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Generic types of stratigraphic cycles controlled by eustasy

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ABSTRACT

Thought experiments imply that stratigraphic cycles controlled directly by eustasy include keep-up, catch-up, catch-down (foreshortened or truncated), and give-up variants, different patterns of thickness and facies being governed by the interplay of sedimentation rate and accommodation space. Most examples of these types are, in addition, base-cutout cycles, wherever lowstands of sea level dropped below the top of the underlying cycle. Overall thicknesses of multiple cycles at any locale are controlled ultimately by net subsidence rate. Accordingly, even keep-up and catch-up cycles can faithfully record full accommodation only where tectonic subsidence during cycle formation paced eustatic fluctuation. Paradoxically, however, only condensed cycles that fortuitously compensate for syncycle tectonic subsidence can accurately record the eustatic amplitude, as adjusted for water loading.

INTRODUCTION

Stratigraphers commonly attempt to elicit eustatic history from cyclic strata by using stratal thicknesses and facies trends as proxies for accommodation space and eustatic fluctuation in sea level. As Bond and Kominz (1992) noted, however, the link between eustatic cause and stratigraphic effect is complex. All stratigraphic attributes record the interaction between rates of change in both accommodation space and sedimentation rate (cf. Jervey, 1988; Schlager, 1993). An accurate interpretation of eustatic history, moreover, requires understanding changes in accommodation space from both tectonic and eustatic influences. In this paper we suggest a conceptual scheme of generic cycle types that represent varied responses of stratigraphy (facies and thickness) to changes in accommodation space influenced by eustasy. Variable stratigraphic response to eustasy must be recognized and considered appropriately in order to extract varied eustatic signals from the stratigraphic record. We hope that our classification of generic cycle types will contribute toward that goal. For simplicity, we restrict discussion here to marine cycles and alternating marine-nonmarine cycles for which the influence of eustatic fluctuation on depositional environments is direct. We also focus implicitly on glacioeustatic cycles, although our concepts are general and are also applicable to other types of eustasy.

TYPES OF EUSTATIC CYCLES

Several end-member types of eustatic cycles can be distinguished by hypothetical relations between accommodation space and sedimentation rate. To delineate these, we adapt and expand terminology developed originally for carbonate systems (Kendall and Schlager, 1981; Neuman and McIntyre, 1985), as follows (Fig. 1).

1. Keep-up cycles are cycles in which sedimentation paces the creation of accommodation space; resultant cycles record maximum accommodation and are thus "thickness complete," but are dominantly aggradational and thus "facies incomplete." In marine strata, for example, shoal-water facies characterize the entire cycle and progradation is absent or minimal. In practice, note that fully aggradational keep-up cycles will show no evidence of cyclicity, except where exposure surfaces separate shoal-water facies of adjacent cycles.

2. Catch-up cycles are those in which sedimentation initially lags behind creation of accommodation space, but progressively overtakes sea level at highstand; resultant "thickness complete" cycles differ from keep-up cycles in that they form "facies complete," fully progradational units, such as those common in growing deltas or expanding carbonate platforms. In effect, catch-up cycles embody a sediment-starved phase followed by a progradational phase, during which accommodation space is filled.

3. Catch-down cycles are cycles in which sedimentation lags behind initial creation of accommodation space but eventually overtakes falling sea level; resultant cycles are "thickness incomplete," but could be either "facies complete" or "facies incomplete," as in the following subcategories: (a) foreshortened cycles—sea-level fall occurs rapidly enough to "force," but not eliminate, progradation; resultant cycles are "facies complete" but exhibit a condensed set of progradational facies; (b) truncated cycles—sea-level fall occurs rapidly enough to thwart progradation, thereby creating a "facies-incomplete" cycle; cycle termination could be marked by either a subaerial exposure surface or shoal-water facies that are developed directly atop subtidal facies; the expected intervening facies are ab-

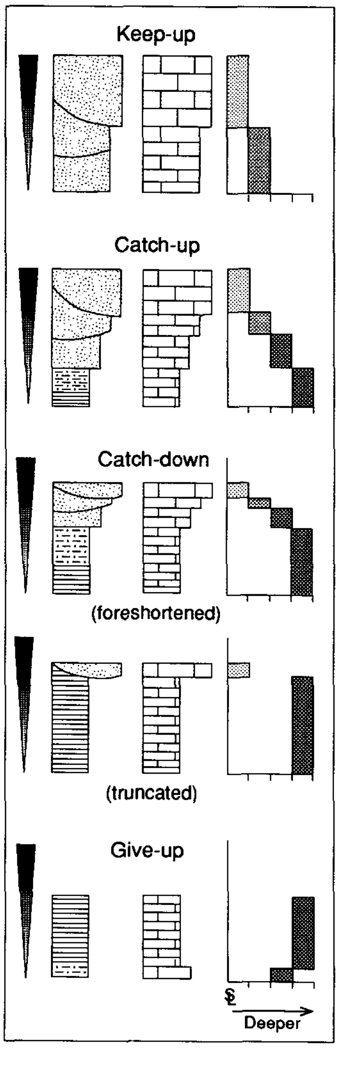

Figure 1. Schematic representation of cycle types in generic clastic (left) or carbonate platform (right) systems. Width of cycle at any given horizon corresponds to relative water depth of subfacies (narrow = deep, wide = shallow). Shaded elongated triangle to left of each pair represents full accommodation potential (i.e., sum of maximum accommodation produced by tectonic, isostatic, and short-term eustatic influences during cycle development); note that this equals preserved cycle thickness only for keep-up and catch-up types. Graph to right of each cycle pair illustrates schematic, facies-determined paleobathymetry through cycle development. Keep-up types tend to be aggradational (shoal facies only), catch-up and catch-down types tend to be progradational, and give-up types are aggradational to weakly retrogradational (deep facies only).

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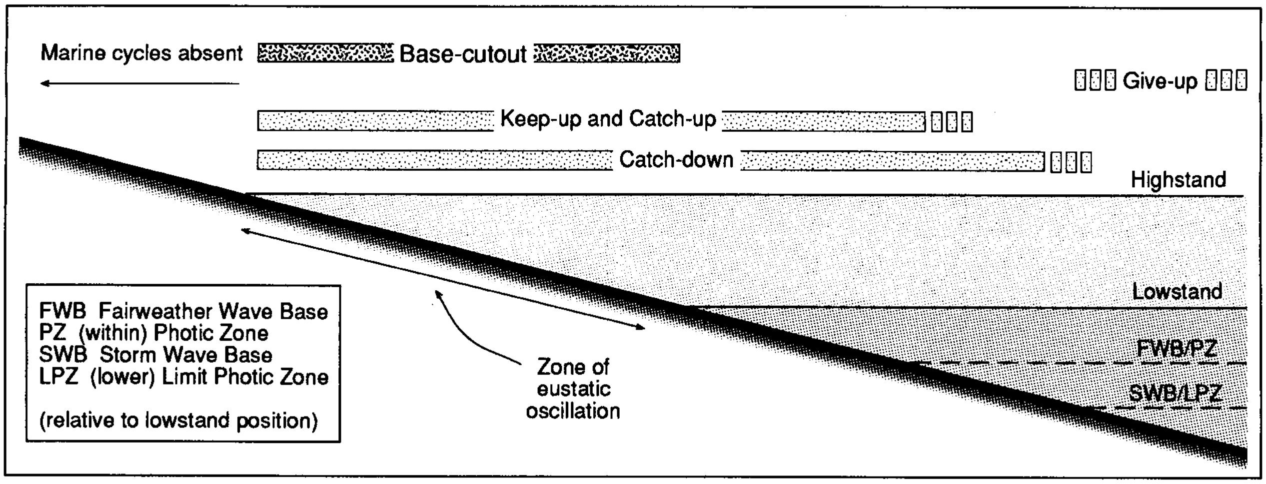

Figure 2. Schematic depiction of possible paleogeographic distribution of cycle types relative to zone of eustatic oscillation (i.e., shoreline belt that shows evidence of effects of eustasy).

sent (cf. stratal relations developed in response to the "forced regressions" of Posamentier et al., 1992).

4. Give-up cycles are those in which sedimentation lags severely behind creation of accommodation space, resulting in cycles that are both "facies incomplete" and "thickness incomplete"; although limited subtidal aggradation may occur, all facies reflect subtidal environments. The cycle top records little if any response to the subsequent lowstand, and deposition is instead "reset" upon renewed increase in accommodation space (give-up cycles are essentially the "amalgamated" subtidal cycles of Goldhammer et al., 1990).

5. Base-cutout cycles are cycles located sufficiently high up on the shelf that they record only part of the full eustatic range in accommodation because of exposure at lowstand. They are called "base cutout" because renewed (eustatic) accommodation represents only a fraction of the accommodation space created during a eustatic cycle. For the part of the eustatic cycles they represent, base-cutout cycles could be either keep-up, catch-up, or catch-down cycles (thus they are essentially the condensed cycles of Goldhammer et al., 1990). Fluvial deposition during lowstand may enhance base-cutout condensation of the subsequent cycle by reducing the accommodation space made available by eustatic rise in sea level. Where fluvial aggradation continues or begins during initial phases of a sea-level rise but prior to shoreline transit across the depositional site, the position of the cycle boundary may be indeterminate.

Of all these cycle types, only keep-up and catch-up varieties that are not base cutout potentially record the full accommodation space produced during cycle development; others preserve only a part of that accommodation and are thus condensed in one way or another. Formation of "thickness-complete" keep-up and catch-up cycles hinges ultimately on sufficient sediment supply (siliciclastic or carbonate) to fill available accommodation space.

Although the single factor that most determines cycle type is thus the response of sedimentation to accommodation, sedimentary response may hinge partially on paleogeographic position relative to

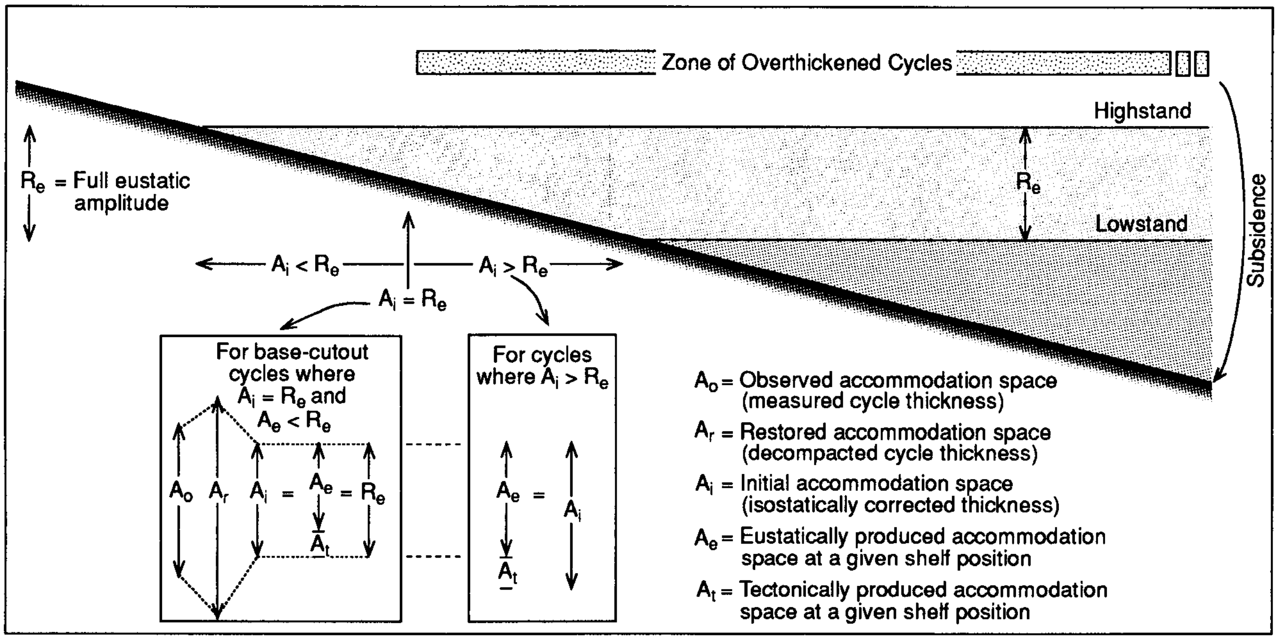

Figure 3. Relations of full or complete (keep-up or catch-up) cycles on hinged shelf. Locus where $A_i = R_e$ shown at arbitrary position on shelf (i.e., dependent on relation of A_t to A_e). All values corrected isostatically for sediment load and eustatic rise are assumed to be calculated for water-loaded conditions. Note that fundamental relations would not change if bottom configuration or subsidence pattern were more complex, or eustatic lowstand fell below shelf-slope break.

the zone of eustatic oscillation. Therefore, we might expect to detect some degree of paleogeographic zonation of cycle types (Fig. 2).

Given an adequate sediment supply, it may be possible to measure the eustatic component of accommodation from the stratigraphic record, but available accommodation space actually represents the sum of eustatic, tectonic, and isostatic influences. Accordingly, cycle thickness can never be equated directly with the absolute magnitude of eustatic change (cf. Burton et al., 1987). Attempts to gauge magnitudes of glacioeustatic fluctuation directly from cycle thicknesses will thus fail. Ultimately, the preserved stratigraphic record of any sequence keyed to strandline control must be governed by tectonic subsidence (cf. Sadler, 1993). Without subsidence, there would be no marine record regardless of how dramatically glacioeustatic sea level rose and fell, because net (long-term) accommodation space is added by glacioeustasy alone. Consequently, tectonic subsidence rate dictates maximum cycle thickness even if the stratigraphic cyclicity is an artifact of eustasy.

To produce a keep-up or catch-up cycle that is thickness complete requires (1) adequate sediment supply and (2) rates of tectonic subsidence sufficient to bring the top of the preceding cycle down to the elevation of the eustatic lowstand position before sea level begins its cyclic rise. If this preceding subsidence is inadequate, the cycle will be base cutout. However, tectonic subsidence at rates sufficient to allow development of full keep-up or catch-up cycles will also cause them to be "overthickened" by some amount greater than the eustatic amplitude, because tectonic subsidence probably continues even as sea level rises toward the highstand position. Paradoxically, then, the only cycles for which thickness faithfully records eustatic amplitude are base-cutout keep-up or catch-up cycles, for which the part of the cycle missing compensates exactly for the net tectonic subsidence during cycle development, or catch-down cycles, for which the amount of foreshortening or truncation similarly compensates for tectonic subsidence. More condensed cycles will record only some fraction of the eustatic range, and cycles that are less condensed will be overthickened beyond the full eustatic range by an increment equal to the net tectonic subsidence developed during cycle formation (Fig. 3).

However, recovering any measure of eustatic fluctuation from cycle thickness requires adjustment of observed thicknesses to allow for (1) the amount of isostatic as well as tectonic subsidence inferred to have occurred locally during the duration of cycle formation, and (2) the amount of compaction that has affected the preserved thickness of a cycle (cf. Burton et al., 1987). Adjustment for syncycle subsidence will reduce the inferred eustatic accommodation space, whereas adjustment for postdepositional compaction will increase the inferred eustatic accommodation space. In general, as the eustatic accommodation space produced by a rise in sea level will be enhanced by isostatic water loading of the substratum, eustatic accommodation space, in the context of this paper, should be interpreted as water-loaded eustatic fluctuation.

CONCLUSIONS

The interrelations between rates of change of accommodation space and sedimentation rate are complex, and produce varied cyclostratigraphic results from eustatic influences. Extracting the true accommodation signal from the stratigraphic record is the key to deciphering combined tectonic and eustatic controls on sedimentation, but full accommodation space is potentially recorded only by non–base-cutout keep-up and catch-up cycles; notably, the formation of such cycles requires a delicate balance of rates that includes paced subsidence and eustatic fall. Where eustatic lowstands fall below the sediment surface to induce base-cutout cycles, even keep-up and catch-up cycles fail to reflect the full accommodation space created by combined eustasy and subsidence during cycle development. Amplitudes or magnitudes of high-frequency glacioeustatic change bear little or no simple relation to cycle thicknesses, because tectonic subsidence ultimately dictates cycle preservation and thickness. Extraction of the eustatic signal, therefore, remains elusive because the only cycles for which thickness directly and faithfully records eustatic amplitude (as enhanced by water loading) are condensed cycles wherein the partial eustatic and the tectonic components of accommodation space sum to the full eustatic range. It is important to remember that the classification and attendant implications outlined herein apply only to systems demonstrably eustatically driven; the fundamental step of determining cause of stratal cyclicity is critical.

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