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Influence of subsidence on the anatomy of marine siliciclastic sequences and on the distribution of shell and bone beds

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Skeletal concentrations are common foci for palaeontological collecting, yet vary widely in their expected levels of taphonomic bias depending on whether they are comparatively simple event-concentrations, more complex accretionary accumulations of either normal or condensed thickness, or residual lags that mark horizons of significant erosional/corrosional truncation of the record (Table 1). These different types and their intermediates also have different potential for use in basin analysis, for example as marker beds, bathymetric indicators, and clues to hiatuses. The stratigraphy and taphonomy of marine siliciclastic sequences from a spectrum of basin types have been examined to determine the extent to which shell and bone beds are linked to physical stratigraphic features such as discontinuity surfaces and transgressive-regressive cycles at various scales, and thus the extent to which physical processes might influence palaeontological data. This series of basin-scale studies has also provided an opportunity to assess the practical utility of skeletal concentrations in reconstructing basin history and to investigate subsidence-related variation both in skeletal accumulation and in the anatomy of siliciclastic sequences.

Field studies have been restricted to post-Palaeozoic, primarily Neogene sections in warm temperate to subtropical palaeolatitudes and have focused on marine facies tracts developed in shelf and shallower water depths during phases of 'coastal onlap'. (Sequence stratigraphic terms are used here to describe physical aspects of the record, and do not imply any particular chronostratigraphic value or genetic, i.e. eustatic, origin.) The results of this work indicate that: (a) skeletal concentrations are distributed fairly systematically within marine sequences, both in response to bathymetric variation in water energy and benthic productivity, and in response to upsection and proximal-distal variation in net sedimentation rate (summary in Kidwell 1991); (b) the physical dimensions and

internal anatomy of sequences vary within and among basins, and are correlated with order-of-magnitude differences in total subsidence rate (= rock accumulation rate as measured over 1–10 Ma intervals); and (c) the relative abundances of skeletal concentration types vary among sequences and among basins according to subsidence rates. Typical patterns for points (b) and (c) are summarized here.

Records of moderate subsidence (tens of centimetres per thousand years; a few hundred metres per million years). These records are characterized by 'classic' third-order sequences such as illustrated in textbooks: the transgressive surface is usually well-separated from the lower sequence boundary by predominantly non-marine strata, and the relatively thin transgressive systems tract and typically thicker highstand tract are composed of discrete upward-shallowing parasequences. The Aptian–Albian Mannville Group in the Alberta foreland basin provides a good example, as would many sequences in the US margin of the Gulf of Mexico where most elements of sequence analysis were first developed.

Sequences in such settings typically contain a variety of concentration types, which deserve careful taphonomic differentiation. For example, in the shale-rich transgressive systems tract of the Mannville Group (i.e. the mollusc-bearing 'Ostracode Zone'), event-beds of granulated shell debris mark the base of many parasequences in offshore sections, shell beds containing material from many amalgamated and admixed events comprise the uppermost shallowest parts of many parasequences in onshore sections, and diagenetically complex, shell-poor hiatal limestones mark maximum flooding surfaces in the most distal parts of the basin (Banerjee & Kidwell 1991). All of these concentrations, each with a distinctive taphonomic signature, are useful in marking discontinuity surfaces in the transgressive record, but they vary greatly in relation to sur-

Table 1. Stratigraphical categorization and palaeontological quality of marine skeletal concentrations (adapted from Kidwell 1991).

	Origin	Palaeontological resolution
Event concentration	Single, ecologically brief episode of hardpart concentration (biogenic or hydraulic)	Fidelity and resolution vary depending upon source of hardparts; some comprise high-resolution censuses
Composite concentration	Accretion or amalgamation of multiple event concentrations and generations; average or expanded thickness relative to coeval strata	Fidelity and resolution can be no better than that of component events, and will usually be poorer; potential complications from live:dead feedback and environmental condensation
Hiatal concentration	Accretion or amalgamation of events and generations during period of slow net sedimentation; complex concentration is thin (condensed) relative to coeval strata	Expect generally lower resolution than for 'normal' composite concentrations owing to slower net rates of accumulation; potential complications from live: dead and diagenetic feedbacks; biostratigraphically as well as ecologically disparate faunas may be admixed
Lag concentration	Exhumation and concentration of resistant hardparts during erosion or corrosion, associated with significant stratigraphical truncation	Potentially lowest fidelity and resolution, owing to mixing of hardparts from disparate facies and ages, vigorous culling, and potential for recolonization

Table 2. Summary of observed features

Total subsidence rate (for a 1–10 Ma interval)	Sequence anatomy	Skeletal concentrations
Moderate subsidence (tens of cm ka ⁻¹)	'Classic' sequence anatomy: transgressive surface separated from lower sequence boundary; transgressive and highstand systems tracts composed of shallowing-upward parasequences	Full array of concentration types owing to range of scales of distinct discontinuity surfaces within shelf sediments (bedding planes, minor flooding surfaces, reworkings, parasequence set boundaries, and various condensed intervals)
High subsidence (hundreds of cm ka ⁻¹)	'Stretched' sequences may have poorly defined boundaries owing to few through-going surfaces; strong mosaic sedimentation at parasequence scale	Dominated by event and composite concentrations; hiatal and lag concentrations are stratigraphically infrequent and commonly geographically restricted to basin margins and structural palaeohighs
Low subsidence (≤ few cm ka ⁻¹)	Highly telescoped records; transgressive surface often coincides with lower sequence boundary; flooding surfaces commonly anastomosed or obliterated, so parasequences indistinct	Hiatal and lag concentrations more frequent, typically of longer duration, and more widespread geographically than in any other type of setting; event and composite concentrations present but suspect

faces (some mantle, some are capped by, and others are sandwiched between discontinuities) and in the expected degree of bias in their fossil assemblages.

Records of high subsidence (hundreds of centimetres per thousand years; one kilometre or more per million years). Stratigraphically, these records are characterized by expanded sequences with few through-going surfaces of unambiguous origin. Parasequences can be difficult to identify in some parts of the section. Even where small-scale shallowing-upward cycles are obvious, these units are commonly difficult to trace over significant distances. The Miocene to Pliocene record of the rift-to-transensional Salton Trough (northern Gulf of California) provides a good example in which classic sequence anatomy has been virtually swamped by coarse clastic input around the margin of the basin and by a thick progradational record of the ancestral Colorado Delta which fills the rest of the basin (Winker 1987). Anatomically similar (but lithologically dissimilar) records accrue in rift, transtensional, and fore-arc settings of $\geq 1 \text{ km Ma}^{-1}$ elsewhere along the American Pacific rim.

Taphonomically, these records are dominated by comparatively straightforward event- and composite concentrations. Complex hiatal and lag concentrations are largely restricted to the basin margin and other persistent structural highs within the basin, and to the initial phase of basin development when sediment supply may lag significantly behind tectonic subsidence. These taphonomically and palaeontologically complex concentrations thus tend to be limited geographically and stratigraphically, compared to records of lower subsidence rates. In the Salton Trough, for example (Kidwell 1987, 1988), thin and laterally impersistent bioclastic beds sole and cap coastal alluvial fan cycles along the basin margin but are not significantly condensed stratigraphically. Relatively thick composite shell concentrations are also present along the margin, both banked up against rocky shorelines and submarine cliff-faces and along the subtidal fringes of progradational coastal fans. The contemporaneous deltaic record is similarly dominated by localized event- and composite concentrations, including the small oyster bioherms and shelly tidal ridges that cap many delta-front cycles. Some of these delta-front coquinas have been modified into tabular bodies during episodes of marine reworking, but so little stratigraphic truncation

has occurred that the resulting bodies are lags only in the broad sense.

Records of low subsidence (a few centimetres or less per thousand years; less than 10 metres per million years). These records are characterized by stratigraphically telescoped sequences in which the transgressive surface commonly coincides with the lower sequence boundary. Both transgressive and highstand systems tracts are thin, and parasequences are difficult to identify (either poorly developed originally, or obliterated subsequently by reworking). The Miocene Chesapeake Group (in part) of the US Atlantic passive margin provides a series of 3rd order sequences formed under these conditions, each 10 m thick and each recording c. 1 Ma.

Simple event-concentrations are common in aggradational/progradational intervals of such sequences, but many of the most impressive and taxonomically diverse concentrations are taphonomically complex hiatal and lag types. For example, in the Miocene Chesapeake deposits, hiatal shell concentrations (1–3 m thick) rest directly on third-order sequence boundaries, contain c. 100 molluscan species each, and comprise the entire marine transgressive record of the host sequence. A sediment-starved hiatal bone bed with maximum planktonic diversity marks maximum transgression within the larger second-order sequence set, and lags rich in bones, teeth, and molluscan steinkerns mark both the lower second-order sequence boundary and third-order truncation surfaces high in the second-order highstand tract (Kidwell 1989).

Discussion and conclusions. Not unexpectedly, subsidence rates or, more precisely, the tectonic, eustatic, isostatic, and sediment supply factors that determine total subsidence, appear to strongly influence the internal anatomy of third-order siliclastic sequences (Table 2). Some of these variations have been mentioned in the geological models of van Wagoner *et al.* (1990) and Einsele & Bayer (1991), and others have been postulated by, or are consistent with, the numerical models of Reynolds *et al.* (1991). The variations actually observed in the record are largely what one would expect intuitively: (1) high subsidence (accumulation rate) records have 'stretched out' sequences with poor definition of unit boundaries and highly mosaic sedimentation (patchy in time and space); (2) low subsidence settings have stratigraphically telescoped records in

which minor discontinuity surfaces converge and anastomose laterally and in which depositional components (e.g. systems tracts, parasequences) are diminutive or difficult to distinguish precisely due to partial or complete cannibalization; and (3) only the records of moderate subsidence conditions contain sequences with classic anatomy, probably because these are the kinds of records from which the classic model was derived. Subsidence rate, rather than tectonic setting, seems to be the more significant factor, inasmuch as records formed under moderate subsidence may have 'classic' sequences whether they occur in passive margin, foreland basin, or backarc settings. Moreover, subsidence rate may vary from sequence to sequence through the history of a single basin depending on such factors as thermal history and climate-controlled sediment supply, and may vary laterally at any given time from one side of a basin to the other.

Through these anatomical differences in sequences, subsidence also appears to influence the nature and distribution of skeletal concentrations. Although all types of concentrations can occur in all types of basins, the studies summarized here suggest that their relative abundances do vary (Table 2). Palaeontological sampling conducted without regard to the taphonomy of fossiliferous horizons thus may be expected to yield a dataset in one stratigraphical interval that is biased in a different way from a comparably collected dataset in another interval, and the general kind of bias should be predictable on the basis of subsidence rate.

Pragmatically, this should be restated: different strategies should be adopted for serial (up-section) palaeontological collection in different subsidence settings if one wishes to compare datasets between settings. Taphonomic analysis is probably most important in settings of moderate subsidence, because in a single section one is likely to encounter an entire array of skeletal types, intermixed stratigraphically: from collection horizon to horizon, the temporal resolution of single samples may vary dramatically. In high subsidence settings, most concentrations are comparatively high resolution event and composite types, and so taphonomic analysis can focus on identifying the relatively rare hiatus and lag concentrations. In low subsidence settings, much of the entire palaeontological record may be somewhat condensed, so that even those concentrations that appear to be high-resolution event types should be examined with scepticism. It should be stressed that the sequence- and basin-scale taphonomic patterns described here are superimposed upon those ordinarily expected along bathymetric gradients within depositional tracts ('taphofacies' variation in differential destruction of hardparts, or in exotic input) and among different groups within a single bed

(differential preservation of age classes, species, and phyla).

The basin-scale patterns described here are also of interest from the perspective of larger-scale sedimentary budgets. The strong relationship observed between sequence anatomy and skeletal accumulation is not trivial: sedimentary dilution is not the only possible control on the structure of the fossil record, nor one that necessarily should dominate it. For example, skeletal abundance could alternatively be limited to sites of high benthic production or allochthonous skeletal input within shelf systems, or restricted primarily to sites of preferential preservation (i.e. low intensity biostratigraphic and diagenetic conditions). Evidence that the physical processes that control sequence development also influence skeletal accumulation should thus further encourage basin analysts to exploit concentrations as signatures of sedimentary dynamics at a variety of scales, including those ranging up to 1–10 Ma.

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