

# RESEARCH ARTICLES

## PATTERNS OF STRATIGRAPHIC CYCLICITY

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**ABSTRACT:** All stratigraphic cyclicity results from cyclic sedimentation; therefore patterns of stratigraphic cyclicity can be interpreted correctly only once cyclic sedimentation has been properly understood. Cyclic sedimentation occurs at any site at which there is cyclic variation in either or both of the two proximate controls on sedimentation: these are sediment budget (here defined as a generalization of sediment supply) and sedimentation capacity (here defined as a generalization of accommodation). Different patterns of cyclic variation in these controls produce different types of sedimentation cycle, which result in different patterns of stratigraphic cyclicity. A quantitative model for cyclic sedimentation suggests that the possible types of sedimentation cycle fall naturally into four families. Of these families, the most difficult to use for reconstructing sedimentation conditions is the “sawtooth” family; sawtooth cyclicity occurs when changing sedimentation conditions prevent stability from ever being reached. The model shows that sequence boundaries in cyclic successions need not be closely tied to inflection points in baselevel curves; sequences can start at any time from shortly after the baselevel null point on a cycle’s falling-baselevel limb to shortly before the baselevel high point on a cycle’s rising-baselevel limb, i.e., a time range of almost three-quarters of a cycle. The model also suggests that cyclic successions may intrinsically be more complete than noncyclic ones.

### INTRODUCTION

The cyclicity found so commonly in stratigraphic successions has always fascinated stratigraphers. This is not surprising, for cyclicity is an example of the order for which scientists strive. When faced with a succession in which there is cyclicity, a stratigrapher instinctively wants to know more.

Stratigraphic cyclicity is a varied and, at times, complex phenomenon (Weller 1964; Duff et al. 1967; Schwarzacher 1993; de Boer and Smith 1994; Miall 1995). It exists in many different forms, it is found at many different spatial and temporal scales, and it results from the operation of many different mechanisms. All stratigraphic cyclicity is nevertheless the same in one fundamental respect—its production involves cyclic sedimentation. The ability to predict the results of cyclic sedimentation is therefore a prerequisite for interpreting patterns of stratigraphic cyclicity.

This paper has two aims: (1) to establish a theoretical framework within which the stratigraphic results of sedimentation can be predicted quantitatively; (2) to use this theory to study some of the patterns of stratigraphic cyclicity produced by cyclic sedimentation. The initial part of the paper focuses on the first aim: it identifies the proximate controls on sedimentation on which a general theory of sedimentation can be based, it clarifies a concept—baselevel—that is critical in the definition of these controls, and it sets down rules for predicting the stratigraphic results of sedimentation at different types of sedimentation site. The main part of the paper focuses on the second aim: it reports on the analysis of a model for cyclic sedimentation, it shows how the results of this analysis can be generalized, and it addresses the problem of how to reconstruct sedimentation conditions from patterns of stratigraphic cyclicity.

The modeling work described here is strictly one-dimensional, and it therefore contrasts sharply with most of the recently published examples of stratigraphic modeling: these are almost all two- or three-dimensional. The single piece of work with which it has most in common is that carried out by Turcotte and Willemann (1983); that work also used a one-dimensional sedimentation

model and was largely theoretical in its emphasis. The differences between the present work and that of Turcotte and Willemann reflect the more restricted intention of those authors: “to show the necessary assumptions and the method for computing synthetic stratigraphic sequences” (Turcotte and Willemann 1983, p. 95). Turcotte and Willemann did not attempt to describe the range of possible types of sedimentation cycle, or to show the patterns of stratigraphic cyclicity to which those cycle types lead, or to develop any strategy by which sedimentation conditions could be reconstructed.

It may seem of questionable value to work with one-dimensional sedimentation models, because sedimentation processes clearly are not one-dimensional. It might seem better to rely on two- and three-dimensional models, for example those models that have been developed recently to predict the spatial and temporal variation of sediment flux at the Earth’s surface (Flemings and Jordan 1989; Tipper 1991, 1992; Jordan and Flemings 1991; Kooi and Beaumont 1994; Slingerland et al. 1994; Tucker and Slingerland 1994; Braun and Sambridge 1997; Syvitski et al. 1998; Weltje et al. 1998). There is, nonetheless, an excellent rationale for continuing to work with one-dimensional models, namely that the results they give should *all* be capable of being found in suitable examples of compatible two- and three-dimensional modeling. If these results can all be found, then that is well and good; if they cannot, then clearly there are questions to be asked of that modeling. For instance, are there hidden structural constraints in it? Or have unrealistic boundary conditions been specified? Or has the estimation of parameters been inadequate? One-dimensional modeling prompts the asking of questions such as these. It is the scalpel with which the results of two- and three-dimensional modeling should be dissected.

**Some Terminology.**—In this paper I use the term “sedimentation” always in its broad sense: it is “the entire complex of interrelated . . . processes that bring about the accumulation of sediments” (Fairbridge and Bourgeois 1978, p. 682). I use the terms “deposition” for “the laying down of sediment”, “erosion” for “the taking up of sediment, excluding transportation” (Bates and Jackson 1980, p. 210), and “stasis” for “neither deposition nor erosion”. The meanings of the abbreviations and symbols used in the paper are summarized in Appendix 1.

### PROXIMATE CONTROLS ON SEDIMENTATION

Stratigraphers have long accepted sediment supply and accommodation as the proximate controls on sedimentation (Barrell 1917; Grabau 1924), and it is on these two controls that the modern stratigraphic theory of sedimentation is based (Jervey 1988; Posamentier et al. 1988; Schlager 1993; Shanley and McCabe 1994). Within this theory, the terms “sediment supply” and “accommodation” have the following meanings: (1) the sediment supply at a site on the Earth’s surface is the amount of sediment being transported into that site; (2) the accommodation at a site is the amount of “available space” there—space in which some or all of the sediment supplied to the site can be deposited. Most stratigraphers treat “available space” as space below baselevel (Jervey 1988, p. 47; cf. Barrell 1917, p. 747); those who have treated it as space below water level have understandably encountered difficulties (e.g., Leeder 1999, p. 266).

Sediment supply and accommodation are usually assumed to be independent controls, ones whose effects can in principle be separated (Schlager 1993; Shanley and McCabe 1994, their fig. 2). This is a prudent assumption. In truth, of course, there has to be some correlation between supply and accommodation, if only because each is ultimately a response to larger-

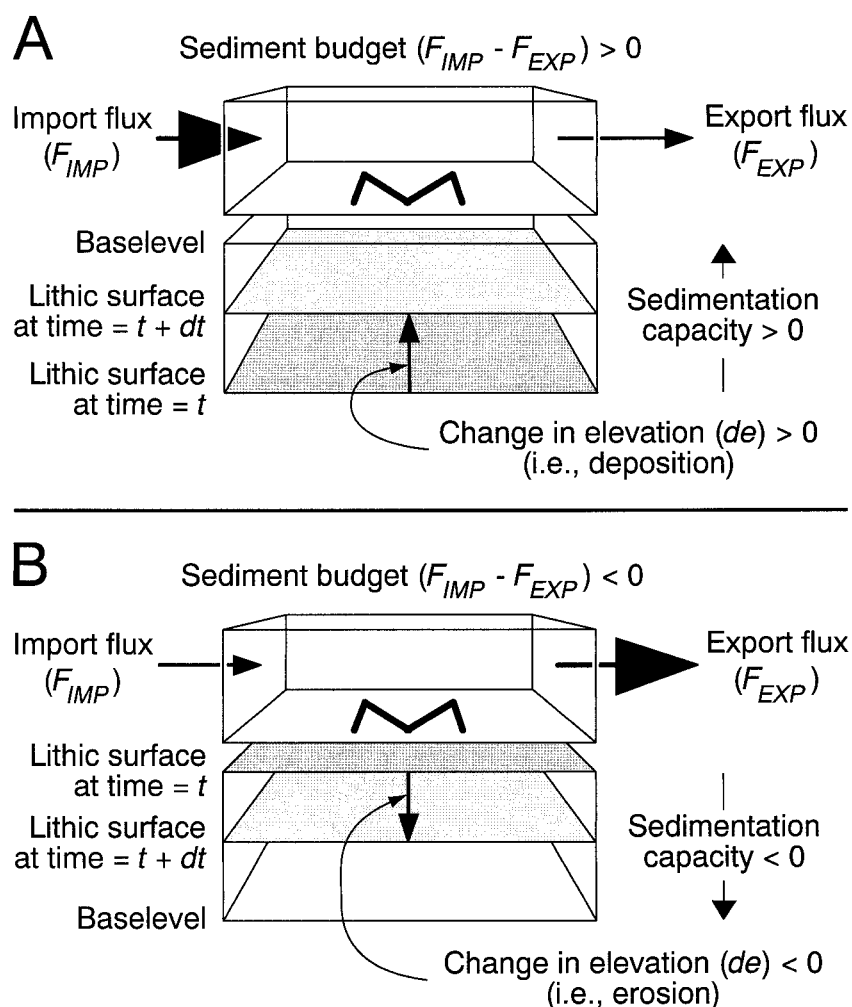


FIG. 1.—Sediment budget and sedimentation capacity. **A**) Definition diagram for depositional site. **B**) Definition diagram for erosional site. Upper block in each diagram shows import and export sediment fluxes ( $F_{IMP}$ ,  $F_{EXP}$ ) over surface area of site ( $M$ ). Lower block in each diagram shows relationship of baselevel and lithic surface, during time interval  $dt$ . Rate of change of lithic surface elevation =  $de/dt$ . For mass balance,  $F_{IMP} - F_{EXP} = M \times (de/dt)$ .

scale controlling factors such as climate change and tectonics (Schlager 1993). However, this correlation is not simple enough to let supply and accommodation be treated as different sides of the one coin. There are well documented examples of supply–accommodation relationships that differ radically from place to place within the same general sedimentation environment (e.g., Swift and Thorne 1991).

The theory of sedimentation based on sediment supply and accommodation is now applied routinely to most sedimentation environments. As it stands, however, its application strictly should be limited to environments that are entirely erosion-free. The reason for this is that sediment supply and accommodation—as they conventionally are defined—are controls on sedimentation that apply *only* at sites of deposition and sites of stasis. To remove this limitation, new controls on sedimentation must be recognized, ones that apply at all sedimentation sites. This is easily done by generalizing the ideas of sediment supply and accommodation: “sediment supply” becomes “sediment budget”, and “accommodation” becomes “sedimentation capacity” (Fig. 1). The sediment budget of a site is defined as the difference between the amount of sediment being imported into the site and the amount being exported; it is measured by the net flux of sediment across the site’s boundaries (import flux minus export flux). The sedimentation capacity of a site is defined as *either* the amount of space there in which sediment can be deposited *or* the amount of space there from which sediment can be released into transport by erosion; it is measured by the vertical distance between baselevel and the lithic surface (baselevel elevation minus lithic surface elevation). Sediment budget is identical to sed-

iment supply at sites from which no sediment is being exported; sedimentation capacity is identical to accommodation at sites at which no erosion is possible. Just as for sediment supply and accommodation, so sediment budget and sedimentation capacity are assumed to be independent controls.

The definitions of sediment budget and sedimentation capacity are sharply contrasting ones: sediment budget is defined directly in terms of a readily measurable physical quantity (sediment flux), whereas sedimentation capacity is defined indirectly, via one of stratigraphy’s most notoriously contentious concepts (baselevel). Clearly it would have been better to have defined both controls directly, and I would have done this had I thought it was feasible. However, there seems to be no good direct definition of sedimentation capacity. I have therefore followed the obvious precedent—the conventional definition of accommodation—and have defined sedimentation capacity in terms of baselevel.

#### BASELEVEL: FOUR KINDS OF EQUILIBRIUM

Baselevel has always been a contentious concept, and until recently it would have seemed an unlikely basis for defining anything (Davis 1902; Wheeler 1964a; Schumm 1993). Now, however, there is broad agreement on a relatively precise meaning for baselevel in stratigraphy: stratigraphic baselevel is “. . . some conceptual surface of equilibrium that separates erosion from deposition” (Shanley and McCabe 1994, p. 547). This meaning is ideally suited to defining sedimentation capacity, because any site at which there is equilibrium between erosion and deposition must certainly

be one at which sedimentation capacity is zero. The only question—and it is of course a critical one—is what kind of equilibrium this might be. There seem to be four possibilities: locally stable equilibrium, descriptive equilibrium, long-term equilibrium, and dynamic equilibrium.

**Locally Stable Equilibrium.**—The idea of baselevel as a surface of equilibrium can be traced back to Barrell. He wrote (Barrell 1917, p. 778): “. . . baselevel . . . is that surface toward which the external forces strive, the surface at which neither erosion nor sedimentation [i.e., deposition] takes place”. To Barrell, baselevel was a surface of locally stable equilibrium, the form of which was repeatedly being altered by tectonic activity, climate change, and eustasy. As the elevation of this baselevel surface was altered at a site, the sedimentation system there found itself out of equilibrium. It was then automatically acted on by equilibrium-restoring “external forces”—either the supply of sediment (which promoted deposition) or the physical activity of the environment (which promoted erosion). If the elevation of the baselevel at the site had been raised above the lithic surface, then more of any sediment supplied to that site would be laid down; the lithic surface would be built up to the new baselevel. If the elevation of the baselevel at the site had been lowered below the lithic surface, then enhanced physical activity at the site would carry sediment away; the lithic surface would be scoured down until the new baselevel was reached.

**Descriptive Equilibrium.**—Barrell’s view of baselevel became widely accepted by stratigraphers (Twenhofel 1939; Krumbein and Sloss 1951, 1963; Dunbar and Rodgers 1957), and it was not until Wheeler (1964a, 1964b) that anyone seriously challenged it. Wheeler viewed baselevel very differently from Barrell, in three ways. Firstly, he viewed it as a descriptive surface, not as a controlling one: “. . . [baselevel] controls nothing” (Wheeler 1964a, p. 600). Secondly, he viewed it as an irregular and unsteady surface: “In its detailed configuration, baselevel may be envisaged generally as an intensely active surface, and with the [lithic] surface in virtually all areas lying within the field of amplitude of its incessant ‘vibrations.’” (Wheeler 1964a, p. 603). Thirdly, he viewed it as a surface synonymous with stasis: no site at which there was stasis could be off the baselevel surface, and no site at which there was even the slightest deposition or erosion could be on it. He wrote (Wheeler 1964a, p. 603; italics added here for emphasis): “[Baselevel] drops below the [lithic] surface wherever particles, *however small*, are removed from this surface and rises above as they come to rest, *however temporarily*.”

**Long-Term Equilibrium.**—Wheeler justified departing so radically from Barrell’s view of baselevel by pointing to contradictions to which that view had led (Wheeler 1964a). The most glaring of these appeared to him to be the suggestion that baselevel is the boundary between areas of “temporary” and “permanent” deposition (Krumbein and Sloss 1963; Ross 1989; Emery and Myers 1996). This suggestion most certainly is contradictory if the baselevel referred to is baselevel *sensu* Barrell—as Wheeler assumed. It is not at all contradictory, however, if the baselevel referred to is what can be termed “time-averaged baselevel”; this is the surface whose elevation is the long-term average elevation of baselevel *sensu* Barrell. Time-averaged baselevel differs from baselevel *sensu* Barrell in two ways. Firstly, it is not a surface of equilibrium in any proper sense of that word (e.g., Chorley and Kennedy 1971); the best that can be said is that it is some indicator of a sedimentation system’s long-term equilibrium. Secondly, it does not separate the *actual* occurrence of deposition from the *actual* occurrence of erosion—as does baselevel *sensu* Barrell; instead, it separates the *usual* occurrence of deposition from the *usual* occurrence of erosion. Erosion occurs below time-averaged baselevel, although not as commonly as does deposition; deposition occurs above time-averaged baselevel, but not as commonly as does erosion. Stratigraphers who have written about “temporary” deposition occurring above baselevel have effectively been referring to time-averaged baselevel.

**Dynamic Equilibrium.**—Time-averaged baselevel is not the only time-averaged surface that has something to do with equilibrium; another such surface is the time-averaged lithic surface. The elevation of this latter sur-

face is simply the long-term average of the instantaneous lithic surface elevation, and it therefore appears as a “central” value about which the instantaneous lithic-surface elevation is fluctuating. Most stratigraphers would probably consider the time-averaged lithic surface to be no more than another indicator of long-term equilibrium. Others, however, would go much further. First, they would make the assumption that the instantaneous elevation of the lithic surface in a sedimentation system is a measure of that system’s state—this is probably a reasonable assumption; next, they would note that this state is almost invariably found to be fluctuating about some slowly varying “central” value; finally, they would argue that sedimentation systems *therefore* are in what is termed “dynamic equilibrium” (Swift and Thorne 1991; Thorne and Swift 1991; Thorne 1994). This dynamic equilibrium is analogous to the “grade” exhibited by geomorphic systems (Gilbert 1877; Mackin 1948; Strahler 1950; Culling 1957; Hack 1960; Chorley 1962) and to the “regime” exhibited by hydrologic systems (Lindley 1919; Blench 1957; Leopold et al. 1964).

Dynamic equilibrium is the kind of equilibrium that characterizes open systems: these are systems that allow both energy and mass to cross their boundaries in either direction, and whose states are commonly found to fluctuate relatively rapidly about steady or slowly varying “central” values (Chorley and Kennedy 1971). All sedimentation systems necessarily are open systems, and it is therefore reasonable to suggest that many of them may commonly be in dynamic equilibrium. If the sedimentation system at a given site actually is in dynamic equilibrium, then there will certainly be short-term fluctuations in the depositional and erosional rates at that site; the instantaneous elevation of the lithic surface there will then indeed be found to fluctuate in the short term about a steady or slowly varying “central” value. This argument cannot be turned about, however. The fact that the instantaneous elevation of the lithic surface at a site is found to fluctuate in the short term about some steady or slowly varying “central” value does not demonstrate that the sedimentation system at that site is in dynamic equilibrium; neither does the existence of short-term fluctuations in most sedimentation systems demonstrate that sedimentation systems in general are in dynamic equilibrium. Certainly it may be true that some types of sedimentation systems are “locked on” to a dynamic equilibrium (Swift and Thorne 1991, p. 11)—one example may be shoreface systems (Bruun 1962)—but the possibility that most sedimentation systems are normally out of equilibrium should not be discounted. It is worth taking to heart the experience of geomorphologists and hydrologists brought up in the “open systems” tradition of the sixties and seventies: they took only a short time to find numerous surface systems that are normally out of equilibrium (Ferguson 1977; Karcz 1980; Thorn 1988).

#### BASELEVEL: A SET OF PROPOSITIONS

Of the four kinds of equilibrium that might be used in defining baselevel, two can immediately be ruled out: long-term equilibrium can be ruled out because it is not a proper equilibrium, and dynamic equilibrium can be ruled out because sedimentation systems certainly exist that are not in dynamic equilibrium. Two possibilities then remain: locally stable equilibrium, and descriptive equilibrium. Of the views of baselevel to which these possibilities lead (baselevel *sensu* Barrell and baselevel *sensu* Wheeler), it is baselevel *sensu* Barrell that is the more appropriate for defining sedimentation capacity. Baselevel is therefore here taken to be based on locally stable equilibrium. It is defined in full in the following propositions.

**Proposition #1.**—*Every sedimentation system has a locally stable equilibrium, its baselevel.* Sedimentation systems at sites that are at baselevel are in equilibrium; there necessarily is stasis at those sites. Sedimentation systems at sites that are not at baselevel are not in equilibrium, and they seek to react to this nonequilibrium either by erosion or by deposition. They seek to react by erosion if they are above baselevel, i.e., if their sedimentation capacity is negative; they seek to react by deposition if they are below baselevel, i.e., if their sedimentation capacity is positive.

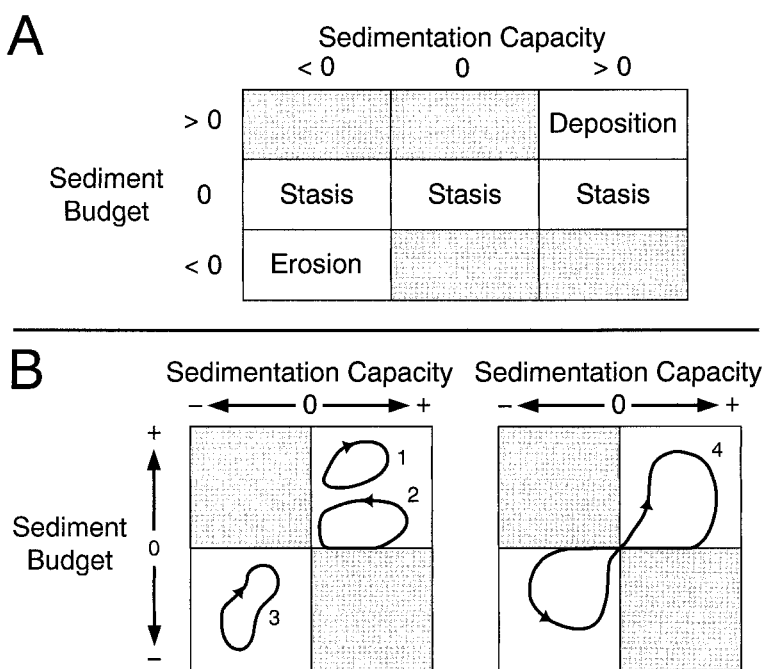


FIG. 2.—Sedimentation at sites with different combinations of sediment budget and sedimentation capacity. **A)** General contingency table. **B)** Hypothetical patterns of cyclic sedimentation, plotted as trajectories in time. Trajectory 1: continuous deposition throughout cycle. Trajectory 2: mostly continuous deposition, with one interval of stasis due to supply failure. Trajectory 3: continuous erosion throughout cycle. Trajectory 4: repeated pattern of deposition–stasis–erosion.

**Proposition #2.**—*Erosion does not occur at all sites above baselevel; deposition does not occur at all sites below baselevel.* Stratigraphers still commonly miss this critical point, even though it was clearly identified by Twenhofel sixty years ago: “The base level of erosion is the lowest level to which any group of agents *can* reduce a surface” and “The base level of deposition is the highest level to which a deposit *can* be built” (Twenhofel 1939, p. 8; italics added here for emphasis). Deposition occurs at a site below baselevel *only* when the sediment budget there is positive (cf. Dunbar and Rodgers 1957, p. 128); erosion occurs at a site above baselevel *only* when the sediment budget there is negative. Deposition and erosion do not occur automatically whenever a sedimentation system finds itself out of equilibrium; they occur *only* when the sediment budget is appropriate.

**Proposition #3.**—*A site at which there is stasis is not necessarily at baselevel.* Some sites at which there is stasis are manifestly below what any reasonable stratigrapher would accept as baselevel, e.g., starved basins in deep water; some other sites at which there is stasis are manifestly above baselevel, e.g., uplifted, low-relief surfaces on old cratons. The occurrence of stasis at a site does not indicate that the site is at baselevel (as argued by Wheeler); it indicates *only* that the sediment budget at that site is zero.

**Proposition #4.**—*A system’s baselevel changes in time in response to changes in boundary conditions.* Changes in the boundary conditions of a sedimentation system are due (a) to global and regional factors such as tectonic activity, climate change, and eustasy (as suggested by Barrell), and (b) to local factors such as deposition and erosion at neighboring sedimentation sites (as described for systems in dynamic equilibrium by Swift and Thorne). These changes determine what the system’s new baselevel ultimately will be, but they do not necessarily produce immediate and predictable alterations to that baselevel. The reason for this is that the system, because it is an open system, has the capability of regulating itself to counter changes in its boundary conditions (von Bertalanffy 1968). The system’s baselevel will consequently fluctuate until the system and its immediate neighbors have adjusted themselves to conditions at their mutual boundary. All the time that this fluctuation is taking place, the system will be seeking to return to equilibrium, i.e., it will be seeking to change its lithic surface elevation, either by erosion or by deposition. This erosion or deposition will take place whenever the sediment budget permits.

These propositions about baselevel effectively form a theoretical framework for sedimentation: they define the way in which sediment budget and sedimentation capacity together control the occurrence of deposition, erosion, and stasis (Fig. 2A). They can therefore be used to predict the sedimentation history of any site for which the variations in time of sediment budget and sedimentation capacity are known. From that sedimentation history, the stratigraphic succession produced at the site can then be predicted.

CYCLIC SEDIMENTATION AND STRATIGRAPHIC CYCLICITY

*General Considerations*

Cyclic sedimentation occurs at any site at which the sediment budget and/or the sedimentation capacity varies cyclically in time (Fig. 2B). The results of this sedimentation are preserved whenever the net thickness of sediment laid down during each cycle is positive. What clearly is of prime interest to the stratigrapher here is the correspondence between the pattern of stratigraphic cyclicality preserved at a site and the nature of the cyclic variation in sediment budget and sedimentation capacity that produced that cyclicality. For instance, are there particular patterns of cyclicality that correspond to particular types of cyclic variation? If so, is this true for patterns of cyclicality generally? Might it be possible to reconstruct sedimentation conditions simply by looking for diagnostic patterns of stratigraphic cyclicality?

The correspondence between patterns of stratigraphic cyclicality and types of cyclic variation in budget and capacity is assuredly complex, and questions such as these will certainly not be answerable directly. Progress is possible only via some indirect, modeling-based approach. The first step in this approach involves developing an appropriate one-dimensional model for cyclic sedimentation; this model will operate within the general theoretical framework for sedimentation described earlier, but will also have inbuilt restrictions on how sedimentation capacity and sediment budget can vary in time. (These restrictions exist solely to simplify the initial analysis of the model, and they will later be relaxed.) The second step in the approach involves using the model to calculate the patterns of cyclicality corresponding to all possible types of cyclic variation in budget and capacity. The third step involves relaxing the restrictions and assessing their effects.

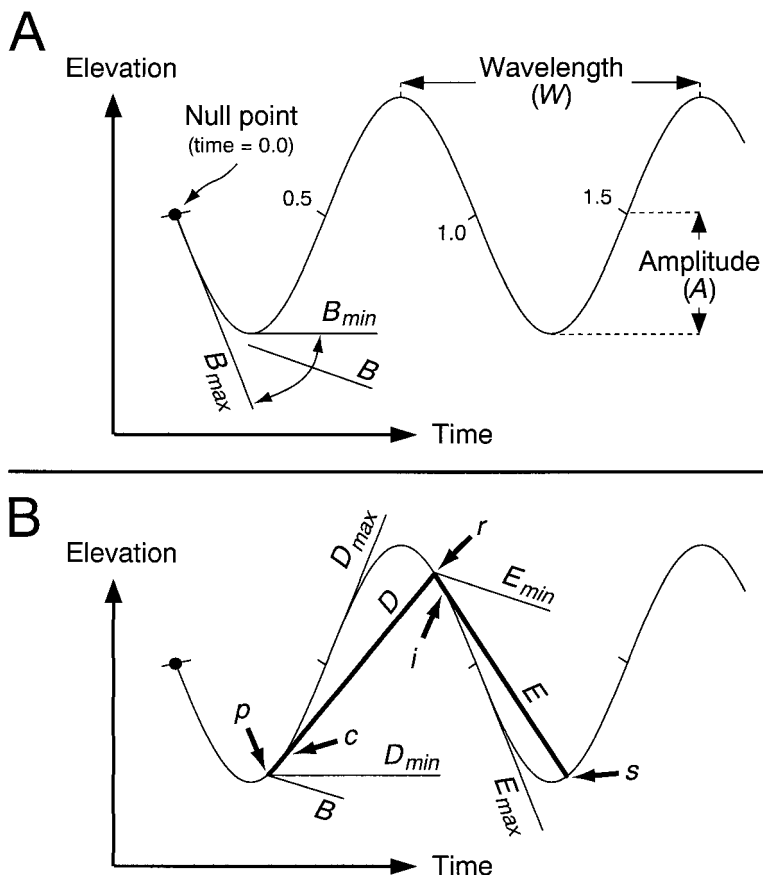


FIG. 3.—Definition diagram (elevation–time plot) for one-dimensional model for cyclic sedimentation. Time is scaled in units of baselevel wavelength ( $W$ ), with origin at baselevel null point (black bullet). **A**) Baselevel sinewave, with minimum and maximum possible values of basement subsidence rate  $B$ .  $B_{min}$  is horizontal, and  $B_{max}$  is tangent to baselevel sinewave at time = 0.0. **B**) Minimum and maximum possible values for limiting deposition rate  $D$  and limiting erosion rate  $E$ .  $D_{min}$  is horizontal;  $D_{max}$  is tangent to baselevel sinewave at time = 0.5;  $E_{min}$  is parallel to actual subsidence rate line  $B$ ;  $E_{max}$  is tangent to baselevel sinewave at time = 1.0. Heavy line shows track of lithic surface for cycle described in text. Lithic surface follows baselevel sinewave from  $p$  to  $c$ , then actual limiting deposition rate line  $D$  to  $r$ , then baselevel sinewave to  $i$ , then actual limiting erosion rate line  $E$  to  $s$  ( $= p + 1$ ). For full definition of lower-case italicized points, see Appendix 1.

The final step involves using the now-determined correspondence between cyclicity and cyclic variation to let the type of cyclic variation at a site be reconstructed from the pattern of stratigraphic cyclicity preserved there.

**A One-Dimensional Model, and an Example of a Sedimentation Cycle**

The appropriate model to use is undoubtedly the one stratigraphers turn to first in most one-dimensional modeling exercises: baselevel variation at the site in question is assumed to be sinusoidal, and is combined with linear tectonic subsidence (Fig. 3). This model was used in the first major paper on synthetic cyclic stratigraphy (Turcotte and Willemann 1983); other examples of its use are given by Sadler (1981), Jervey (1988), and Drummond and Wilkinson (1993). As it stands, this model already provides a suitable restriction on sedimentation capacity: it prescribes how sedimentation capacity varies in time in the absence of sedimentation. A comparable restriction on sediment budget can be provided by demanding that the sediment budget of a site always be exactly enough to keep that site at baselevel, except when either of two fixed budget limits are reached.  $L_{SUR}$  (the “surplus limit”) is the maximum permitted surplus in the sediment budget at the site in question (i.e., the maximum permitted net sediment flux);  $L_{DEF}$  (the “deficit limit”) is the maximum permitted deficit in the sediment budget (i.e., the minimum permitted net sediment flux).

The model has five independent variables: the amplitude and wavelength of the baselevel sinewave ( $A$  and  $W$ ; dimensions  $L$  and  $T$ , respectively), the rate of tectonic subsidence ( $B^*$ ; dimensions  $LT^{-1}$ ), and the surplus and deficit limits ( $L_{SUR}$  and  $L_{DEF}$ , respectively; dimensions  $L^3T^{-1}$ ). These variables can be reexpressed as three dimensionless variables: the dimensionless subsidence rate ( $B$ ), the limiting deposition rate ( $D$ ), and the limiting erosion rate ( $E$ ).  $B$  is obtained by scaling  $B^*$  in terms of  $A$  and  $W$ , and then writing it as a percentage of the maximum rate of tectonic sub-

sidence for which cyclic sedimentation is possible: thus  $B = B^* \times (W / 2\pi A) \times 100$ .  $D$  and  $E$  are obtained in a similar manner from  $L_{SUR}$  and  $L_{DEF}$ , respectively, but with an extra correction for the surface area of the sedimentation site (this is shown as  $M$  in Figure 1); thus  $D = L_{SUR} \times (W / 2\pi A) \times 100 / M$ , and  $E = L_{DEF} \times (W / 2\pi A) \times 100 / M$ .

Sedimentation cycles are produced for all combinations of  $B$ ,  $D$ , and  $E$  for which  $0\% < B < 100\%$ ,  $B\% \leq D \leq (100 + B)\%$ , and  $0\% < E \leq (100 - B)\%$ . The form of the cycle corresponding to any given combination is defined by eight points ( $ceikpqr$ s; Appendix 1). The positions of these points are readily determined using a straightforward iterative algorithm; each point is adjusted in turn until the stable cycle form is reached. A Pascal implementation of this algorithm is available from the author.

An example of a sedimentation cycle is shown in Figure 3B. Deposition in this cycle starts at point  $p$ , where the rate line  $B$  cuts the rising limb of the baselevel curve. The supply of sediment to the site is fast enough initially to keep the lithic surface at baselevel, but the budget surplus limit is eventually reached (at point  $c$ , where the rate line  $D$  is tangential to the baselevel curve); at this point the sediment supply can no longer keep pace with the site’s ability to increase its capacity, and the lithic surface therefore sinks below baselevel. Eventually, however, the site’s ability to increase its capacity drops, and the lithic surface rises back towards baselevel; it eventually reaches baselevel at point  $r$  (where the rate line  $D$  through the point  $c$  cuts the now-falling baselevel curve). Erosion then takes over from deposition. The removal of sediment from the site is fast enough initially to keep the lithic surface at baselevel, but the budget deficit limit is eventually reached (at point  $i$ , where the rate line  $E$  is tangential to the baselevel curve); at this point the sediment removal can no longer keep pace with the site’s ability to decrease its capacity, and the lithic surface therefore rises above baselevel. Finally, the site’s ability to decrease its capacity

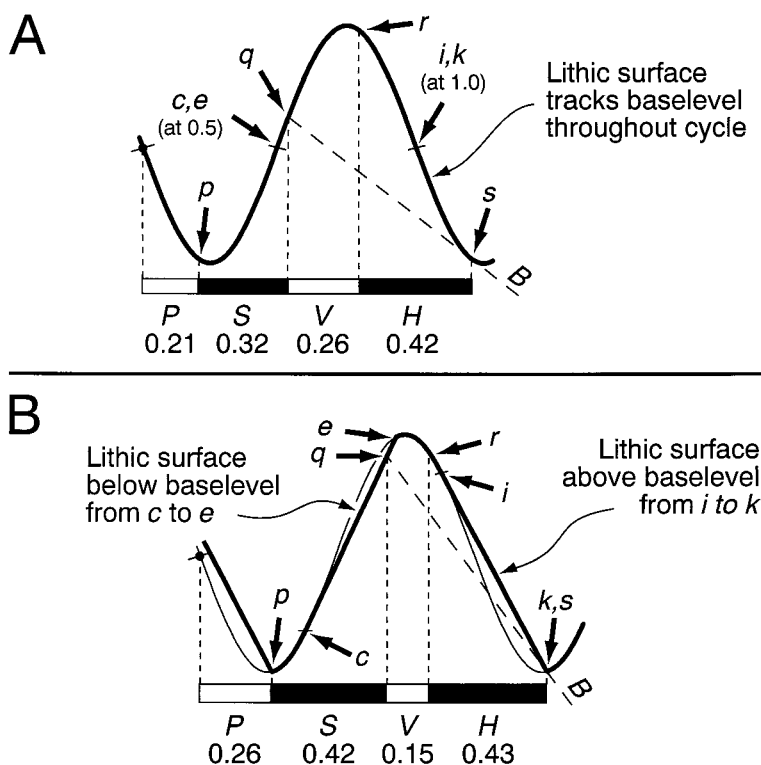


FIG. 4.—Elevation-time plots for two contrasting cycles. In this and all subsequent elevation-time plots, heavy line shows track of lithic surface and light line shows baselevel sinewave. Line *B* is subsidence rate line. Striped bar at base of each plot shows values of cycle form descriptors: *P* (phase lag) is measured from baselevel null point (black bullet), in units of *W*; *S* is sequence proportion; *V* is vacuity proportion; *H* is hiatus proportion;  $S + V + H = 1$ . **A**) Baselevel-tracking cycle ( $T_c = 45$ ). **B**) Cycle in which lithic surface does not track baselevel. Lithic surface is at baselevel only from *p* to *c* and from *e* to *i*. For definition of lower-case italicized points, see Appendix 1.

drops, and the lithic surface falls back towards baselevel; it reaches baselevel again at point *s*, where the rate line *E* through point *i* cuts the now-rising baselevel curve, exactly one wavelength after point *p*.

**Descriptors of Cycle Form**

Cycles corresponding to different combinations of *B*, *D*, and *E* differ greatly from each other in detail. All of them have a similar basic form, however, and they can therefore all be described using standardized form descriptors. These descriptors are the “phase lag”, the “cycle proportions”, the “cycle type”, and the “sequence type”. The phase lag (*P*; Fig. 4) measures the time at which deposition in a cycle starts; this time is measured from the baselevel null point on the cycle’s falling-baselevel limb, in units of cycle wavelength. The cycle proportions (*S*, *V*, *H*; Fig. 4) are the proportions of a cycle’s wavelength that correspond respectively to preserved deposition, to deposition that is later eroded, and to erosion; thus *S* is the “sequence proportion”, *V* is the “vacuity proportion”, and *H* is the “hiatus proportion”. The cycle type ( $T_c$ ) is a code that describes how sedimentation capacity changes in time over a complete cycle; the code values—see Appendix 2 for how these are derived—reflect the natural geometric relationships between different cycle types. The sequence type (Fig. 5) is a set of abbreviations describing the number and order of the facies components of which a sequence is built. These may be baselevel components (BL), deepening-upward components (DU), or shallowing-upward components (SU).

**Families of Cycle Types, and Families of Sequence Types**

The model produces 20 types of sedimentation cycle, which fall naturally into four families (Fig. 6): “sawtooth” cycles, “sharp-base” cycles, “sharp-top” cycles, and “smooth” cycles. The fundamental differences between the families are in the ways in which the lithic surface passes through baselevel. In a sawtooth cycle, the lithic surface passes instantaneously through baselevel both when sedimentation capacity is going negative (lithic surface rising above baselevel) and when it is going positive

(lithic surface falling below baselevel). In a sharp-base cycle, only the positive-going passage is instantaneous; there is an at-baselevel interval during the negative-going passage. Sharp-top cycles are the opposite of sharp-base cycles: the negative-going passage is instantaneous and the positive-going passage has the at-baselevel interval. In smooth cycles, both passages have at-baselevel intervals. One special type of smooth cycle, the “baselevel-tracking cycle”, has no passages through baselevel; it is produced at sites where the limiting deposition and erosion rates are high enough to ensure that lithic surface and baselevel always coincide (Fig. 4A).

The model produces ten types of sequence, which also fall naturally into four families (Fig. 7). Within each family are grouped those sequence types that have the same underlying order to their facies components. For the first family, this order is BL–DU–SU–BL; for the second family, it is BL–BL; for the third family, it is DU–SU–BL; for the fourth family, it is BL. The sequence types within each family are most easily thought of as being related to each other by erosion; thus the DU–SU sequence type in the third family is the DU–SU–BL sequence type with its upper BL component removed. Clearly there are several sequence types that will usually be indistinguishable from each other in practice: the BL sequence types in the first, second, and fourth families, and the BL–BL sequence type in the second family. It might seem pointless to differentiate these sequence types, but it is not—*superficially identical though they are, these sequence types have radically different phase-lag connotations*. BL–BL sequences typically indicate deposition starting *significantly before* the baselevel zero-point on the rising limb of the baselevel curve, i.e., *P very much less than 0.5*; first-family and second-family BL sequences typically indicate deposition starting *shortly before* that zero-point, i.e., *P slightly less than 0.5*; fourth-family BL sequences *always* indicate deposition starting *after* that zero-point, i.e., *P greater than 0.5*.

**The Effects of Rate Differences**

The effects that differences in the rates *B*, *D*, and *E* have on the cycle form descriptors are shown in Figures 8 to 12.

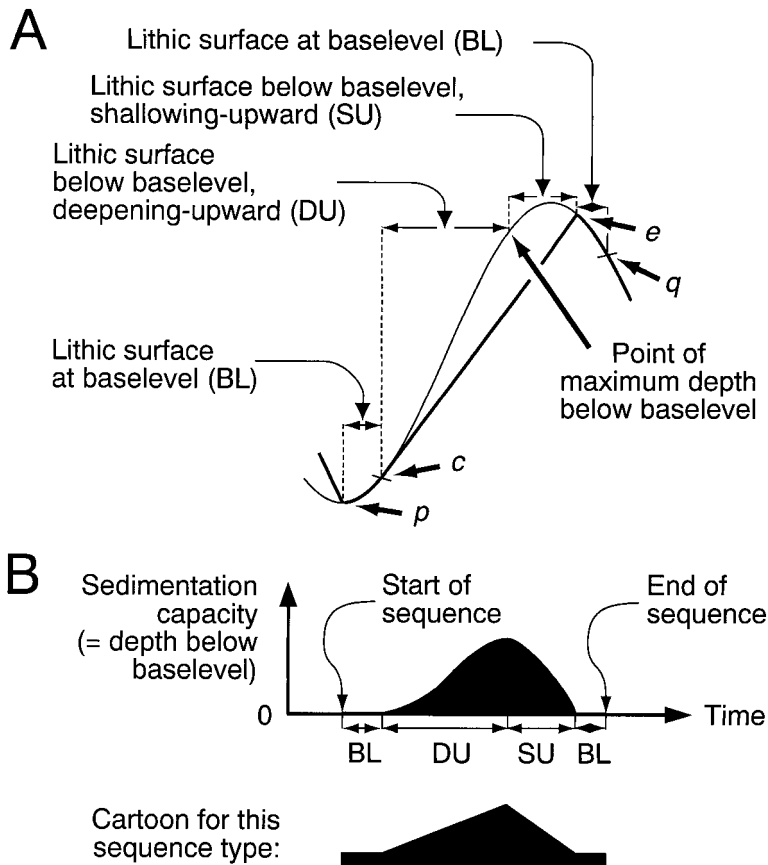


FIG. 5.—The facies components that make up sequences, shown **A**) on elevation-time plot of part of a cycle, and **B**) on corresponding plot of sedimentation capacity against time. BL is facies component laid down at baselevel; DU is facies component laid down in deepening-upward conditions; SU is facies component laid down in shallowing-upward conditions. Sequence type here is BL–DU–SU–BL. For definition of lower-case italicized points, see Appendix 1.

**Sequence Proportion (S; Fig. 8).**—Sequence proportion increases both with increasing subsidence rate (for set limiting deposition and erosion rates) and with decreasing limiting deposition rate (for set subsidence and limiting erosion rates). Maximum values of sequence proportion are produced (a) when the subsidence and limiting deposition rates are almost equal, and (b) when the subsidence rate is high and the limiting erosion rate low. Minimum values of sequence proportion are produced when the subsidence rate is low, especially when the limiting deposition rate is high.

**Phase Lag (P; Fig. 9).**—Phase lag is controlled chiefly by the subsidence and limiting erosion rates. When the limiting erosion rate is set, phase lag increases with decreasing subsidence rate. The range of values that phase lag can have varies greatly: this range is greatest when no erosion is allowed; it is less when some erosion is allowed, e.g.,  $E = 50\%$  in Figure 9; it is least when erosion is always fast enough to stop the lithic surface rising above baselevel, i.e.,  $E = (100 - B)\%$ . Sequences formed at sites where no erosion is allowed can evidently start at any time from shortly after the baselevel null point (i.e., shortly after time 0.0) to shortly before the baselevel high point (i.e., shortly before time 0.75). In contrast, sequences formed at sites where erosion is always capable of stopping the lithic surface rising above baselevel can start only before the baselevel low point (i.e., before time 0.25).

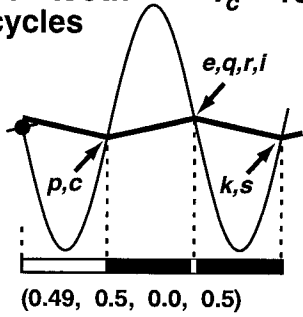
**Cycle Type ( $T_C$ ; Fig. 10).**—The incidence of different cycle types is best traced on plots of subsidence rate against limiting deposition rate, for set limiting erosion rates. When no erosion is allowed: (a) continuous de-

position takes place when the limiting deposition rate is *almost equal* to the subsidence rate; (b) sharp-top cycles are produced when the limiting deposition rate is *slightly greater* than the subsidence rate, especially when the subsidence rate is relatively high ( $B \geq 50\%$ ); (c) sawtooth cycles are produced when the limiting deposition rate is *significantly greater* than the subsidence rate, but only when the subsidence rate is relatively low ( $B \leq 50\%$ ); (d) sharp-base cycles are produced when the limiting deposition rate is *very much greater* than the subsidence rate; (e) smooth cycles are produced when the subsidence and limiting deposition rates are both high, and when the subsidence rate is very low. As the amount of erosion allowed is increased (e.g.,  $E = 30\%$ ,  $50\%$  in Figure 10): (a) sawtooth and sharp-base cycles are produced for fewer combinations of  $B$  and  $D$ ; (b) sharp-top cycles become more and more of type  $T_C = 51$ ; (c) sharp-base cycles of type  $T_C = 26$  give way to sharp-base cycles of types  $T_C = 22$  and  $30$ ; (d) smooth cycles are produced in greater variety and for more combinations of  $B$  and  $D$ . When erosion is always capable of stopping the lithic surface rising above baselevel: (a) continuous deposition takes place when the limiting deposition rate is almost equal to the subsidence rate; (b) otherwise only smooth cycles are produced.

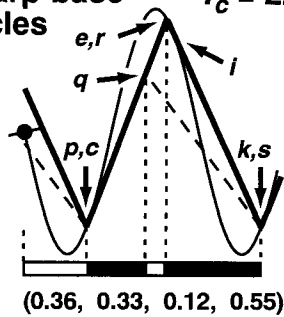
**Sequence Type (Fig. 11).**—The incidence of different sequence types is also best traced on plots of subsidence rate against limiting deposition rate, for set limiting erosion rates. When no erosion is allowed: (a) first-family sequence types (BL–DU–SU–BL, BL–DU–SU) are produced when the subsidence rate is relatively high ( $B \geq 50\%$ ); (b) third-family sequence

FIG. 6.—Elevation-time plots for examples of all possible cycle types. Values of rates  $B$ ,  $D$ , and  $E$  are given in Table 1. Striped bar at base of each plot shows values of cycle form descriptors  $P$ ,  $S$ ,  $V$ , and  $H$  (parenthesized numbers, left to right; cf. Fig. 4). For definition of lower-case italicized points, see Appendix 1. For details of cycle type codes ( $T_C$ ), see Appendix 2.

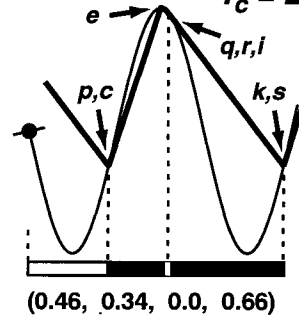
**Sawtooth cycles**  $T_c = 18$



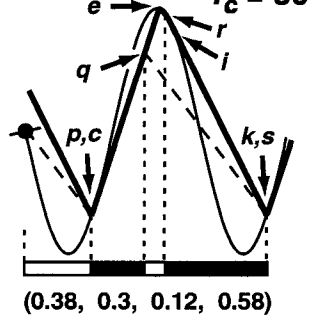
**Sharp-base cycles**  $T_c = 22$



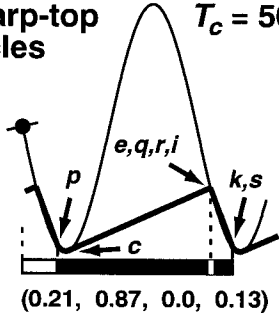
$T_c = 26$



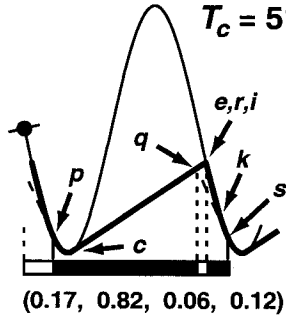
$T_c = 30$



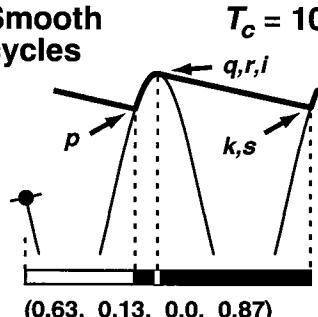
**Sharp-top cycles**  $T_c = 50$



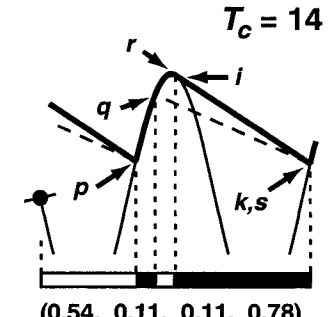
$T_c = 51$



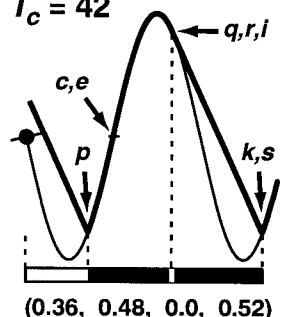
**Smooth cycles**  $T_c = 10$



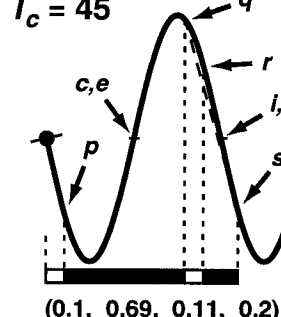
$T_c = 14$



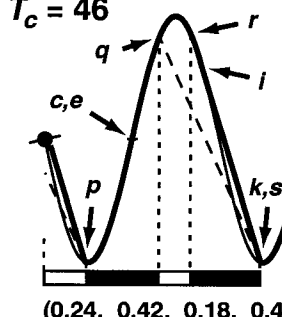
$T_c = 42$



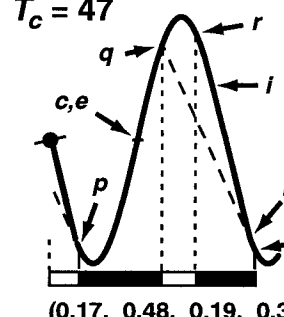
$T_c = 45$



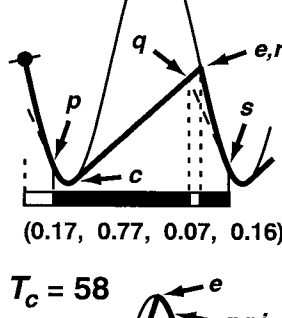
$T_c = 46$



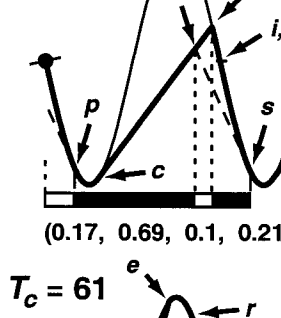
$T_c = 47$



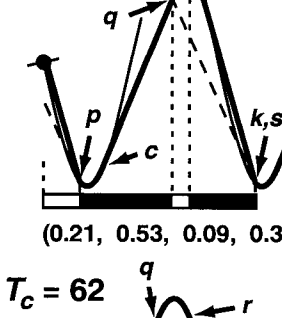
$T_c = 49$



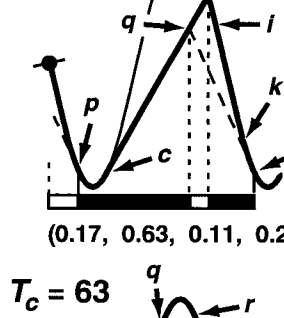
$T_c = 53$



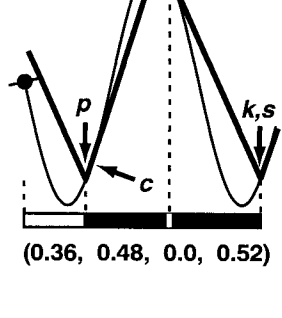
$T_c = 54$



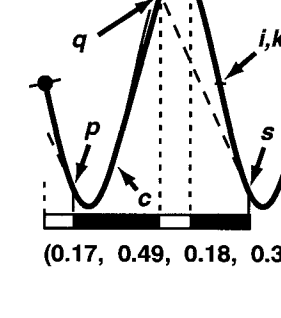
$T_c = 55$



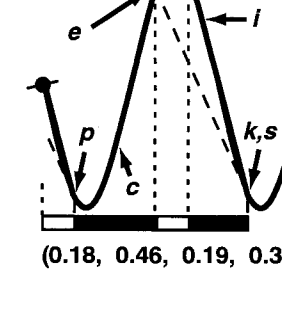
$T_c = 58$



$T_c = 61$



$T_c = 62$



$T_c = 63$

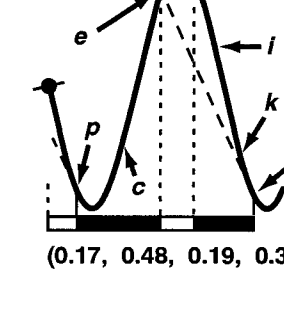


TABLE 1.—Input and output variables for cycle type examples shown in Figure 6.

Cycle Type $T_c$	Subsidence Rate (%) $B$	Limiting Deposition Rate (%) $D$	Limiting Erosion Rate (%) $E$	Phase Lag $P$	Sequence Proportion $S$	Vacuity Proportion $V$	Hiatus Proportion $H$	Sequence Type
10	5	105	0	0.63	0.13	0.00	0.87	BL
14	10	110	5	0.54	0.11	0.11	0.78	BL
18	5	10	0	0.49	0.50	0.00	0.50	DU-SU
22	30	90	20	0.36	0.33	0.12	0.55	DU-SU
26	30	100	0	0.46	0.34	0.00	0.66	DU-SU-BL
30	30	100	15	0.38	0.30	0.12	0.58	DU-SU
42	50	150	0	0.36	0.48	0.00	0.52	BL-BL
45	80	180	20	0.10	0.69	0.11	0.20	BL-BL
46	50	150	25	0.24	0.42	0.18	0.40	BL-BL
47	50	150	40	0.17	0.48	0.19	0.33	BL-BL
49	50	70	50	0.17	0.77	0.07	0.16	BL-DU-SU
50	60	70	0	0.21	0.87	0.00	0.13	BL-DU-SU
51	50	65	35	0.17	0.82	0.06	0.12	BL-DU-SU
53	50	80	50	0.17	0.69	0.10	0.21	BL-DU-SU
54	50	105	30	0.21	0.53	0.09	0.38	BL-DU-SU
55	50	90	45	0.17	0.63	0.11	0.26	BL-DU-SU
58	50	120	0	0.36	0.48	0.00	0.52	BL-DU-SU-BL
61	50	130	50	0.17	0.49	0.18	0.33	BL-DU-SU
62	50	140	35	0.18	0.46	0.19	0.35	BL-DU-SU
63	50	140	45	0.17	0.48	0.19	0.33	BL-DU-SU

types (DU-SU-BL, DU-SU) are produced when the subsidence rate is relatively low ( $B \leq 50\%$ ); (c) the fourth-family sequence type BL is produced when the subsidence rate is extremely low and the limiting deposition rate is high; (d) the second-family sequence type BL-BL is produced when the limiting deposition rate is as high as it can be for the given subsidence rate, provided that that subsidence rate is greater than about 20%. As the amount of erosion allowed is increased (e.g.,  $E = 50\%, 70\%$  in Figure 11): (a) first-family sequence types systematically replace third-family ones; (b) the BL-DU sequence type becomes ever more dominant; (c) the BL sequence type belonging to the fourth family is replaced by the BL sequence types belonging to the first and second families. When erosion is always capable of stopping the lithic surface rising above baselevel: (a) second-family sequence types are produced when the limiting deposition rate is the maximum possible for the given subsidence rate; (b) otherwise only first-family sequence types are produced.

**S-V-H Triangles (Fig. 12).**—The effects that rate differences have on the cycle proportions are readily seen on triangular plots drawn with  $S$ ,  $V$ , and  $H$  as vertices. These effects are relatively straightforward when subsidence rates are medium to high (i.e.,  $B \geq 30\%$ ): (a)  $V$  is always less than  $H$ ; (b) any increase in the limiting erosion rate for a given limiting deposition rate tends to decrease  $H$  without substantially affecting the ratio of  $S$  to  $V$ ; (c) any increase in the limiting deposition rate for a given limiting erosion rate tends to decrease the ratio of  $S$  to  $H$ , without affecting  $V$ ; (d) the baselevel-tracking cycle is the cycle with the highest  $V$ , i.e., the cycle for which the highest proportion of once-preserved time is removed by erosion. Rate differences have more complicated effects when subsidence rates are low (i.e.,  $B \leq 30\%$ ): (a)  $V$  can be greater than  $H$ , especially when

limiting erosion rates are high; (b) when limiting deposition and erosion rates are both high, then an increase in either of these rates will tend to decrease  $V$ ; (c) the baselevel-tracking cycle is no longer the cycle with the highest  $V$ .

*The Uniqueness and Stability of Sedimentation Cycles*

Each of the sedimentation cycles described here is both unique and stable. It is unique because its form is specific to one particular set of sedimentation conditions; it is stable because short-term perturbations of those conditions only temporarily affect its production. Not all cycles have the same degree of stability, however. Some of them—the smooth cycles—are always highly stable; others—the sawtooth cycles—are not. The more stable a cycle is, the faster it reestablishes itself after sedimentation conditions have been perturbed.

The differing degrees of stability that different cycle families have are clearly illustrated by tracing the ways in which representative cycles react to simple short-term perturbations (Fig. 13). One such perturbation is an abrupt rise of the lithic surface, just as deposition in a cycle is about to start; another is an abrupt fall, again just as deposition is about to start. Smooth cycles react fastest to these perturbations; they reestablish themselves almost immediately when the perturbations are small, and they will always have reestablished themselves within one baselevel cycle. Sharp-top cycles and sharp-base cycles are slower to react, but they too will have reestablished themselves within one baselevel cycle, except after large perturbations. Sawtooth cycles are the slowest to react, and the sawtooth cycle corresponding to a particular set of sedimentation conditions will often only be the seldom-reached limit of a prolonged series of oscillations (Fig. 13C). Deposition and erosion will occur alternately within each oscillation, with the timings of the passages through baselevel changing steadily as the stable cycle form is approached.

Because every cycle is unique, it is produced only as long as its particular sedimentation conditions are maintained. Therefore even the slightest change in sedimentation conditions—and note that I now mean permanent change, not short-term perturbation—results in a cycle of one form being replaced by a cycle of another form. These two forms will almost certainly be distinguishable from each other when compared in terms of phase lag and cycle proportions; this is because even small changes in  $B$ ,  $D$ , and  $E$  produce measurable changes in  $P$ ,  $S$ ,  $V$ , and  $H$ . However, the same two forms will not necessarily be distinguishable in terms of cycle type and sequence type (Figs. 10, 11). It is certainly unwise to cite the repeated occurrence of the same type of sequence in a stratigraphic succession as incontrovertible evidence of unchanging sedimentation conditions.

Changes in the way in which baselevel is fluctuating at a site affect cycle form in exactly the same way as do changes in sedimentation conditions; this is because the rates  $B$ ,  $D$ , and  $E$  are scaled in terms of baselevel amplitude and wavelength. Changes in baselevel fluctuation can therefore be expected to be able to produce changes in phase lag and cycle propor-

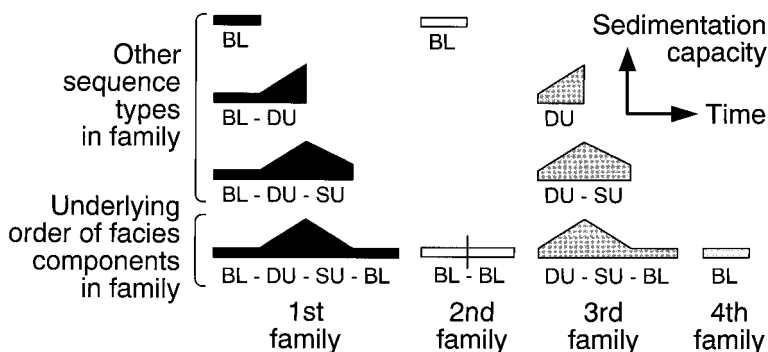
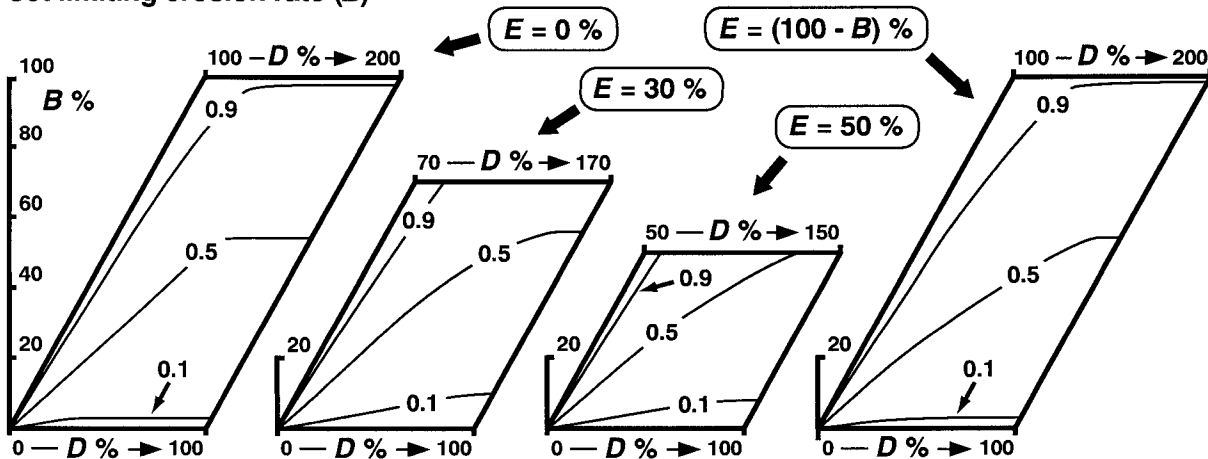
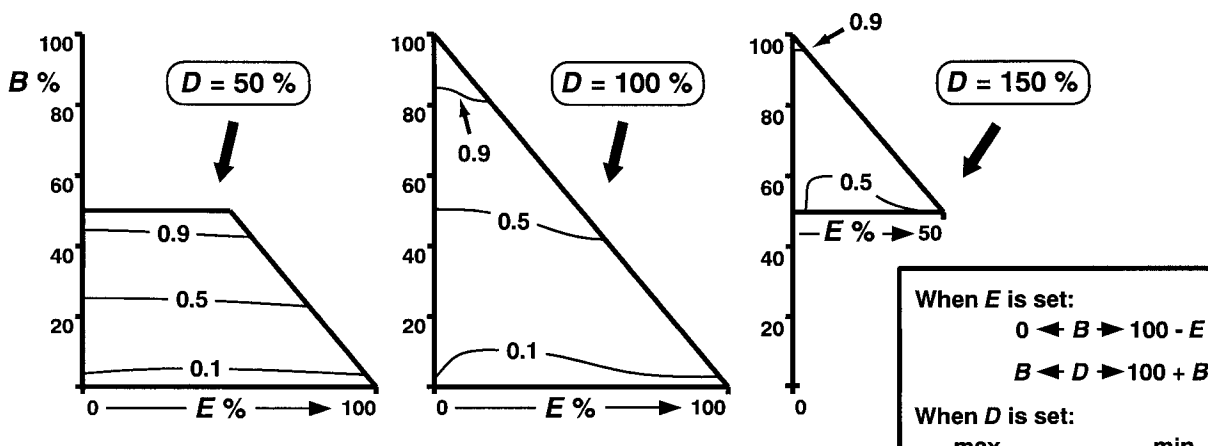


FIG. 7.—The ten possible sequence types, grouped into families and shown as cartoons on plots of sedimentation capacity against time. For derivation of cartoons, see example in Figure 5B. Shading used to differentiate families is used again in Figure 11.

Set limiting erosion rate (E)



Set limiting deposition rate (D)



Set subsidence rate (B)

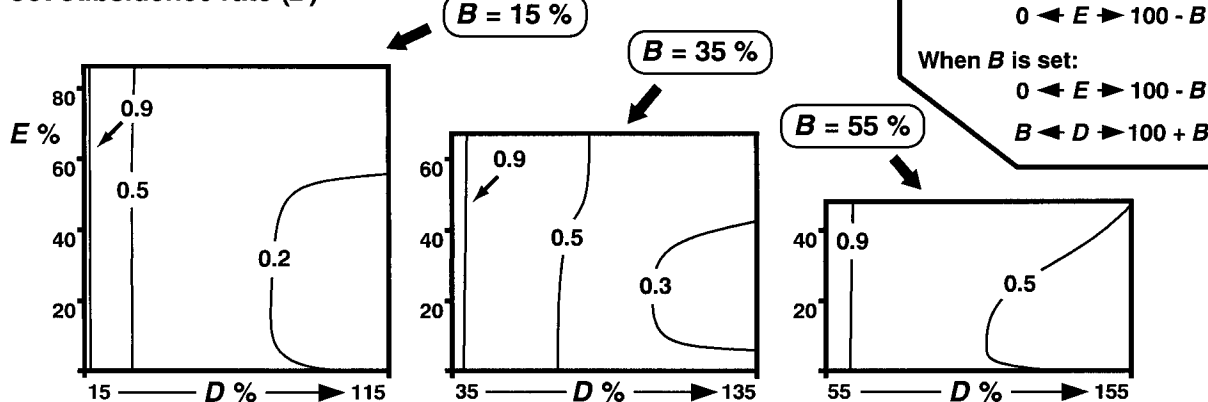


FIG. 8.—Contoured plots of sequence proportion (S). Upper panel: contours of S for set values of E. Center panel: contours of S for set values of D. Lower panel: contours of S for set values of B. Inset box at lower right gives maximum and minimum rates.

tions, without necessarily producing changes in cycle type and sequence type. Some sequence types may evidently be able to be produced continually and without apparent change, even when the amplitude and the wavelength of baselevel fluctuation are both changing substantially. This possibility should worry many over-enthusiastic sequence stratigraphers.

Relaxing the Model's Restrictions

The model for cyclic sedimentation that has been analyzed here is undoubtedly artificial, particularly in view of its inbuilt restrictions on sediment budget and sedimentation capacity. It is nevertheless a robust model,

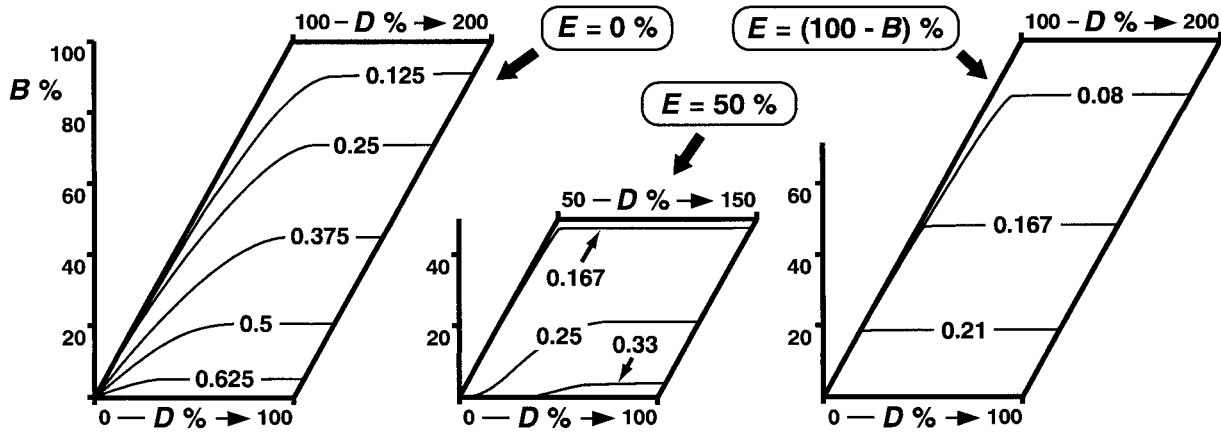


Fig. 9.—Contoured plots of phase lag ( $P$ ) for set values of  $E$ .

and the principal results of the analysis seem hardly to change when these restrictions are relaxed. This can be shown by considering (a) the effects of compound baselevel fluctuation, and (b) the effects of time-varying budget limits.

**Compound Baselevel Fluctuation.**—Baselevel fluctuation should be expected usually to have a compound waveform, if only because of the way in which baselevel elevation is controlled (see earlier discussion). Such a

compound waveform can be represented as the sum of several independent sinewave components, each with its own amplitude, wavelength, and phase. It is probably reasonable to assume that the longer-wavelength components have the higher amplitudes, as in the Vail-Haq sea level curve.

Baselevel fluctuation such as this is unlikely ever to produce regular sedimentation cycles; this is clear, even for the simplest two-component situation (Fig. 14). But highly irregular cycles are also unlikely. Compound

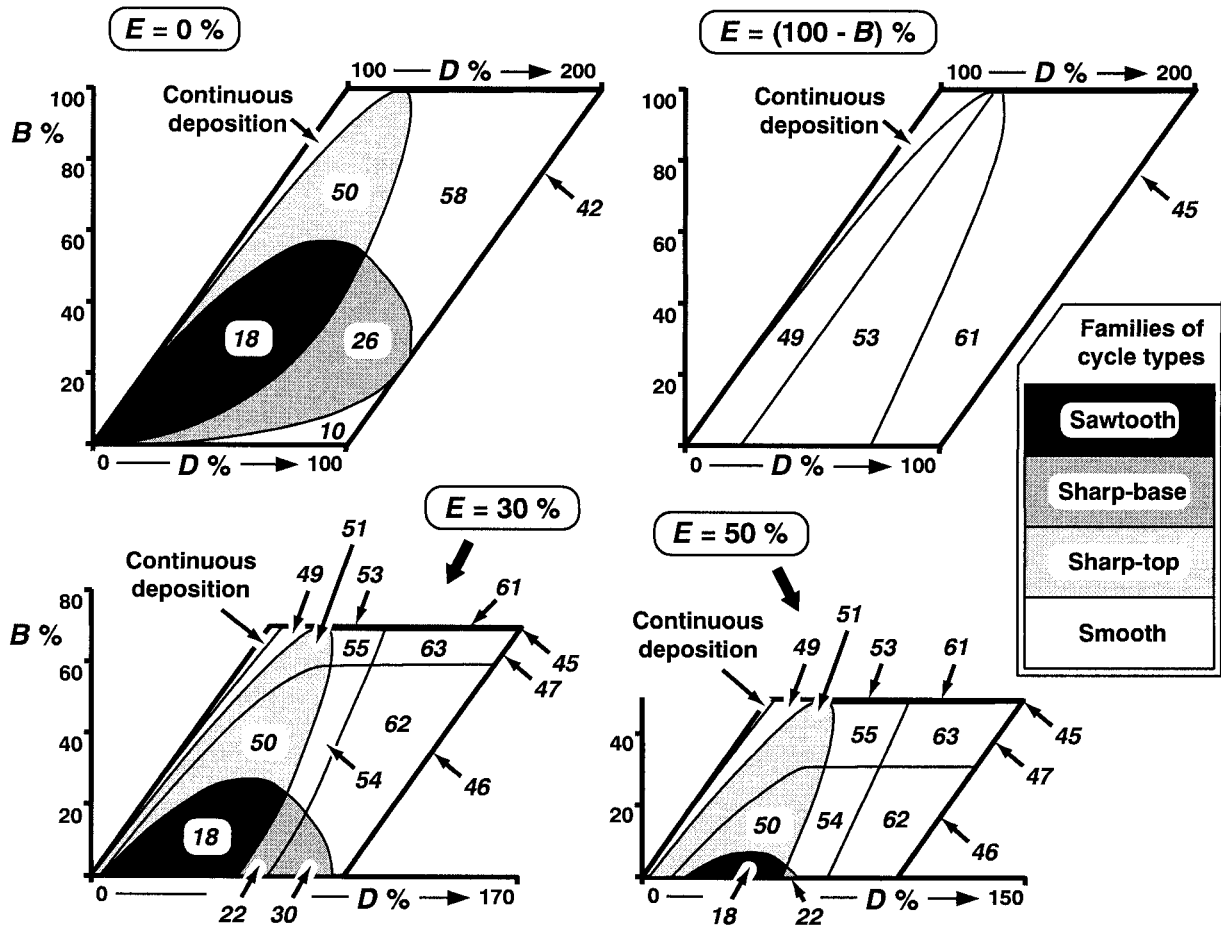


Fig. 10.—Regions of occurrence of different cycle types, for set values of  $E$ . Values of  $T_c$  are italicized, and cycle types in same family are shaded alike (see inset box at right). Note that this shading is different from that used for sequence families in Figures 7 and 11.

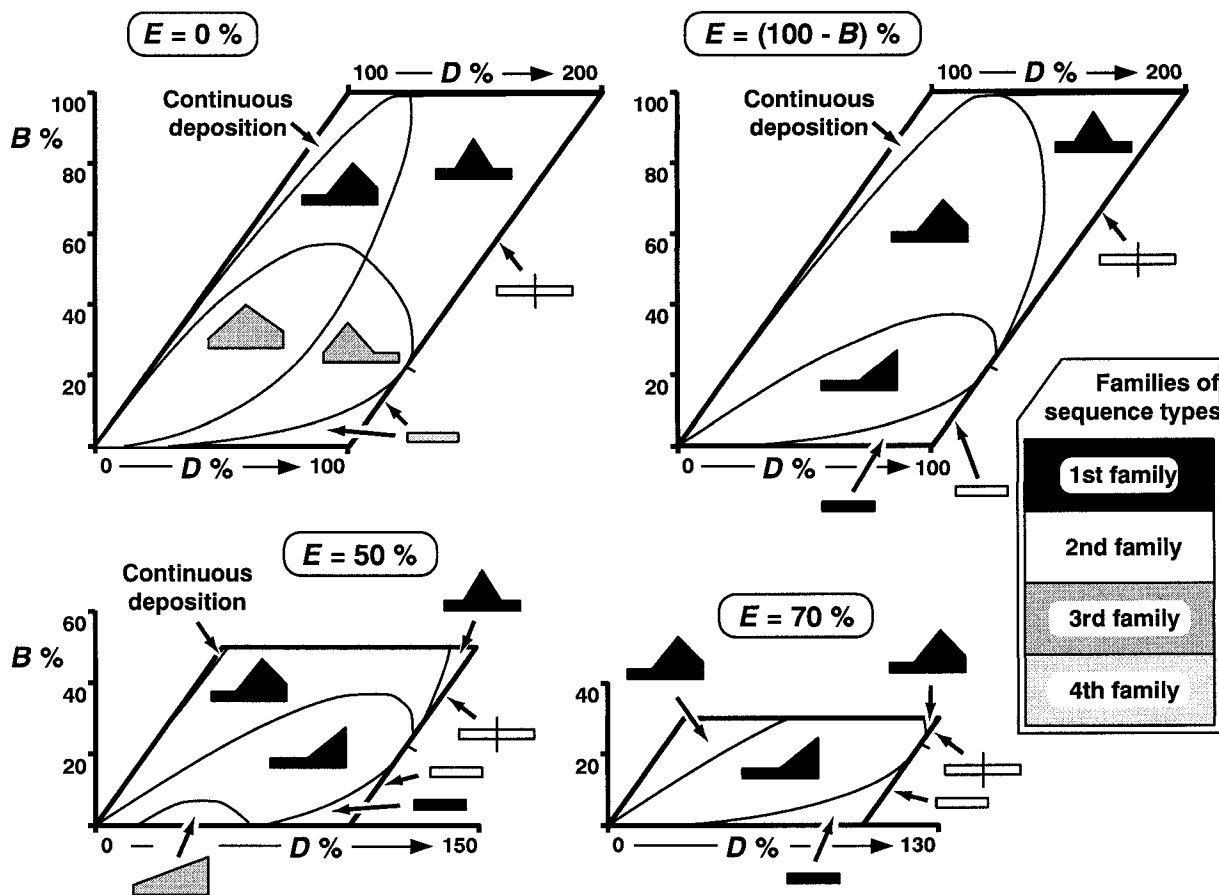


FIG. 11.—Regions of occurrence of different sequence types, for set values of  $E$ . Sequence types are represented by their cartoons (see Figure 7), and sequence types in same family are shaded alike (see inset box at right).

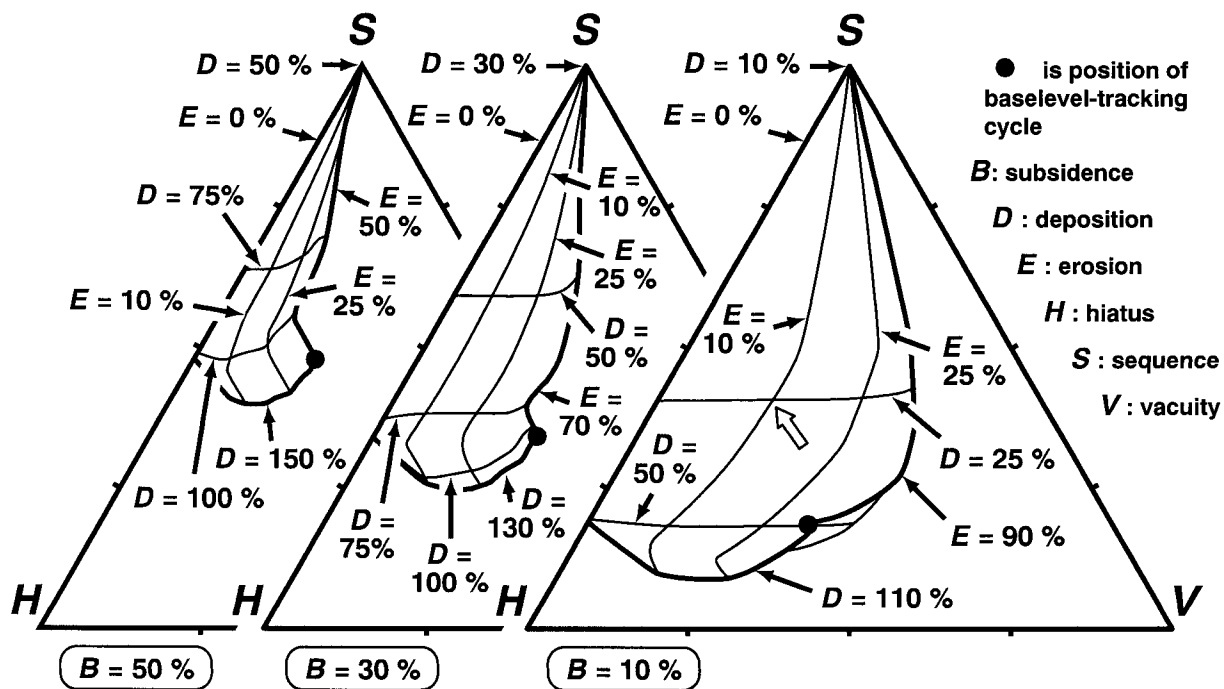


FIG. 12.— $S$ - $V$ - $H$  triangles, for three selected values of  $B$ , with selected iso- $D$  and iso- $E$  lines. For example (open-arrowed point): cycle proportions are  $S = 0.4$ ,  $V = 0.17$ ,  $H = 0.43$ ; rates are  $B = 10\%$ ,  $D = 25\%$ ,  $E = 10\%$ .

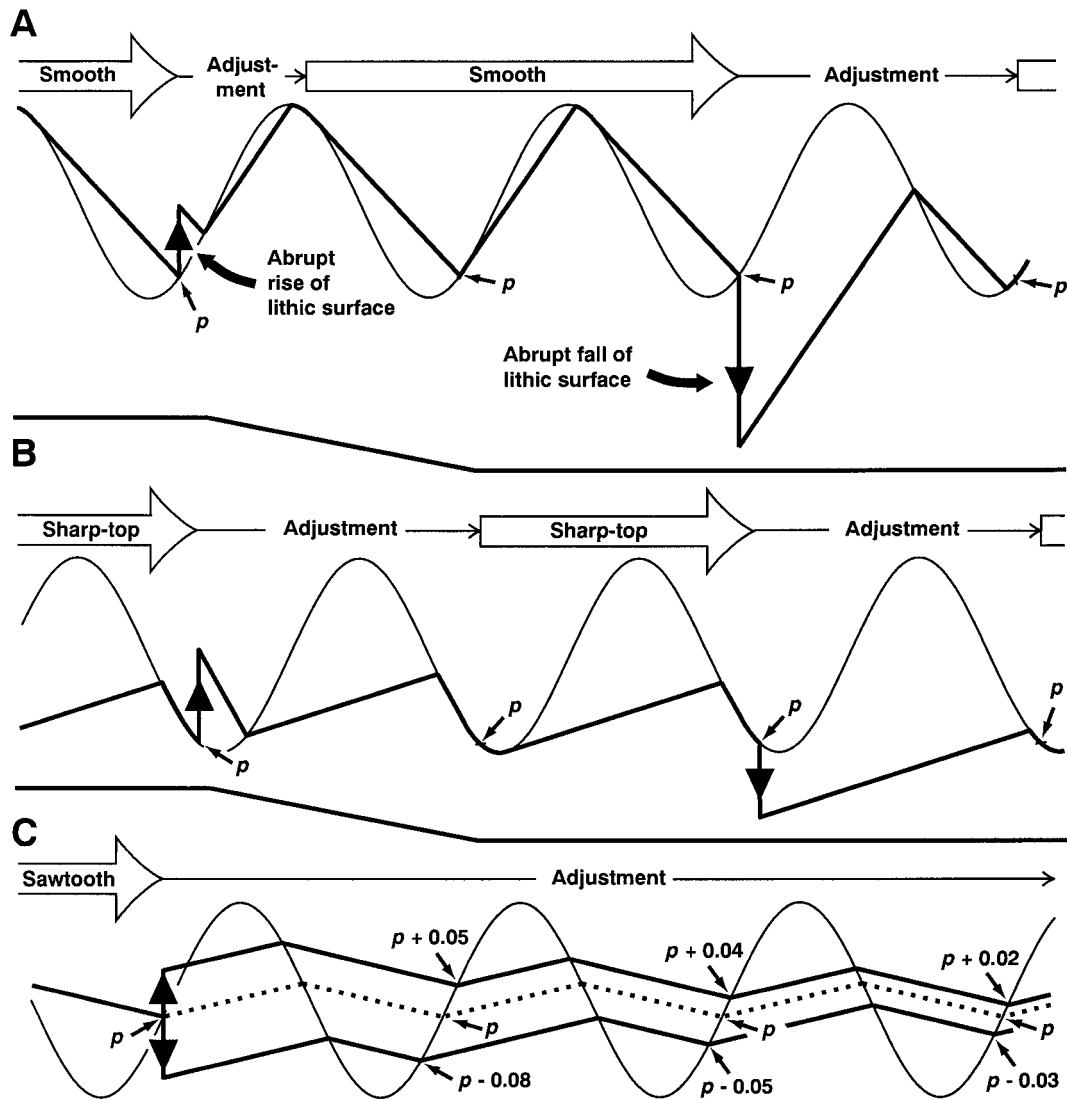


FIG. 13.—Elevation–time plots showing reaction to two short-term perturbations of sedimentation conditions, for cycles belonging to different families; see text for details. Open arrows mark periods during which stable cycle type is being produced. Between these periods are intervals of adjustment, when stable cycle type reestablishes itself. Italicized point *p* is time at which deposition starts. **A)** Smooth cycle. **B)** Sharp-top cycle. **C)** Sawtooth cycle. To save space in plot C, both perturbations are shown occurring at same time. The two lithic surface tracks converge on the lithic surface track for the unperturbed cycle (dashed line).

baselevel fluctuation is most likely to produce cycles that differ from each other in detail, but that are all broadly comparable to the cycle that would be produced by the longest-wavelength component acting alone. The average values of the cycle descriptors for cycles produced by compound baselevel fluctuation can therefore be expected to be not dissimilar to the corresponding values for that longest-wavelength cycle.

This assertion might seem surprising, because (a) the rising-baselevel limbs of compound baselevel curves will inevitably be punctuated by short-term baselevel falls, and (b) the falling-baselevel limbs of compound baselevel curves will inevitably be punctuated by short-term baselevel rises (Fig. 14). It might be thought that the short-term falls would result in deposition on rising-baselevel limbs commonly being interrupted by erosion, and that the short-term rises would result in erosion on falling-baselevel limbs commonly being interrupted by deposition. Such interruptions are relatively insignificant, however. Short-term erosion seldom occurs at times of rising baselevel (except when subsidence rates are low), because the rate at which baselevel can fall in the short term when it is rising in the long term rarely exceeds the subsidence rate. And short-term deposition

at times of falling baselevel—though it certainly does occur—is almost invariably removed by erosion, almost at once.

**Time-Varying Budget Limits.**—There certainly are sites for which fixed budget limits are reasonable: any site fed by transport paths of strictly limited capacity is an example. At most sites, however, the limits on sediment budget—if they exist at all—are likely to vary in time. The effects of time-varying budget limits are most easily shown for the surplus limit ( $L_{SUR}$ ), using two end-member situations (“increasing- $L_{SUR}$ ” and “decreasing- $L_{SUR}$ ”). In the increasing- $L_{SUR}$  situation, a site’s sediment budget increases slowly from zero as sedimentation capacity increases, and continues to increase ever faster, even as sedimentation capacity decreases. In the decreasing- $L_{SUR}$  situation, a site’s sediment budget initially keeps pace with increasing sedimentation capacity, but eventually drops to zero. The increasing- $L_{SUR}$  situation is exemplified by sedimentation on shallow-water carbonate platforms (Tipper 1997); the decreasing- $L_{SUR}$  situation is exemplified by sedimentation at sites where ever-coarser material is being bypassed with time.

The sedimentation cycles produced in the increasing- $L_{SUR}$  and decreas-

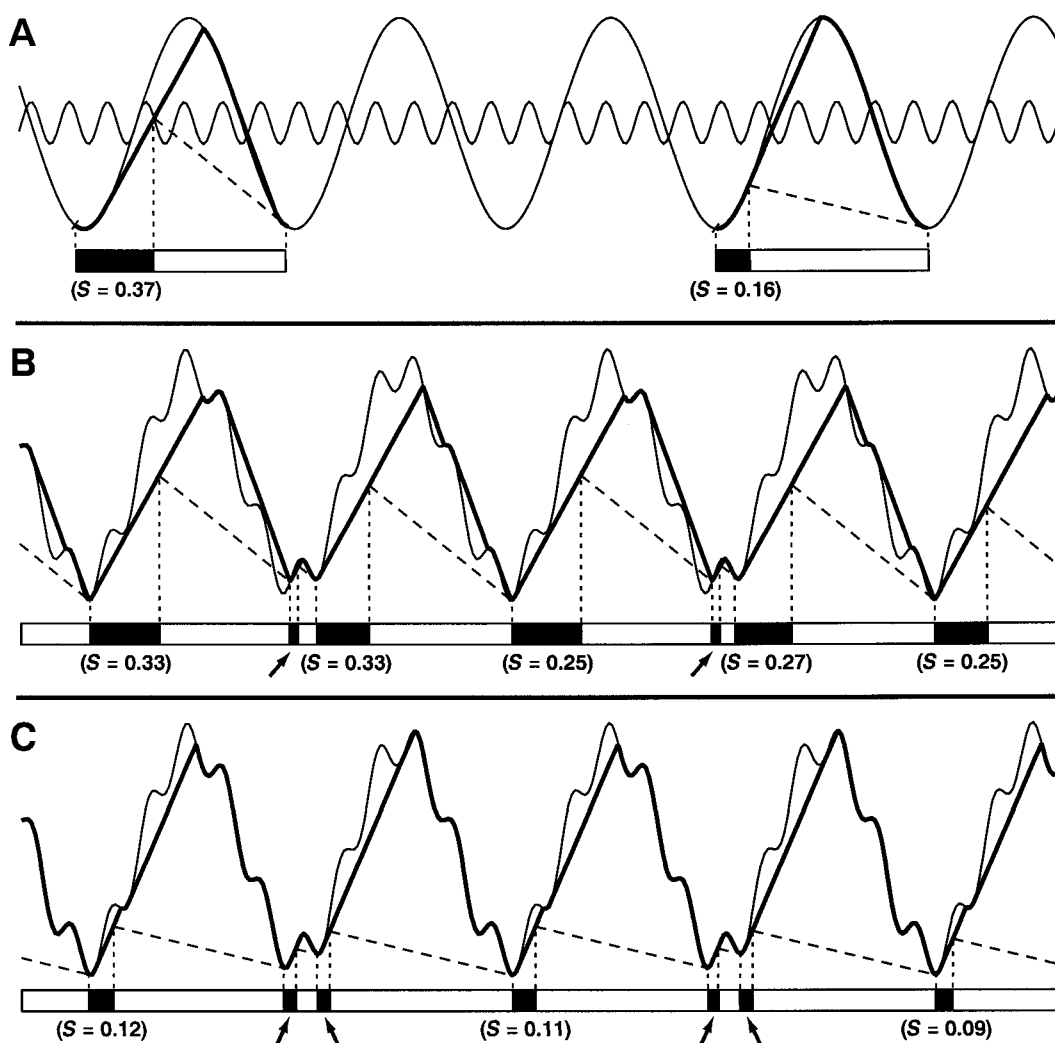


FIG. 14.—Elevation-time plots showing effects of compound baselevel fluctuation, for two sinewave components. Black-shaded intervals on time axis are sequences. **A**) The two components to be summed. Amplitude ratio = 5-to-1; wavelength ratio = 5.5-to-1. Also shown are stable cycles produced by the longer-wavelength component alone: at left, for rates  $B = 26\%$ ,  $D = 86\%$ ,  $E = 60\%$ ; at right, for rates  $B = 8\%$ ,  $D = 87\%$ ,  $E = 92\%$ . **B**) Cycles produced for summed components, for rates  $B = 26\%$ ,  $D = 86\%$ ,  $E = 60\%$ . Except for some very short sequences (arrowed), the sequence proportion ( $S$ ) is always broadly comparable with its corresponding value for the longer-wavelength component alone ( $S = 0.37$ ). **C**) As for plot B, but for rates  $B = 8\%$ ,  $D = 87\%$ ,  $E = 92\%$ . There are more shorter sequences (arrowed), but the sequence proportion is still broadly comparable with its corresponding value for the longer-wavelength component alone ( $S = 0.16$ ).

ing- $L_{SUR}$  situations are most appropriately compared with the corresponding constant- $L_{SUR}$  cycle: this is the cycle for which the surplus limit is constant and which has the same phase lag and hiatus proportion (Fig. 15A). The obvious differences between increasing- $L_{SUR}$  cycles, decreasing- $L_{SUR}$  cycles, and the corresponding constant- $L_{SUR}$  cycles are seen in the sequences that those cycles produce. Sequences produced by increasing- $L_{SUR}$  cycles never start with a BL facies component; they start instead with successive DU and SU components, which may finally be overlain by a BL component. In contrast, sequences produced by decreasing- $L_{SUR}$  cycles always start with a BL component; this may then be overlain by DU, SU, and BL components. Increasing- $L_{SUR}$  sequences are comparable to third-family sequence types, whereas decreasing- $L_{SUR}$  sequences are comparable to first-family sequence types. Increasing- $L_{SUR}$  cycles generally have higher values of sequence proportion than constant- $L_{SUR}$  cycles, which in turn have higher values than decreasing- $L_{SUR}$  cycles. The differences between the three values are nonetheless insubstantial, and the conclusions reported earlier on the ways in which rate differences affect sequence proportion still seem to hold (Fig. 8).

The effects of time-varying deficit limits are not mirror images of the effects of time-varying surplus limits. There are no differences in cycle-form descriptors between a varying- $L_{DEF}$  cycle and its corresponding constant- $L_{DEF}$  cycle, i.e., the cycle for which the deficit limit is constant and which has the same phase lag and hiatus proportion. This is true no matter how the deficit limit varies in time (Fig. 15B). It is the total amount of erosion occurring in a cycle that acts to control that cycle's form; the timing of the erosion is largely irrelevant.

#### A Strategy for Reconstructing Sedimentation Conditions

The stratigrapher who has recognized cyclicality in a succession invariably wants to reconstruct the conditions under which that cyclicality formed. It would seem possible to do this on the basis of the modeling results so far described, by using the following three-step strategy. First the individual sequences stacked together in the succession should be separated out and identified; then the sedimentation cycles that produced those sequences should be determined; finally the subsidence rates and the limiting depo-

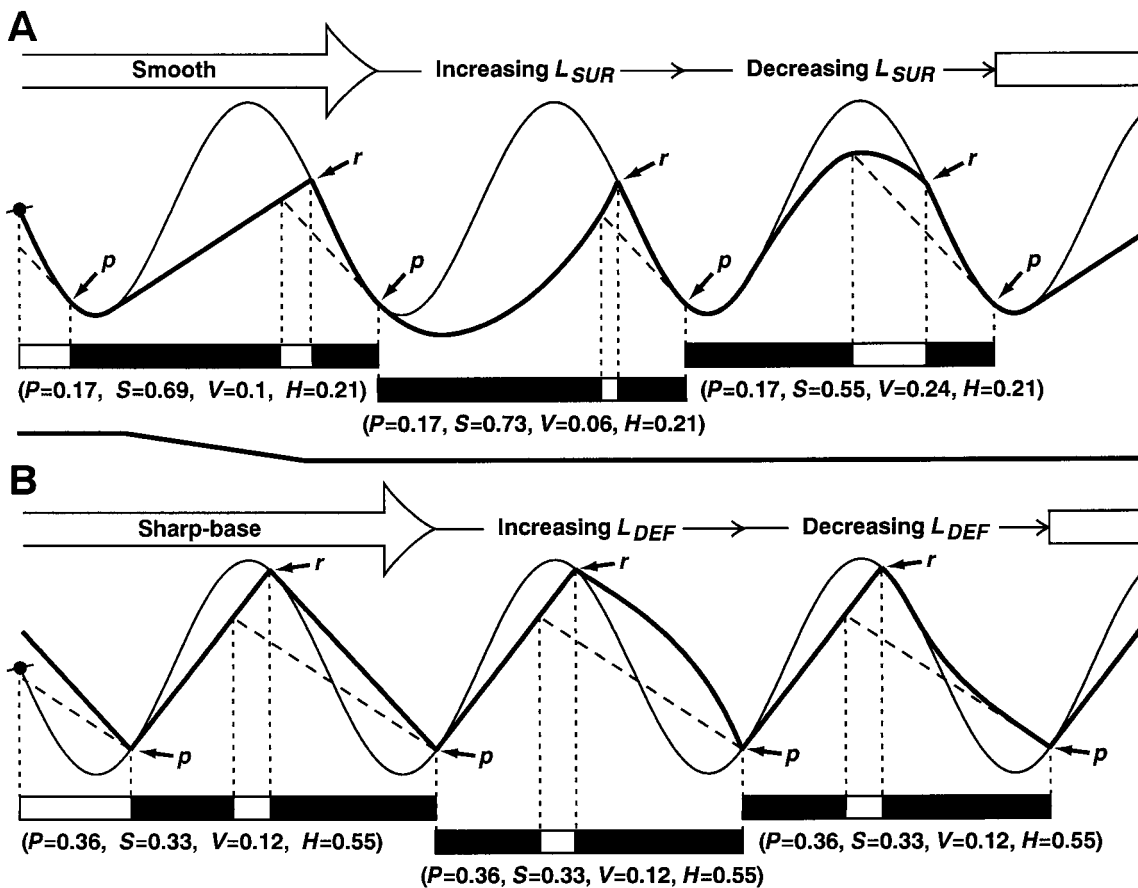


FIG. 15.—Elevation-time plots showing effects of time-varying budget limits. Points  $p$  and  $r$  are deliberately made the same for each cycle. A) Constant- $L_{SUR}$  cycle (smooth) is replaced by increasing- $L_{SUR}$  cycle and then by decreasing- $L_{SUR}$  cycle. B) Constant- $L_{DEF}$  cycle (sharp-base) is replaced by increasing- $L_{DEF}$  cycle and then by decreasing- $L_{DEF}$  cycle.

sition and erosion rates corresponding to those cycles should be estimated. The extent to which this strategy is likely to work in practice can be gauged by looking at some of the problems that will certainly arise in its use.

**The Problem of Sequence Separation.**—The most obvious criterion to use for separating out the individual sequences in a succession is abrupt facies change at sequence boundaries. By itself, however, this criterion is unsatisfactory, for it lets only those sequence types be distinguished that do not necessarily finish at baselevel, i.e., the sequence types BL-DU-SU, DU-SU, BL-DU, and DU. In order to be able to separate out all possible types of sequence, it is necessary to be able to recognize sequence bound-

aries across which there is no abrupt facies change. This can sometimes be done by looking for exposure and erosion surfaces (Hillgärtner 1998).

**The Problem of Cycle Type Determination.**—Cycle type cannot be determined unequivocally from sequence type (Fig. 16). The most that can be said is (a) that BL, BL-BL, BL-DU, and BL-DU-SU sequences are produced by sharp-top cycles or smooth cycles, (b) that DU and DU-SU sequences are produced by sawtooth cycles or sharp-base cycles, (c) that BL-DU-SU-BL sequences are produced by smooth cycles, and (d) that DU-SU-BL sequences are produced by sharp-base cycles. To go further than this, some kind of statistical stationarity must be assumed for the

Sequence family and type

Cycle family	Cycle type ( $T_C$ )	1st family		2nd family	3rd family		4th family
		BL-DU-SU-BL	BL-DU-SU BL-DU, BL	BL-BL BL	DU-SU-BL	DU-SU DU	BL
Sawtooth	18					✓	
Sharp-base	22					✓	
	26, 30				✓	✓	
Sharp-top	50, 51		✓				
Smooth	10, 14						✓
	42, 45, 46, 47			✓			
	49, 53, 54, 55		✓				
	58, 61, 62, 63	✓	✓				

FIG. 16.—The correspondence between cycle family and type, and sequence family and type. To identify cycle types, see Figure 6; to identify sequence types, see Figure 7.

succession being studied: this means that all of the sequences found in that succession must be assumed to have formed under similar sedimentation conditions. Consider, for instance, a succession of alternating BL–DU and DU sequences. If stationarity can be assumed, then these sequences can be taken to have been produced by cycles of type  $T_C = 50$  and  $T_C = 18$ , respectively: these cycle types have similar subsidence and limiting deposition rates, at medium limiting erosion rates (Figs. 10, 11).

**The Problem of Rate Estimation.**—Rates will sometimes have to be estimated on the basis of sequence type alone; this will happen when the cycle type for a particular sequence cannot be determined. All that is then possible is to use the following generalizations: (1) BL–DU–SU sequences are likely to indicate relatively high subsidence rates; (2) BL–DU sequences are likely to indicate limiting deposition rates significantly greater than subsidence rates, and medium to high limiting erosion rates; (3) DU–SU sequences are likely to indicate very low limiting erosion rates, with limiting deposition rates slightly greater than subsidence rates; (4) DU sequences are likely to indicate low subsidence rates, medium limiting deposition rates, and medium limiting erosion rates; (5) BL–DU–SU–BL sequences are likely to indicate high subsidence and limiting deposition rates; (6) DU–SU–BL sequences are likely to indicate high limiting deposition rates and very low limiting erosion rates; (7) BL and BL–BL sequences are likely to indicate *either* that the limiting deposition rate was the maximum possible for the given subsidence rate (if they are second-family sequences), *or* that the subsidence rate was low and the limiting deposition rate medium or high (if they are first-family or fourth-family sequences).

**The Problem of Nonstationarity.**—Many cyclic sedimentation systems change substantially in time over a wide range of time scales, and it may therefore be quite unwarranted to assume stationarity for many cyclic successions. Nonstationarity is likely to pose particularly serious reconstruction problems whenever changing sedimentation conditions produce cycles that are superficially similar to the cycle types considered here, but fundamentally different. An example might be a cycle for which the preserved sequence is BL–DU–SU–DU–SU–BL. This might seem to be a cycle of type  $T_C = 63$  (Fig. 6), albeit one in which small variations in sediment supply took place as baselevel rose; it might, however, really be a cycle in which catastrophic short-term supply failure resulted in a complete rise-and-fall of baselevel having gone unrecorded, i.e., an example of the “missed beat” phenomenon (Goldhammer et al. 1990). It is not at all clear how nonstationarity such as this should be guarded against—indeed there may be no way of guarding against it. Possibly the best that can be said is that the safest cycles to use for reconstructing sedimentation conditions, *especially when stationarity cannot be assumed*, are either smooth cycles or cycles probably related to smooth cycles; sawtooth and sawtooth-related cycles should be avoided, because of their propensity to oscillation (Fig. 13).

**The Problem of Facies Interpretation.**—The most general problem involved in using the suggested reconstruction strategy is that of interpreting what individual facies in a succession mean in terms of sedimentation capacity, i.e., depth below baselevel. In some situations, of course, this meaning is relatively clear; the facies that form the building blocks of shallowing-upward cycles are possibly the best examples (but see Wilkinson et al. 1996). These situations are exceptional, however. Typically a cyclic succession will contain only a small number of facies whose interpretation in terms of sedimentation capacity is unarguable; the other facies will be ones for which more than one interpretation of sedimentation capacity is possible, and which therefore allow competing interpretations of the succession’s cyclicity to be made.

**The Problem of Apparent Nonequivalence.**—In some cyclic successions there may seem to be no recognizable sequences of the types considered here. One possible explanation for this is that the succession in question is highly incomplete, and that all that remains in it are unrelated fragments of the original stratigraphic record; I discuss this point in the next section of this paper. A second explanation is that the succession is

not one-dimensional; data projected onto the succession’s axis from neighboring outcrops or boreholes may have introduced spatio-temporal masking (Tipper 1998). (*It must be stressed that the sedimentation model used here is one-dimensional, and that the reconstruction strategy based on it therefore requires one-dimensional data. This strategy cannot be expected to work correctly on pseudo-one-dimensional mixtures of two- and three-dimensional data.*) A third explanation is that the succession is one that cannot be analyzed naturally in terms of the sedimentation model used here. One example of this would be a succession containing repeated shallowing-upward sequences; these are conventionally interpreted in terms of sedimentation models in which special lag parameters are incorporated (Tipper 1997), and they can be produced only with difficulty by the model used here (see earlier discussion, under “Time-Varying Budget Limits”). Another example would be a succession laid down at a site at which sedimentation is entirely budget-controlled.

#### FOUR CONCLUSIONS AND A DILEMMA

Perhaps the most fundamental conclusion that should be drawn from the work reported here is one that should hardly need to be drawn: sedimentation cycles should generally be expected *not* to be all remarkably similar to each other. Yet this conclusion apparently does need to be drawn, for I can find little indication that stratigraphers—even those stratigraphers who certainly have appreciated how varied a phenomenon stratigraphic cyclicity can be—have truly appreciated that realistically variable sedimentation conditions necessarily lead to a great diversity of cycle forms.

A second conclusion is related to the first: sedimentation cycles of different forms are not just variations on the one same theme. There are families of cycles that differ significantly from each other in their sensitivity to changes in sedimentation conditions, and hence in their stability. It will always be more difficult to interpret the less sensitive of these cycles correctly (and hence to use them to reconstruct sedimentation conditions), simply because cycle form is indicative of sedimentation conditions only when stability has been reached. Sawtooth cycles will always be particularly difficult to interpret, because sawtooth cyclicity is often a transient state that exists when continuously changing sedimentation conditions prevent stability from ever being reached. Repeated sawtooth cyclicity should never be taken as evidence of stable sedimentation conditions, for it can equally well be excellent evidence of instability.

A third conclusion concerns the timing of sequence boundaries. The sequence boundary in a cycle can evidently occur almost as early as the cycle’s baselevel null point (i.e., phase lag just greater than 0.0), and it can also occur almost as late as the cycle’s baselevel high point (i.e., phase lag just less than 0.75). This potential difference in timing of almost three-quarters of a cycle conflicts substantially with the conventional wisdom that sequence boundaries are tied closely to inflection points in baselevel curves (Posamentier et al. 1988; Wehr 1993). Christie-Blick (1991) has suggested that sequence boundaries may lead and lag inflection points by up to one-quarter of a cycle, but even this suggestion is too low. There clearly is the potential for slight differences in sedimentation conditions at neighboring sites to produce sequence boundaries that are substantially out of phase, and the implications that this has for cyclostratigraphic correlation are obvious (cf. Christie-Blick and Driscoll 1995, p. 452).

A final conclusion concerns the completeness of cyclic stratigraphic successions, and it is a conclusion that is particularly worrying:  $S$ , the sequence proportion, is a measure of a cycle’s completeness, and the great majority of cycles have values of  $S$  that are very much higher than the completeness values usually obtained for real stratigraphic successions (e.g., Sadler 1981). Only when subsidence rates are only slightly greater than zero does it seem to be possible to produce cycles in which the sequence proportion is realistically low, i.e., no greater than about 0.01. If it is accepted that sedimentation cycles are indeed produced in the way described here, then

clearly there is a dilemma: how can cyclic successions be produced that are sufficiently incomplete?

It would seem feasible to escape from this dilemma in three ways: (1) by suggesting that cyclic successions are always inherently more complete than noncyclic ones; (2) by suggesting that compound baselevel fluctuation—despite what was said about it earlier in this paper—does indeed give marked reductions in sequence proportion; (3) by questioning whether real stratigraphic successions are really as incomplete as they are usually thought to be. The first argument is certainly an attractive one, for it suggests that the degree of development of cyclicity in a succession may perhaps be a measure of that succession's completeness. As yet, however, this argument is purely hypothetical; a considerable amount of work is required before it can be tested. The second argument effectively demands that erosion commonly occur on the rising-baselevel limbs of compound baselevel curves, not—as was argued earlier—that it seldom occurs there. This in turn demands (a) that there be many short-term baselevel falls on those limbs, (b) that those falls generally be faster than the rate of subsidence, and (c) that the sediment budget always be sufficient to keep the sedimentation capacity low (this ensures that the lithic surface is always within reach of fast, short-term baselevel falls). To obtain frequent, fast, short-term baselevel falls, the shorter-wavelength components of compound baselevel curves cannot have lower amplitudes than the longer-wavelength components (as was earlier assumed); they must have higher amplitudes. It may be that “shorter-wavelengths mean higher-amplitudes” is a reasonable model for compound baselevel fluctuation, but it is not one that stratigraphers seem so far to have considered.

The third argument that can be used to escape from the completeness dilemma hinges on the way in which stratigraphic completeness is defined. At present, completeness is usually defined in purely temporal terms: it is the proportion of the timespan of a conventional one-dimensional stratigraphic section that is represented by preserved deposition (Sadler 1981; Schindel 1982; Tipper 1983). Completeness nevertheless has a spatial component to it as well as a temporal component, and these two components mask each other in most stratigraphic field data (Tipper 1998). This spatio-temporal masking phenomenon makes the collection of reliable completeness data extremely troublesome, and it may therefore be that some of the conventional wisdom about stratigraphic completeness—for instance that extremely low values of completeness are normal—is simply not correct. It is perhaps best to suspend judgment on whether or not the sedimentation cycles modeled here are unrealistically complete, at least until spatio-temporal masking is routinely allowed for when data for completeness estimation are being collected. The cycles modeled here may indeed be more complete than real cycles are, but real cycles may also be considerably more complete than they are currently believed to be.

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- BL Baselevel facies component (Fig. 5).
- c* Point at which lithic surface falls below baselevel on cycle's rising-baselevel limb, i.e., point at which rate-limited deposition begins (Fig. 4); if  $D = (100 + B)\%$ , then  $c = 0.5$ .
- D* Dimensionless limiting deposition rate (Fig. 3).
- DU Deepening-upward facies component (Fig. 5).
- e* Point at which lithic surface rises to baselevel after having earlier fallen below it, i.e., point at which rate-limited deposition ends (Fig. 4); if  $D = (100 + B)\%$ , then  $e = 0.5$ .
- E* Dimensionless limiting erosion rate (Fig. 3).
- H* Cycle form descriptor; hiatus proportion (Fig. 4).
- i* Point at which lithic surface rises above baselevel on cycle's falling-baselevel limb, i.e., point at which rate-limited erosion begins (Fig. 4); if  $E = (100 - B)\%$ , then  $i = 1.0$ .
- k* Point at which lithic surface falls to baselevel after having earlier risen above it, i.e., point at which rate-limited erosion ends (Fig. 4); if  $E = (100 - B)\%$ , then  $k = 1.0$ .
- $L_{DEF}$  Deficit limit on sediment budget ( $= E \times M$ ).
- $L_{SUR}$  Surplus limit on sediment budget ( $= D \times M$ ).
- M* Surface area of site (Fig. 1).
- p* Point at which deposition in cycle begins, i.e., start of sequence (Fig. 4).
- P* Cycle form descriptor; phase lag (Fig. 4).
- q* Point at which rate line *B* through point *s* intersects track of lithic surface, i.e., point at which sequence ends and vacuity begins (Fig. 4).
- r* Point at which erosion in cycle begins, i.e., start of hiatus (Fig. 4).
- s* Point at which erosion ends and deposition begins again, i.e., start of next sequence (Fig. 4).
- S* Cycle form descriptor; sequence proportion (Fig. 4).
- SU Shallowing-upward facies component (Fig. 5).
- $T_C$  Cycle type descriptor (Fig. 6; Appendix 2).
- V* Cycle form descriptor; vacuity proportion (Fig. 4).
- W* Wavelength of baselevel sinewave (Fig. 3).

## APPENDIX 2: CODING SYSTEM FOR CYCLE TYPE ( $T_C$ )

All but one of the eight points defining a cycle always appear in the same order in time (*pceriks*). This allows a coding system to be developed that reflects the natural geometric relationships between different cycle types. The system is a six-bit binary one, with the bits corresponding (left to right) to the intervals “*pc*”, “*ce*”, “*er*”, “*ri*”, “*ik*” and “*ks*”. If an interval is of zero length, i.e., if the points defining it are coincident, then its bit is set to “0”; otherwise its bit is set to “1”. As an example, consider a cycle in which points *e* and *r* coincide, but all other points are distinct. This cycle is coded as “110111”, which is equivalent to decimal 55; the cycle type is therefore  $T_C = 55$  (Fig. 6). If slight changes in rates were made, then points *i* and *k* might become coincident; the form of the new cycle would be slightly different to that of the old one, as would be its code; the new cycle would be coded as “110101”, i.e.,  $T_C = 53$ .

## APPENDIX 1: PRINCIPAL ABBREVIATIONS AND SYMBOLS

- A* Amplitude of baselevel sinewave (Fig. 3).
- B* Dimensionless basement subsidence rate (Fig. 3).