in Carboniferous cyclothems provide data on which conclusions about depositional controls for mixed carbonate-siliciclastic systems can be based. The complexity and abundant occurrence of cyclothem deposits make them good starting points for developing a general model. Carbonate and siliciclastic deposits and changes in sediment grain size occur in ordered sequences and are related to position in cycles, as shown in fig. 2, which shows sections of cyclothems in Texas deposited under a wide range of conditions [see other examples in Yancey and McLerran (1988)]. Cyclothems from other regions could have been used equally well, but these have been studied in detail. The generalized vertical sequence of marine and nonmarine deposits in a cyclothem are shown in fig. 3, which is similar to the familiar sequence of cyclothem deposits shown by Moore (1936) for Kansas cycles, as modified by Heckel and Baesemann (1975). The model can be extended to cover a wide range of cyclic depositional sequences, including the original Illinois-type cyclothem described by Weller (1931) and the Texas-type cycles illustrated by Brown et al. (1973).

The sections shown in fig. 2 indicate that deposition during transgression tends to produce a reversed sequence of units from that deposited during regression, not a completely different type of lithologic sequence. Transgressive sequences are as variable as regressive sequences but show the same tendency to develop a lithologic sandwich of siliciclastics holding a center of carbonates within the hemicycle. Transgressive lags and condensed sections are rare in cyclothems.

Inasmuch as cyclothems are genetic units of strata deposited during a period of rising sea level followed by stillstand and falling sea level, they contain sediments deposited under conditions of regularly changing water depths with lithologic changes tracking changes in water depths. Trends in water depth change are also documented by zonations of macrofossils and microfossils. The macrofossil and microfossil depth zonation for Late Pennsylvanian midcontinent shelf deposits shown in fig. 3 is an outgrowth of conodont depth zones proposed by Heckel and Baesemann (1975) combined with macrofossil zones presented by Adlis et al. (1988). Adlis et al. (1988) presented stable isotope profiles within cyclothems that show that temperature variations correspond to depth trends inferred from macrofossils, microfossils, and lithology and provide a basis for making estimates of water depths.

Lithologies such as sandstone-dominated units, carbonates, and phosphatic black shales tend to occupy predictable depth-related positions in cyclothems. Variation is common, but the sequence is ordered and variations are due to omission of particular lithologies, not reversal of sequence or random placement in the cyclothem.

Sandstone-dominated units are characteristic of nearshore depositional environments, where high-energy currents or sustained wave action concentrates sands. Adjoining areas of lower energy conditions receive mud deposits, producing the typical sequence of interbedded sandstone and mudstone units associated with shallow-water deposition. Carbonates are excluded from most nearshore environments by shoreline sources of siliciclastic sediment. The extent to which carbonate sedimentation is displaced shelfward is determined by the amount and type of siliciclastic sediment supplied to the shoreline. Distinctive fossils in deposits of these environments are large shells with thick walls, typified by fossils of the myalinid assemblage.

Marine carbonates nearly always occur between nearshore siliciclastics and deeper water cycle-center shales within transgressive and regressive hemicycles of Missourian age cyclothems (fig. 2). The carbonate may vary in character and thickness [to the extent that it is suppressed entirely in one or both hemicycles, as in the East Mountain (fig. 2A), Colony Creek (fig. 2B), and Finis (fig. 2C) cycles, or enhanced to the point of dominating the hemicycle, as in the Necessity (fig.

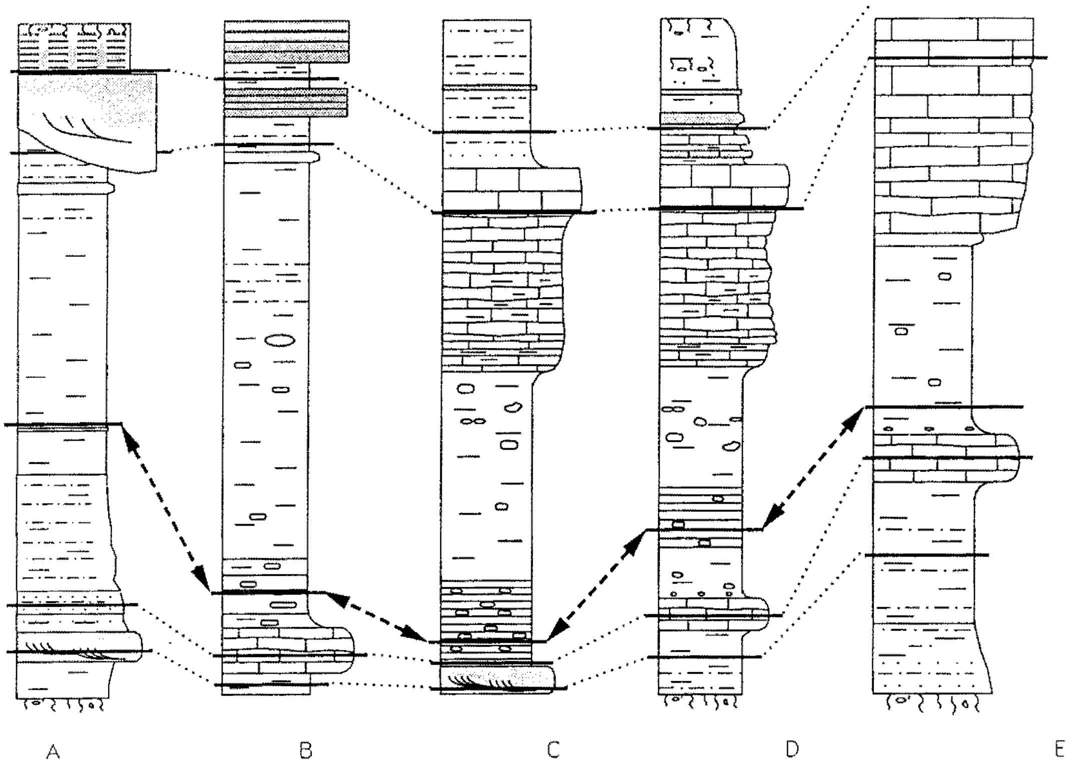

Figure 2. Suggested correlation of units in cyclothems that are lithologically different. The dashed line correlates cycle-center horizons separating transgressive and regressive hemicycles; the dotted lines show equivalent positions of shore zone and nearshore shelf environments in transgressive and regressive hemicycles. Water depths are documented by macrofossil and microfossil zones present in deposits. All cycles based on Late Pennsylvanian Eastern Shelf sections in north-central Texas and scaled to the same vertical dimension [cycles are approximately 15 m (50 ft) thick, except for section E, which is approximately 7 m (23 ft) thick]. (A) Nonlimestone cyclothem with transgressive sandstone and regressive sandstones; top East Mountain cycle with Lake Pinto sandstone at top, US–180, Mineral Wells, Texas. (B) One-limestone cyclothem with transgressive limestone and regressive sandstone beds; Colony Creek cycle with top of Ranger limestone at base, Brad, Texas. (C) One-limestone cycle with regressive limestone, transgressive sandstone (marine), and thick phosphatic black shale; Finis cycle with Jacksboro limestone in regressive hemicycle, Jacksboro, Texas. (D) Two-limestone cyclothem with thick cycle-center shale and shoal-water carbonate grainstone at top of regressive limestone; Necessity cycle with Bunger limestone in transgressive hemicycle and lower Gunsight limestone in regressive hemicycle, Lake Brownwood, Texas. (E) Two-limestone cyclothem with thick nearshore siliciclastic interval in transgressive hemicycle; upper Winchell cycle, Lake Brownwood spillway, Texas.

2D) and Winchell (fig. 2E) cycles and most Missourian age cycles in Kansas] but does not change relative position. In some regressive sequences carbonate deposition continued up to the shoreline, as marked by the deposition of well-washed grainstones (often oolitic) and exposure surfaces developed directly on the carbonate, but most regressive carbonates are covered with a thin or thick layer of nearshore siliciclastics. The common occurrence of argillaceous carbonates and occasional occurrence of carbonates with siliciclastic sand content show that carbonate and siliciclastic deposition intergraded. The placement of carbonate in Texas and Kansas cyclothem deposits corresponds to deposition in moderate to shallow water depths on shelf surfaces. Distinctive fossils in deposits of these environments are fusulinids and platy algae.

Cycle-center deposits are clay shales and often include platy black shales with common phosphate nodules. These are similar to many basinal black shales, deposited during conditions of dysoxic bottom waters or development of dysoxic pore fluids in the sediment. They contain distinctive fossils (ammonoids and gondolellid conodonts) that occur primarily in deposits of deep-water environments. Cycle-

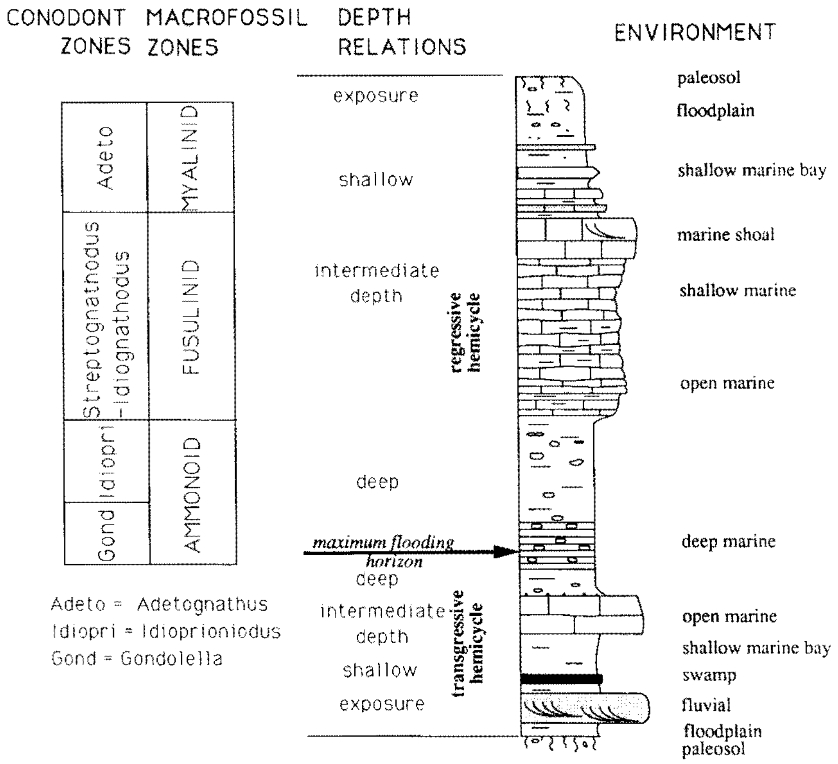

Figure 3. Depth, depositional environment, and fossil zone relations in Late Pennsylvanian cyclothems. The stratigraphic column portrays a composite cyclothem, with a full range of lithologies and marine and nonmarine depositional environments. Fossil zones adapted from Heckel and Baesemann (1975) and Adlis et al. (1988).

center black shales have been related to development of a dysoxic zone at the bottom of the water column during maximum transgression (Boardman et al., 1984; Coveney et al., 1991), in the presence of a thermocline or halocline that reduces the amount of organic degradation in bottom sediments. These black shales accumulated under conditions of high organic productivity and low rates of sediment deposition. As such, the shales fit easily into the concept of depth-controlled changes in sedimentation. The boundary between cycle-center shales and carbonates is usually sharp or occurs within a narrow zone. Cycle-center shales contain little carbonate.

Mixed carbonate-siliciclastic depositional model for Carboniferous cyclothems

Carboniferous cyclothems contain siliciclastic deposits in the portion of the cycle that was deposited in deepest water in positions that were outboard of carbonate deposition on a shelf surface (Yancey, 1986). This relationship is apparent from the sandwiching of carbonate deposits between shallow-water siliciclastics and deeper-water siliciclastics in nearly all cyclothem sequences in vertical and lateral directions. When seen on a shelf surface, a pattern of nearshore siliciclastics, inner to middle shelf carbonates, and outer shelf siliciclastics is produced (fig. 4).

This pattern of deposition shows that the simplistic framework with nearshore siliciclastics and outboard carbonates (a relationship suggested in Moore's ideal cyclothem) is only half the picture—a subset of the more complex pattern. In the cyclothem-generated model the locus of carbonate deposition occurs preferentially on the middle to inner shelf in shallow to moderate water depths, not on the outer shelf. The whole shelf is a mixed carbonate-siliciclastic depositional system, with concurrent siliciclastic sedimentation occurring in a disjunct pattern of innermost and outer shelf positions. Such patterns of deposition can be logically explained and integrated with the simpler model of nearshore siliciclastic deposition and outboard carbonate deposition on a shelf.

In this depositional model carbonate sediment production and deposition are responsive to water depth control and less sensitive to the inhibiting effects of siliciclastic sedimentation than has been assumed by previous workers. Depth control is a function of light penetration of the water column, because most carbonate producers are plants or animals with

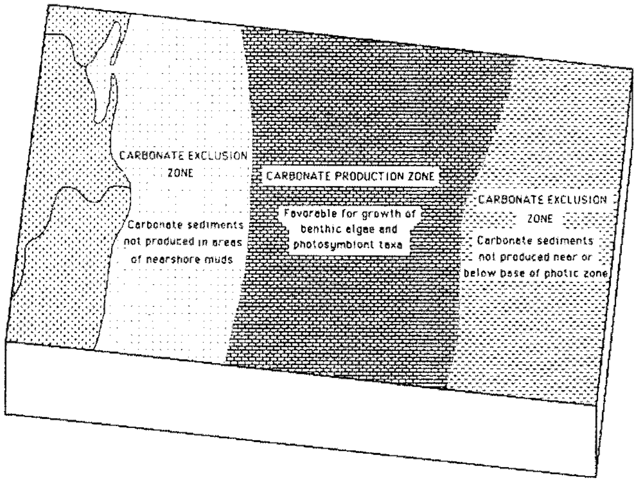

Figure 4. Relationship of carbonate and siliciclastic sedimentation on an inclined shelf surface of the Pennsylvanian. Carbonate deposition is limited to areas of growth of benthic carbonate-producing organisms, which are excluded from most nearshore locations and deep-water locations.

photosymbionts living in their tissue (Hallock and Schlager, 1986). If extracellular precipitation of carbonate by photosynthesizing microbes is important (Thompson and Ferris, 1990), the microbes are also limited to the photic zone. Deeper-water seafloor, located on the outer portions of shelves, lay in areas where the light intensity was too low for carbonate sediment producers to generate enough skeletal material to produce carbonate sediment. Concurrent transport of siliciclastic sediment across the shelf, even in small amounts, provides enough sediment to produce a siliciclastic outer shelf sediment cover. This implies that siliciclastic sediment is transported across and beyond the carbonate zone and that active carbonate production and deposition occur under a wide range of siliciclastic deposition. The whole shelf surface is within a large mixed carbonate-siliciclastic depositional system. These types of mixed carbonate-siliciclastic complexes are deposited on graded, ramplike shelf surfaces, which should be considered the norm for shelves, in contrast to a concept of shelf deposition on a horizontal surface. Some aspects of this model invoke processes and relationships that are unfamiliar in carbonate or mixed carbonate-siliciclastic modeling, but the model more adequately explains occurrences of mixed carbonate-siliciclastic deposits in numerous cases, especially in cyclothem deposits, which can contain carbonate and siliciclastic sediments in almost any proportion.

Thus cyclothem deposition is a consequence of normal shoreline input of siliciclastic sedimentation onto shelf surfaces where carbonate sediments are generated in favorable locations and where dysoxic bottom water conditions develop in areas of high organic input and low sedimentation rate. Carbonate sediment deposition is controlled by the combination of light penetration (lower limit of the photic zone) and siliciclastic deposition, with wide ranges in the boundary conditions set by these two factors. If the light level is high, carbonate sediment production can continue under moderately high levels of siliciclastic deposition. The interaction of these two factors on the seafloor determines the location and extent of carbonate deposition. Siliciclastic sediment type is determined by the sand to mud ratio, the amount of organic input, the rate of sedimentation, and oxygenation of the water column. Variation in these factors produces variations of the familiar cyclothem model.

The growth of phylloid calcareous algae was an important factor controlling carbonate deposition in quiet-water shelf environments with direct accumulation of skeletal debris, which in turn provided a place for the growth of lime-mud producers. This is best seen in regressive carbonates of cyclothems, where calcareous phylloid algae occur frequently as a major skeletal component of the deposits or in a thin phylloid-algal zone at the base of the unit. Phylloid algae, like some of their modern descendants among the peyssonnelliaceans (James et al., 1988), preferred mud substrates and were capable of colonizing lime-mud or clay-mud bottoms. They are usually the main macroskeletal remains to be found in transitions from clay mud to lime mud, and the appearance of phylloid algae correlates closely with the change to carbonate deposition. Deposits containing phylloid algae often contain many thin shale (clay-mud) breaks and show repeated colonization of phylloid algae on mud surfaces. The commonness of phylloid algae in cyclothem carbonate sediments is a function of the continued entry of siliciclastic mud into carbonate areas during cyclothem deposition. Phylloid-algal deposits usually occur as broad, sheetlike deposits and less often as raised banks or mounds.

Deposition on a sloping shelf

The depth-related depositional trends seen in cyclothems and deductions about sediment transport that they generate suggest that cyclothems were deposited on shelf surfaces similar to those on modern continental shelves, which have inclined ramplike surfaces. There are some semantic and conceptual problems to handle here because the term "shelf" (and "platform") is often used to mean an essentially flat-lying surface with minimal or no gradient, especially for carbonate systems. Read (1985) introduced the term "distally steepened ramp" to refer to carbonate surfaces graded like modern shelves and restricted the term "shelf" to flat-lying surfaces with minimal gradient. This restricted usage of "shelf" is applied in many cases involving carbonate depositional systems but not for mixed siliciclastic-carbonate or siliciclastic depositional systems, although the surfaces may have the same gradient and form. Current literature continues to use the term "shelf" to apply to any surface behind a shelf-slope boundary, which generally consists of inclined surfaces similar to modern shelves. As used here, a shelf is a morphologic feature consisting of a submerged, gently inclined surface (similar to modern continental shelves) separated from a basin by a more highly inclined surface. The outer edge is coincident with a shelf-slope boundary. The patterns of carbonate and siliciclastic deposition seen on inclined shelves would also develop on ramp surfaces.

Areas of cyclothem deposition in western Kansas and north-central Texas best fit the inclined shelf concept. They contain drainage patterns developed during times of exposure that indicate little change in the direction of drainage; the degree of incision of fluvial channels indicates that the channels were flowing on surfaces much above base level. The Eastern Shelf of the Midland basin in north Texas has been studied well, and it illustrates this condition. This shelf maintained a similar morphology during the Pennsylvanian and Permian (van Siclen, 1969) and was more than 100 km (60 mi) wide with a margin that stood as much as 330 m (1,100 ft) above the floor of the Midland basin during the Late Pennsylvanian (Galloway and Brown, 1973). Fluvial channel sandstones on the shelf show a consistent pattern of west-trending flow (Brown et al., 1973; Bloomer, 1977) and a shelf with a regional gradient inclined toward the shelf margin. Comparable channeling occurred on shelf surfaces in Kansas (Mudge, 1956). The accumulation of carbonate deposits had little effect on the gradient, and many Eastern Shelf carbonates occur as tabular accumulations.

Calculations of the slope of the gradient can be made by comparison to wider portions of the continental shelf in the modern Gulf of Mexico, which is similar to the Eastern Shelf in being an aggrading and prograding shelf with a sharp shelf-slope margin. The Gulf of Mexico shelf has maintained this form for 100 m.y. (Winker, 1982). Gradients over large segments of the modern Gulf shelf range within 0.4–0.7 m/km (0.8–1.4 ft/mi) across shelf widths of 100–200 km (62–125 mi), and adjoining coastal plains have gradients of 0.4–0.9 m/km (0.8–1.8 ft/mi) across widths of 200–400 km (125–250 mi). (Gradients were calculated from measurements made on bathymetric and topographic maps of the gulf region.) Similar gradients exist on the Atlantic continental shelf of the southeastern states, and they are accepted as typical for prograding and aggrading siliciclastic continental shelves. Using this relationship, one can calculate water depths on the Eastern Shelf if one knows a shoreline position. Shelf segments with a shoreline position 100 km (60 mi) inward from the shelf-slope edge would have depths of 40–100 m (130–330 ft) on the outer shelf. Marine inundation of more than 100 km (60 mi) from the shelf-slope margin (the distance from shelf edge to outcrop belt) occurred many times during the Late Pennsylvanian, suggesting that water depths of at least 100 m (330 ft) occurred frequently on the outer shelf. The Pennsylvanian (and Quaternary Gulf Coast) shelf remained an aggrading feature because fluctuating sea levels moved the shore zone, an area of high sedimentation rate, back and forth across the shelf to maintain a graded condition on the shelf surface.

This maintenance of an inclined surface is important in understanding sediment deposition because it implies that water depths normally increase away from shoreline. Water depths change in predictable ways during transgression and regression. Lithologic trends observed in vertical sequence are similar to lateral depositional trends, and Waltherian relationships are valid to work out general relationships. This does not support the hypothesis that depositional sequences are either aggradational or progradational in nature, but that concept may be too general to apply to specific portions of cyclothems.

Siliciclastic sediment pass-through over carbonates

A carbonate zone located on the middle to inner shelf should present barriers to the movement of siliciclastic sediment onto the outer shelf, which raises the question of determining the source of clay-mud sediments that accumulate beyond the carbonate zone. The repetitive occurrence of clay-rich muds in the middle of cycles argues for a simple mechanism for transport of clay muds onto the outer shelf. A counterview that all carbonate depositional environments on the shelf disappeared during maximum transgression and gave way to siliciclastic sedimentation spreading across the entire shelf cannot be disproven but is harder to reconcile with observed trends of sediments in the cycles. Upwelling and increased plankton production at maximum transgression could have reduced the photic zone (because of decrease in water clarity) to a point where carbonate production was severely curtailed in some areas, but this does not explain the absence of carbonates from the cycle-center position in nearly all Carboniferous cyclothems. A shelf reconstruction that employs encroaching deltas as a means of disrupting the carbonate zone and spreading clay-rich muds on the outer shelf is possible, but this means of siliciclastic sediment transport is considered too erratic to produce the many cycles with clay shales at midcycle position.

Episodic pass-through of fine-grained sediment moving in storm-generated suspension clouds over the carbonate zone is a simple means of transporting clay muds to areas beyond the carbonate zone without destroying the carbonate factory operating in shallower waters (fig. 5). The Eastern Shelf and other midcontinent shelves contained few topographic barriers to outward dispersal of resuspended sediment. Periodic flooding from rivers flowing into the ocean and storm waves shoaling within the nearshore zone could put sufficient mud into suspension in higher-density water masses to periodically supply the outer shelf locations, even under conditions of an exponential decrease in suspended sediment away from the shore (McCave, 1972). Some siliciclastic mud would be deposited in the carbonate zone, but it would be diluted by the more abundant carbonate generated in place. Late Pennsylvanian limestones commonly contain 20–40% noncarbonate sediment, suggesting

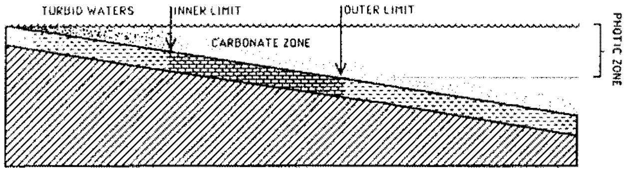

Figure 5. Factors controlling carbonate deposition along a depth transect across an inclined shelf surface. The inner limit is set by the edge of high concentration of siliciclastic muds, whereas the outer limit is set by the intersection of the base of the photic zone on the shelf. Dispersal of fine-grained siliciclastic sediment across the carbonate zone occurs in pulses of gravity-driven flow of bottom-hugging water masses containing suspended sediment. The inner shallow area is a zone of sand and siliciclastic mud deposition; the middle area is a zone of carbonate deposition; and the outer area is a zone of siliciclastic mud deposition.

that large amounts of fine sediment moved over the carbonate zone with some of the sediment settling into the carbonates. The amount of siliciclastic sediment transported across the carbonate zone in this manner may have been small in any one pulse, but substantial deposits could accumulate over a long time. Carbonate mud on the middle to inner shelf would not be carried outward in quantity because resuspension is limited at the greater depths in which carbonate sedimentation occurs.

Rezak (1985) documented this sediment transport process on the modern Gulf of Mexico continental shelf, where suspended fine-grained particles are present in bottom waters up to 20–30 m (65–100 ft) above the seafloor and are most concentrated in the bottom-hugging nepheloid layer. High-standing carbonate banks on the outer shelf receive a coating of silt and clay from this suspension up to 30 m (100 ft) above the surrounding seafloor, but portions of the banks above 30 m (100 ft) are free of silt and clay.

Depth control on carbonate deposition

In cyclothemic depositional systems carbonate sediments were middle-depth deposits because carbonate deposition was limited to or absent in the shallowest and deepest portions of the shelf. Depth control of carbonate sediment production resulted from natural depth limits imposed by autotrophs (calcareous algae, cyanobacterial microbes) and mixotrophs (organisms with microalgal symbionts, for example, hermatypic corals, some sponges, large foraminifers); the upper limit was at zero depth, and the lower limit was at the base of the photic zone. These limits can encompass a wide range of depth, but at most times the range was limited to a narrow depth interval. Siliciclastic sediment input suppressed carbonate sedimentation by displacement at the upper end of the range and by raising the base of the photic zone at the lower end of the range (fig. 5). Under these conditions the width of the carbonate zone varied, but its shelf position relative to the shoreline did not change much under differing siliciclastic input situations. The carbonate zone did not significantly shift outward on the shelf under conditions of higher siliciclastic input.

In shallow depths carbonate deposition was uncommon because of suppression by siliciclastics entering the ocean at the shoreline, which suppressed carbonate producers and drowned out the carbonate component. High concentrations of muds are capable of killing most prolific carbonate-producing organisms. Placement of the boundary was determined by relative rates of siliciclastic and carbonate sedimentation and was quite variable. Low rates of siliciclastic sediment supply allowed carbonate deposition to occur close to shore and in shallow waters, a condition seen in some regressive sequences containing ooid shoal deposits or carbonate beds interlayered with shallow-water siliciclastic deposits. On offshore highs isolated from shoreline siliciclastic supply, the upper limit on carbonate sedimentation was coincident with sea level. Conversely, high rates of siliciclastic sediment supply pushed the boundary farther offshore and into deeper water, until it intersected the base of the photic zone.

At the deep end carbonate deposition was tied to the lower limit of the photic zone, below which carbonate sediment production was suppressed. At low light levels carbonate organisms are not efficient carbonate producers, and carbonate deposition is greatly reduced. The lower limit of the photic zone is also a variable boundary because light penetration is determined by clarity of water; the lower limit of the photic zone is raised as water opacity increases. In shelf areas placement of the lower limit is largely a function of fine-grained siliciclastic sediment input along with growth of plankton in the water column because suspended particles lower the clarity of the water.

The lower depth limit of the carbonate zone can be inferred by comparison with the lower limit of the photic zone in modern oceans because the photochemical basis of photosynthesis has probably not changed since its appearance in biologic systems. Adey and Macintyre (1973), in their discussion of environmental constraints of modern coralline algae, placed an effective depth limit of 80 m (260 ft) for clear waters and 40 m (130 ft) for turbid waters on open coasts of low and high latitudes. Hallock and Schlager (1986) suggested similar limits [20–120 m (65–400 ft)] for effective growth of modern photosymbiotic corals on open coasts. The depth limit of the photic zone may be 200 m (660 ft) in clear waters of the outer shelf and open ocean basins, and living algae have been sampled at extreme depths of several hundred meters in clear tropical waters. In areas of cyclothem deposition, clay muds were deposited all over the shelf; a limit of 80 m (260 ft) for the photic zone is probable, and an effective limit for efficient plant growth at 50 m (160 ft) is reasonable, decreasing to shallower depths in more turbid waters.

Carbonate-siliciclastic zone boundaries

The environmental boundaries between carbonate and siliciclastic depositional areas are zones of transition, so the boundaries of carbonates should show gradational contacts with siliciclastic units. Lateral boundaries appear to be gradational in many cases, but lower and upper boundaries of carbonate units in vertical section are seldom gradational. Lateral boundaries of carbonates are determined mostly by the ability of carbonate-producing organisms to grow. In areas of good growth they generate a large amount of skeletal debris and lime mud, creating a completely carbonate sediment, whereas in marginal areas lime mud is not generated and carbonate content consists of larger skeletal material surrounded by siliciclastics. Preservation of carbonate material in siliciclastics is erratic because of dissolution effects after burial, so the transition zone tends to be irregular and patchy. Away from carbonate areas mechanical concentrates of carbonate shell can form by current sorting, storm-wave winnowing, and biogenic concentration, but these form a small proportion of the carbonate sediment in the system.

The sharp boundaries of carbonates seen in vertical section are often the result of recrystallization, accompanied by a concentration process akin to concretion formation in which carbonate migrates into areas of higher carbonate content. However, sharp boundaries may also be the result of feedback mechanisms that promote ever-increasing production of carbonate when conditions become favorable for carbonate sedimentation. In the outer, deeper part of the cyclothem carbonate zone, the major carbonate producer was phylloid algae, a prolific grower and a major contributor to carbonate banks. Phylloid algae were capable of colonizing mud substrates in the manner of the modern peyssonelliaceans (James et al., 1988), to which they may be related. The accumulation of skeletal components in the sediment would have enhanced settlement and early growth, leading to an increasing rate of growth and accumulation and triggering a surge of carbonate sediment production. The result is a rapid change from siliciclastic to carbonate sedimentation. This is independent of siliciclastic sediment supply, which need not change its rate of supply to the area. Initiation of algal growth can modify the substrate sufficiently in favor of carbonate producers to produce a carbonate depositional environment in the face of little change in water conditions or photic zone. The resultant boundary would be sharp rather than gradational.

Mixed carbonate-siliciclastic model of deposition

The mixed carbonate-siliciclastic depositional model used in this study of cyclothems is part of a general model of mixed carbonate-siliciclastic deposition on shelf surfaces. It uses the concept that carbonates and siliciclastics are components of the same depositional system. This system can be modeled, and for late Paleozoic cyclothems a detailed mixed carbonate-siliciclastic model can be generated that is useful for working with deposits from a range of depositional conditions. The major variables in the general model are (1) the quantity and composition of siliciclastic sediment delivered to the shoreline and carried onto the shelf, (2) the depth of the lower limit of the photic zone as it intersects the shelf surface, (3) the gradient of the depositional surface, and (4) the proportion of benthic production to planktic production of carbonate sediment. In systems where carbonate sediment is predominantly benthic in origin (Paleozoic and Triassic oceans), the first three variables control the distribution of sediment, which results in the common occurrence of outer shelf siliciclastic deposition beyond a carbonate zone. In systems where planktic production of carbonate occurs (Jurassic to modern warm-water oceans), planktic production of carbonate tends to overwhelm benthic production and produces patterns of sediment distribution in which outer shelf surfaces are areas of carbonate deposition. General patterns of sedimentation are set by the benthic/planktic production ratio and by the gradient of the depositional surface, whereas detailed patterns are produced by the amounts of siliciclastic sediment transported onto the shelf and the manner in which the photic zone intersects the shelf.

A wide range of depositional patterns can be detailed with this model because deposition of carbonates and siliciclastics is not mutually exclusive. Concurrent carbonate and siliciclastic deposition occurs over large areas of a shelf, with more localized production of carbonates superimposed on shelfwide dispersal of siliciclastics. Deposition of a large amount of carbonate will persist even under moderate rates of siliciclastic sedimentation if other environmental factors favor the growth of carbonate producers. The presence of siliciclastic sediments does not inhibit carbonate sedimentation as much as is assumed in many case studies. The centers of carbonate deposition can be located on various parts of a shelf surface and need not be limited to the outer shelf or to positions distant from a siliciclastic shoreline. Variations in siliciclastic sediment input, depth of the photic zone, and inclination of the shelf surface produce predictable changes in carbonate and siliciclastic depositional patterns. This model covers depositional systems that are intermediate between and grade into fully siliciclastic and fully carbonate systems.

The model can be applied to systems with planktic carbonate producers, for example, the Cretaceous cyclic deposits of the Western Interior seaway. As described by Kauffman (1969), the Cretaceous cyclothems of that area contain a shallow-water zone (his unit 4A) and a deeper-water zone (his units 4B, 9–12) of carbonate deposition that correspond to carbonate production by benthic organisms and planktic organisms, respectively. The shallow-water carbonate zone is poorly developed because it lacked benthic algae or mixotrophs in the environment; the deeper zone is well developed and contains common planktic foraminifers and nannoplankton. Siliciclastic sediment was transported into the basin across the poorly developed nearshore carbonate zone, which contains mixtures of benthic shell bioclasts and siliciclastics. The environmental control of carbonate production and cross-shelf transport of siliciclastic sediment is evident in this mixed carbonate-siliciclastic system.

Mixed carbonate-siliciclastic depositional models provide the best framework for interpreting late Paleozoic depositional systems. During that time, shoreline positions changed frequently because of eustatic changes in sea level and maintained wide, graded shelf surfaces. Carbonate depositional systems did not aggrade to a single base level and thus did not develop a horizontal platform surface; and in most areas siliciclastic depositional systems did not dominate the shelf by prograding the shoreline to an outer shelf margin. On these surfaces carbonate deposition in moderate to shallow water depths was superimposed on continuous shelfwide dispersal of siliciclastics. Omission or extreme thinning of carbonate deposition resulted from increased quantity of siliciclastic sediment delivered to the marine shelf and the consequent decrease in the depth of the photic zone; the increase in carbonate deposition was due to decreases in siliciclastic sediment input or an increase in the depth of the photic zone.

The common Missourian-age cyclothem of Kansas and the midcontinent (Moore, 1936) is a variant that was deposited on a shelf receiving low to moderate amounts of siliciclastic sediment containing more mud than sand and having low to moderate rates of deposition, which allowed the generation and concurrent deposition of moderate to large amounts of carbonate sediments. Other cycle types were produced under different sets of conditions or during lesser fluctuation in water depth than those producing this type of cyclothem. Varying sea levels caused depositional environments to change position systematically on the shelf, and the carbonate depositional zone is located on the inner shelf at times of high sea level and on the outer shelf at times of lower sea level.

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