Lowstand tempestites: Depositional model for Cretaceous skeletal limestones, Western Interior basin

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ABSTRACT

High-resolution sedimentologic, paleontologic, and stratigraphic data were collected for three Cenomanian-Turonian skeletal limestone packages in the Western Interior basin. Results of the study have significant implications for sequence stratigraphy in fine-grained basinal facies. (1) Skeletal limestones represent calcareous tempestites deposited at or near storm wave base, and their stratigraphic distribution provides a constraint on paleobathymetry. (2) Skeletal limestones are widely traceable and can be correlated to coeval progradational/retrogradational shoreface deposits, placing them in a relative sea-level context. (3) Skeletal limestone origin can be described by a comprehensive depositional model. The model incorporates effects of winnowing/erosion on relative fall, and sediment starvation/condensation on subsequent rise, relating both to the absence of an effective depositional gradient. (4) Application of the model suggests a reinterpretation of relative sea-level history for the Cenomanian-Turonian in the Western Interior that is better constrained than previous estimates.

INTRODUCTION

Skeletal limestones are common in cratonic basin stratigraphic successions. These deposits represent winnowed or condensed accumulations of skeletal material and commonly show evidence of current or wave action and erosion (e.g., Hattin, 1986). In epicontinental basins that are largely filled with hemipelagic mudstones, skeletal limestones (SLs) provide the major source of evidence for changes in flow regime and sedimentation history in offshore areas. As summarized by Kidwell (1991a, 1991b), the dominant mechanisms by which skeletal concentrations form include (1) offshore starvation of siliciclastic sediment and concentration of skeletal debris (suggesting spatial/temporal variation in sediment delivery to produce condensed beds) and (2) physical sorting of sediments due to normal and storm wave action (suggesting decreased accommodation space relative to sediment supply, and reworking of muds to produce winnowed beds). Because the relationships between subsidence, eustasy, and sediment supply may ultimately control both of these mechanisms, SLs can play a critical role in paleoenvironmental reconstruction and sequence stratigraphic analysis (Kidwell, 1991a, 1991b).

SLs are found throughout the mid-Cretaceous Greenhorn Limestone and lateral equivalents in the Western Interior basin (Hattin, 1975, 1986), but they have not been analyzed in a sequence stratigraphic context. A recent investigation of three Greenhorn SL units (Fig. 1) has revealed evidence of (1) proximal trends and upward-fining trends suggesting storm deposition (cf. Aigner, 1985), (2) bedding features reflecting wave base influence, (3) faunal changes suggesting shallowing events, (4) cratonicward thinning and pinchoff of biozones, suggesting erosional truncation, and (5) up-dip correlation to progradational clastic wedges containing incised valley fill sequences. On the basis of these observations a comprehensive depositional model is de-

![Figure 1. Regional stratigraphy of study interval shown by generalized sections for western margin, axial basin, and eastern platform (cross section reflects CC-BH in Fig. 2). Skeletal limestone intervals are indicated by black bars at left; note time-equivalent clastic wedges and variations in lithostratigraphic nomenclature. Biozonation is based on Cobb (1985): P.w.—Plesiacanthoceras wyomingense, C.c.—Calycoceras cantilaurum, M.m.—Metioiceras mosbyense, S.g.—Sciponoceras gracile, N.j.—Neocardioceras juddii, Wat.—Watinoceras, M.m.—Mannites nodosoides, and C.w.—Collignoniceras woollangi. M.—middle, L.—lower, U.—upper.](image-url)
veloped for Greenhorn SLs. They are interpreted as lowstand tempestites formed during events of rapid fall and rise of relative sea level in the basin. Application of the model allows a reinterpretation of sea-level history for Cenomanian-Turonian time. The model is a synthesis of previous observations on skeletal accumulations (e.g., Aigner, 1985; Kidwell, 1991a, 1991b; Hattin, 1986) but focuses specifically on the nature of the Western Interior basin (with a rapidly subsiding western foredeep and eastern craton margin of low subsidence rates and negligible depositional slopes), and the relationship between climatic events and sea-level history. Brett (1995) recently interpreted skeletal accumulations in Devonian strata of upstate New York with a similar approach.

GEOLOGIC BACKGROUND

During early Cenomanian to middle Turonian time, sea-level rose to a peak highstand for the Cretaceous, depositing the Greenhorn cyclothem in the Western Interior basin. The distribution of lithofacies and biotas of Greenhorn age suggest a broad, relatively shallow sea with maximum depth of 200–300 m at peak highstand (Sageman and Arthur, 1994). Kaufman (1984) defined tectono-sedimentologic zones for the basin, including a western foredeep (high subsidence and siliciclastic sedimentation rates), a broad axial basin (maximum bathymetry, low to moderate sedimentation rates), and a wide eastern platform onlapping the stable craton (very low subsidence and sedimentation rates, high carbonate production) (Fig. 2). Sageman and Arthur (1994) suggested that the average depositional gradient from shore to basin center was negligible (<1°), except for clinoforms associated with western progradational wedges (Asquith, 1970).

SL packages characterize three parts of the Greenhorn cyclothem, including both transgressive and early highstand phases (Fig. 1). These units occur in members of the Greenhorn Limestone (Fig. 1) and have been described by Cobban and Scott (1972), Kaufman (1977), and various papers in Pratt et al. (1985). The most extensive work on them by Hattin (1975, 1986) interpreted Lincoln Member SLs in Kansas to have been deposited in a zone of high energy wave impingement that moved across the low-gradient shelf as Greenhorn transgression proceeded (model of Irwin, 1965). Hattin (1986) also briefly noted the potential for storms and shallowing events to produce skeletal concentrations.

OBSERVATIONS

SL packages (1–4 m thick) include isolated or amalgamated laminae, lenses and beds (1–20 cm in thickness) of calciolite to calcarenite interbedded with mudstone beds of variable thickness. SL lithotypes range from bioparites to biosparptoids whose principal allochthons are fine silt to medium sand-sized calcitic inoceramid bivalve prisms and fragments, planktonic foraminiferal shells (typically infilled with calcite), and Ca-phosphatic fish debris (bone fragments, scales, and teeth). Secondary elements include calcispheres and coccolith-rich fecal pellets, quartz grains (silt to fine sand sized), pyrite framboids, and phosphatized coprolites. Allochthons are common throughout mudstone intervals as scattered particles, or as laminae to very thin beds. Mudstones, typically laminated and organic carbon rich, range from black noncalcareous shale and mudstone to olive black/olive gray calcareous and marly shale or marlstone.

Sedimentologic Features

Trends in grain size and sedimentary structures that are observed through individual limestone beds also occur through entire SL packages. Bed bases tend to be sharp, locally show flat or undulating relief, and commonly include cut and fill features, flute marks, tool marks, and clay rip-ups. Bed tops are locally gradational to mudstone, or characterized by starved ripple lamination, and some surfaces show current shadows. Limestone beds are locally massive or slightly graded, but are more commonly planar to cross-laminated. Planar bedded units show evidence of current lamination on weathered surfaces, suggesting plane bed conditions. Cross-bedded units are commonly characterized by gently curving, low-angle cross laminations (3°–10°) with common truncation of swales by overlying laminae, and angular to tangential terminations, suggesting hummocky cross stratification. Spacing between hummocks is commonly <1 m. Some bedding surfaces show complex ripple patterns suggesting combined flow. At sites in Kansas, syndepositional deformation features (slumped bedding) and the prevailing dip direction of cross laminae suggest west to northwestward transport of sediment.

An upward-finishing trend in grain size was observed within many individual beds, especially near the base of the packages where the coarsest material is found. In many cases, the basal 10 cm is characterized by coarse sand and pebble-sized fragments of *Inoceramus*, commonly dominated by pieces of the thick hinge region. Grain size may decrease slightly through the bed (to medium or fine grained at the top), and the upper contact with mudstone may be sharp or gradational. Yet this grain size trend is best developed through entire SL packages. Whereas the basal beds are dominated by coarse- to medium-sized grains, the uppermost units show dominance of shell fragments no larger than silt. In addition to *inoceramid* hinge fragments, several types of intraclasts characterize the basal portions of
the Lincoln SL unit as it is traced across western Kansas. Clasts include eastward-dipping elongate bentonite rip-up pebbles, rare quartz pebbles, and up to 40% angular to subangular, silt- to very fine sand-sized quartz grains.

**Paleoecologic Features**

Some skeletal limestone beds are almost completely composed of whole *Inoceramus* shells. These occur as disarticulated, randomly oriented valves that have been broken and deformed by compaction. Hattin (1975) defined these biosparritudes as "inoceramites"; they reflect significant increase in numbers of preserved macrofauna. Fauunal analyses of standardized samples through the Lincoln and Hartland SL packages (Sageman and Johnson, 1985; Sageman, 1985) clearly reflect increased abundance associated with such beds and show similar trends in species richness as well. Further, both limestone beds and interbedded mudstones within the SL packages show a marked increase in burrows (mainly *Planolites* and *Thalassinoides*) compared to the laminated shales above and below them, as well as evidence for epibenthic scavengers.

**Stratigraphic Features**

Regional correlation of the SL packages is based on ammonite and bivalve biostratigraphy (Cobb, 1985; Kauffman et al., 1993) and event lithostratigraphy (Hattin, 1971, 1975; Kauffman, 1988; Sageman, 1991; Elder et al., 1994). Documentation of selected index taxa and widely traceable bentonite marker beds at the sections in Figure 2 allowed regional stratigraphic trends to be reconstructed. Individual SL beds are variable in thickness over a distance of kilometres, showing lensing and in some cases complete pinch out. However, based on bentonite marker beds and index fossils, the SL packages are traceable over hundreds of kilometres and across several facies belts. When correlated across the transect from Colorado to Kansas in Figure 2, SL packages show proximity trends (Aigner, 1985) with onshore increase in limestone bed thickness and amalgamation, and offshore increase in thickness of mudstone interbeds (indicating predominant basinward transport). In this transect the interval between the base of the Lincoln SL package and the underlying X-bentonite shows anomalously rapid thinning and pinchout toward the east (Sageman and Johnson, 1985). In central Colorado this interval is 6 m thick and contains the *Plesiocanthoceras wyomingense* Biozone. In central Kansas the *P. wyomingense* Biozone is completely missing and the SL package lies directly above the X-bentonite marker bed (Fig. 2). A similar stratigraphic pattern of eastward thinning and bioclastic pinchout is duplicated over 1500 km to the north in the Asheville Formation of the Manitoba Escarpment (McNeil and Caldwell, 1981), suggesting synchronous nondeposition and/or erosional truncation of strata on the eastern cratonic side of the basin.

When the bioclines containing the three SL packages (C. canitum; middle *M. mosbyense*; and lower *C. woolliger*) are traced into the clastic facies of the western margin, they are found to correlate with basinward-prograding clastic wedges in several regions (Fig. 1). These include the Pagle Tongue of the Dakota Formation in Arizona and New Mexico (Cobb and Hook, 1984) and the Dunegan Formation in Alberta (Bhattacharya, 1994) for the Lincoln SL package, the Two Wells Tongue in Arizona and New Mexico (Cobb and Hook, 1984) and the Doe Creek Sandstone of the Kaskapau Formation in Alberta (Bhattacharya, 1994) for the middle Hartland SL package, and the Coo Springs Sandstone Member (Utah) and Hopi Shale Member (Arizona) of the Mancos Shale (Gardner and Cross, 1994) for the upper Bridge Creek SL package. In both the Dunegan Formation (Bhattacharya, 1994) and the Two Wells Sandstone (Mellere, 1994), incised-valley sequences have been documented, indicating that subaerial erosion was coeval with the formation of the SL packages. Although north-south variability in the development of progradational complexes indicates the tectonic influence of the Sevier orogenic belt, many segments of the western margin show stratigraphic patterns that are correlative with those of the eastern stable craton, suggesting control by a common mechanism.

**DISCUSSION**

The sedimentologic data described above suggest that deposition of Greenhorn SL packages reflects increase in benthic current energy to moderate or high levels. In the studied onshore-offshore transect the influence of storm-wave base is indicated by hummocky cross stratification and evidence of erosion (bentonite rip-ups, landward truncation). Trends in grain size and sedimentary structures indicate deposition in a series of waning-flow events, also suggestive of storms. Basinward transport of terrigenous and biogenic material is reflected by apparent imbrication of rip-up clasts, predominant dip directions of cross strata, distribution of quartz grains, and proximity trends (cf. Aigner, 1985). Although increases in faunal diversity and abundance associated with SL packages could partly reflect sampling artifacts resulting from condensation (Holland, 1995), other changes in biofacies (addition of burrowers, scavengers) suggest relative shallowing, increased mixing, and improved benthic oxygenation during SL deposition. Finally, stratigraphic data indicating cratonward thinning of strata in association with winnowing of basininal muds suggests erosional truncation during relative sea-level fall. These features are correlated to basinward shifts in facies (i.e., progradation of the shoreface) and valley incision followed by estuarine fill. Occurrence of correlative features on orogen-proximal and cratonic flanks of the Western Interior basin suggests that SLs are tempestites (Aigner, 1985) that formed in response to impingement by storm wave base during the fall of relative sea level in the basin.

**Depositional Model and Relative Sea-Level Curve**

A depositional model for the Greenhorn SL packages includes the following processes. (1) During sea-level fall bottom muds are eroded and winnowing, and skeletal material accumulates. This process is most effective along the eastern side of the basin, away from the diluting influence of siliciclastic sources, and is mainly driven by storms (Fig. 3). (2) As sea level begins to rise, storm processes continue to rework and transport skeletal material basinward (Fig. 3). Depletion of siliciclastics associated with transgression helps to concentrate skeletal material at this time, and only (a few) large storms influence the deeper areas of the basin. Applying sequence stratigraphic terminology, SL packages correspond to lowstand and early transgressive systems tracts (Fig. 3).}

Kidwell (1991a) developed a model for skeletal accumulations within systems tracts based on the passive margin model (Fig. 3B). Winnowed accumulations are associated with toplap (or onlap) sites, and condensed accumulations predominate on the downlap (maximum flooding) surface. With a very low depositional gradient, however, winnowed and condensed skeletal accumulations may occur in close proximity, intergrading as small changes in sea level produce widespread effects across the gentler slope of the basin (Fig. 3B). Due to lack of slope, typical lowstand deposits do not form on relative fall, but winnowed skeletal accumulations develop. As the basin deepens, further winnowing decreases, previously accumulated skeletal material is reworked, and new shales may be concentrated as detrital flux diminishes. This trend occurs within a single cycle and also reflects the longer-term sea-level trend. For example,
Figure 3. Depositional model for origin of skeletal limestones. A: Processes associated with sea-level fall and subsequent rise, correlation to idealized stratigraphic sequence, interpreted sea-level curve, and equivalent system tracts (HST—highstand, TST—transgressive, LST—lowstand systems tracts). B: Illustration of difference between passive margin-based model (e.g., Kidwell, 1991a) and epeiric sea model for stratal architecture of skeletal accumulations. On right side are idealized stratigraphic sequence and interpreted sea-level curve. Winnowed (w) and condensed (c) skeletal material are represented by shaded and black patterns, respectively, in all diagrams.

Figure 4. Greenhorn stratigraphic sequences are shown with corresponding west-east cross section of Western Interior basin to illustrate role of relative sea-level change and storm wave base (SWB) in the formation of skeletal limestone packages. Reconstruction of relative sea-level history for study interval is compared to Haq et al. (1987) curve. Stage and biozone data and stratigraphic sections as in Figure 1 (A—New Mexico/Utah composite, B—central Colorado, C—central Kansas). Basin cross section modified from Sageman and Arthur (1994).

the Lincoln SL package is dominated by winnowing features but shows increasing evidence of condensation toward the top. The Hartland SL package shows a relative increase in proportion of pelagic components (foraminiferal tests, fish debris), suggesting greater condensation, and the Bridge Creek SL package is dominated by foraminiferal debris and shows even less evidence of wave reworking.

The depositional model in Figure 3 allows construction of a relative sea-level curve for the late Cenomanian and early Turonian (Fig. 4). Selected sections of the Greenhorn cyclothem are shown above a cross section of the basin to illustrate (1) correlation of prograding shoreface deposits with skeletal limestone packages and (2) interpreted effects of storm wave base during sea-level fall. These conditions promote in-place accumulation of skeletal material and/or downslope transport of material by storm-induced density flows (producing tempestites). Only very large storms could influence the central basin, reworking the more distal parts of density flow deposits. Using values suggested in the literature for maximum bathymetry and depth of storm wave base to constrain sea-level changes (Kauffman, 1984; Winn et al., 1987; Gagan et al., 1990; Sageman and Arthur, 1994), a Western Interior relative sea-level curve can be constructed (Fig. 4). This curve shows similarities in the timing of major events to the Haq et al. (1987) curve but has greater magnitude of relative changes.

CONCLUSIONS
Hattin (1975), in citing Irwin’s (1965) model for Greenhorn skeletal limestones, recognized the key feature of these deposits: they develop across a basin floor of extremely low gradient. Under such conditions even small changes in relative sea level can have far-reaching effects within the basin. The Greenhorn skeletal limestone packages are widely traceable. They developed through winnowing by storm events during relative sea-level fall and condensation due to starvation during subsequent rise. In a sense, they are analogous to (but not the same as) forced regressive deposits or lowstand wedges of the passive margin model. In the fine-grained, mud-dominated facies of epicontinental basins where sequence stratigraphic features may be difficult to recognize, skeletal limestones provide a tool for recognition of relative sea-level changes and for estimation of the magnitude of those changes. They offer an excellent complement to studies of siliciclastic architecture in more proximal settings.

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891

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