Is there a role for sequence stratigraphy in chronostratigraphy?

Nicholas Christie-Blick[1], Stephen F. Pekar[1,2] Andrew S. Madof [1]

[1]*Department of Earth and Environmental Sciences and Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA*

[2]*School of Earth and Environmental Sciences, Queens College, City University of New York, Flushing, New York 11367, USA, and Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964, USA*

email: ncb@ldeo.columbia.edu; spekar@qc1.qc.edu; amadof@ldeo.columbia.edu

ABSTRACT: Sequence stratigraphy revolutionized the field of stratigraphy in the late 1970s and 1980s by providing an interpretive depositional framework for integrating diverse stratigraphic data at the scale of sedimentary basins. However, a lack of consensus on criteria for recognizing, mapping and hence dating sequence boundaries, interpretations of uneven quality, and doubts about the universal eustatic origin and global synchrony of unconformity-related sequences limit the usefulness of sequence stratigraphy in chronostratigraphy.

INTRODUCTION

The idea that unconformities and other stratigraphic discontinuities have time-stratigraphic significance, at least as a first approximation, has been a central assumption of sequence stratigraphy for more than 50 years (Sloss et al. 1949; Sloss 1963, 1988; Wheeler 1958; Vail et al. 1977; Vail et al. 1984; Vail 1987; Cross and Lessenger 1988; Van Wagoner et al. 1990; Christie-Blick and Driscoll 1995; Emery and Myers 1996; Posamentier and Allen 1999; Coe 2003; Catuneanu 2006). Unconformities are by definition associated with breaks in sedimentation and, as far as this can be determined from available age control, in most cases overlain by strata that are everywhere younger than underlying strata. That the hiatus associated with a particular unconformity varies in duration as a result of either non-deposition or erosion is not important. The concept of time-stratigraphic significance does not require synchrony of superposed strata, either above or below a surface, only that sedimentation ceased and then resumed (cf. Posamentier and Allen 1999, p. 46).

Recognizing that some unconformities trace laterally into relatively conformable successions, Vail et al. (1977) developed the idea of a correlative conformity as a physical extension of an unconformity, where any hiatus is both small and below the resolution of available stratigraphic tools to detect. The conformity concept proved useful because it allowed the age of an unconformity to be specified at a particular moment in geological time. In the event that no correlative conformity exists within an area of interest, or (in subsurface examples) when no well or borehole is appropriately located, the age of an unconformity can still be bracketed, in some cases quite closely, with respect to the youngest strata below and oldest strata above. It is not necessary, for this purpose, for the ages of bounding strata to be determined at a single location, so long as the unconformity can be traced with confidence from one place to another.

It was Vail's view, and the view of many in what became the Exxon school of seismic and sequence stratigraphy, that most unconformities have time-stratigraphic significance also at a global scale (Vail et al. 1977; Vail et al. 1984; Haq et al. 1987; Posamentier et al. 1988; Sarg 1988; Mitchum and Van Wagoner 1991; Vail et al. 1991; Vail 1992; de Graciansky et al. 1998; Posamentier and Allen 1999). This idea, which has dominated thinking in stratigraphy for 30 years, was based on two lines of reasoning. First, prominent unconformities appear to be of about the same age in widely separated basins, at least at the resolution of stratigraphic constraints and dating techniques. Second, it was argued that basinward shifts in onlap observed at many unconformities require changes in the level of the sea relative to sites of sediment accumulation that are sufficiently large and rapid to imply glacio-eustasy (e.g., Christie-Blick 1982). According to this paradigm, sea-level change provides such a strong, global control on sedimentation that it can be used to gauge time. Armed with a global chart of unconformity timing and at least some independent age control, it is now standard practice to refine local schemes by regarding all manner of stratigraphic features as manifestations of this global signal.

This is essentially the position that has been adopted by the International Commission on Stratigraphy (ICS) in its plan to integrate the geologic time scale with the Mesozoic and Cenozoic bio-chrono-sequence stratigraphic charts of Hardenbol et al. (1998) for European basins (International Commission on Stratigraphy 2007). As Jan Hardenbol writes in his abstract (op. cit. 1998), "A well-calibrated regional biochronostratigraphic framework is seen as an essential step towards an eventual *demonstration* (our italics) of synchroneity of sequences in basins with different tectonic histories." In other words, a fundamental assumption of the 1998 compilation, and inevitably the outcome of a new global synthesis, is that there is such a synchronous pattern to be discovered, and not only for the Mesozoic and Cenozoic, but also for the Paleozoic, for which the ICS envisages the production of "comparable charts."

The issue that we address briefly in this essay is whether the paradigm is consistent with what is currently known of the stratigraphic record, and specifically whether a global unconformity chart has a place in chronostratigraphy – meaning the establishment of a global reference frame for geological time. We conclude that sequence stratigraphy provides a useful context for basin-scale stratigraphic interpretation, and for the quantification of sea-level change over at least the past 34 m.y. when large continental ice sheets are known to have existed (Miller et al. 1998; Pekar et al. 2002; Miller et al. 2005a; Pekar and Christie-Blick in press), but that the global temporal significance of unconformities has been generally oversold.

SEQUENCE STRATIGRAPHY AS A FRAMEWORK FOR INTERPRETATION

The essence of sequence stratigraphy is to make use of all of the physical surfaces that at different scales separate one depositional element from another, in order to determine layer by layer how sedimentary successions are put together (Christie-Blick and Driscoll 1995). That includes surfaces related to flooding and deepening (drowning), and discontinuities associated with progradation and shoaling (e.g., offlap surfaces, sharp-based shorefaces and deltas, and downlap surfaces more generally), as well as more diffuse intervals of sediment starvation and condensation in relatively deep marine deposits (Vail 1987; Loutit et al. 1988; Plint 1988; Schlager 1989, 1991, 1999; Van Wagoner et al. 1990; Christie-Blick 1991; Posamentier et al. 1992; Embry 1995; Pattison 1995; Posamentier and Allen 1999; Hampson 2000; Plint and Nummedal 2000; Posamentier and Morris 2000). Many of these features are quite literally surfaces at more or less any resolution. However, downlap surfaces at seismic resolution are in some cases less well defined at the scale of an outcrop, core or downhole log. Also, while sediment starvation in offshore settings commonly correlates at least approximately with flooding at the shoreline,"maximum flooding" is neither demonstrated for most surfaces so interpreted by sedimentologists and stratigraphers, nor necessarily expressed as a surface.

Some of the most prominent and laterally persistent surfaces are those associated with subaerial degradation, and they are the features that Vail et al. (1984) designated as sequence boundaries. It is, however, the character of the surfaces that makes them sequence boundaries, not the dimensions of the area over which they can be mapped. At updip locations, where the evidence is typically most clear-cut, characteristics include the development of angular discordance between superposed sediments or rocks, or with respect to the intervening unconformity; local valley incision; evidence for the subaerial exposure of marine sediments (with karst in carbonate rocks), abrupt upward shoaling of depositional facies, and/or abrupt basinward shifts in the locus of sedimentation; and biostratigraphic, chemostratigraphic, geochronological, diagenetic, geotechnical or other evidence for a break in sedimentation (e.g., Vail 1987; Sarg 1988; Van Wagoner et al. 1988; Van Wagoner et al. 1990; Christie-Blick and Driscoll 1995; Posamentier and Allen 1999; Plint 2000; Christie-Blick 2001; Pekar et al. 2003; Catuneanu 2006).

An excellent example of sequence boundaries with several of these characteristics, but with very restricted expression, is provided by eight surfaces documented in fluvial-deltaic deposits at the base of the kilometer-deep Wonoka canyons in the Neoproterozoic of South Australia (Christie-Blick et al. 1995; Christie-Blick et al. 2001). The surfaces, which are marked by abrupt upward shoaling from marine carbonate and siltstone to fluvial conglomerate and by incised valleys < 15 m deep, are spaced on average < 30 m apart. They onlap the canyon walls (a lower order sequence boundary), and are for that reason mappable for only a few kilometers in available outcrop. Details are currently being prepared for publication elsewhere.

Unconformities associated with propagating faults, growing folds, basin inversion and diapirs in a broad range of tectonic settings in some cases extend only a few kilometers to as little as a few hundred meters transverse to structures (e.g., Riba 1976; Anadón et al. 1986; Medwedeff 1989; Christie-Blick et al. 1990; Rosales et al. 1994; Driscoll et al. 1995; Ford et al. 1997; Suppe et al. 1997; Poblet et al. 1998; Sharp et al. 2000; Giles and Lawton 2002; Castelltort et al. 2003; Mortimer et al. 2005). Other unconformities in foreland basin, intra-orogenic, rift and passive margin settings pass laterally into flooding surfaces, with definitive sequence boundary character expressed primarily by localized erosion or offlap (e.g., Underhill 1991; Driscoll et al. 1995; Van Wagoner 1995; Miller et al. 1996; Kidwell 1997; Naish and Kamp 1997; Plint 2000; Jiang et al. 2002; Pekar et al. 2003). Such flooding surfaces are typically "concordant" with underlying and overlying strata. They are not in general conformities because the existence of strata of intermediate age in associated incised valleys demonstrates that a hiatus must be present.

Other stratigraphic discontinuities may also be useful in off-platform and terrigenous slope and rise sediments, independent of whether direct correlation is possible with subaerial unconformities, or reasonably inferred (e.g., Schlager and Camber 1986; Schlager 1989, 1999; Damuth et al. 1995; Hiscott et al. 1997), and in shallow marine deposits in which sequence boundaries are poorly expressed (e.g., Montañez and Osleger 1993; MacNaughton et al. 1997; Jiang et al. 2002). The interpretive philosophy is the same. That is to make use of a hierarchy of discontinuities, beginning with those of greatest lateral persistence and/or those against which higher order surfaces terminate. The mark of a quality interpretation is not the number of sequence boundaries that can be identified. It is the confidence with which an interpretation can be defended. Sequence boundaries are much more abundant in some successions than others (cf. Plint 2000 with Montañez and Osleger 1993) for reasons that have to do in part with the interplay of numerous factors governing sediment dispersal and accumulation, and in part with whether appropriate geometric or facies clues are available to interpret.

Advantages of Sequence Stratigraphy

Sequence stratigraphy based upon these principles offers several advantages compared with classical stratigraphy. 1) It's process-oriented, interpretive, and falsifiable, not an exercise in classification (Christie-Blick 2001). Lithostratigraphy, in comparison, involves making choices about contact location and hierarchical nomenclature from any number of perfectly defensible rationales (North American Commission on Stratigraphic Nomenclature 2005). Such choices may or may not prove to be useful. However, because they are established by convention rather than through discovery, the criteria for mapping a lithostratigraphic contact cannot be shown to be incorrect. 2) Sequence stratigraphy provides a genetic depositional framework for integrating other stratigraphic data, independent of existing classification schemes, as well as for siting boreholes and developing a sampling strategy. Sequence boundaries and other stratigraphic discontinuities are proxies for time horizons, passing through laterally changing facies, and commonly from one lithostratigraphic unit to another (e.g., Kennard et al. 1992; Sonnenfeld and Cross 1993; Van Wagoner 1995; Tinker 1998; Eberli et al. 2002; Pekar et al., 2003). They are also the breaks in bio-, magneto- and chemo-stratigraphic records that chronostratigraphy seeks to fill at both updip locations and some downdip or basinal locations, where only a fraction of geological time may be represented by sediments or sedimentary rocks owing to nondeposition/condensation or erosion (e.g., Aubry 1995; Aubry et al. 1999; Pekar et al. 2003). 3) At a basin scale, sequence stratigraphy in many cases allows sedimentary successions to be subdivided more finely than is possible with other approaches. Lower to mid-Cenomanian deltaic deposits of the Dunvegan Formation in the Alberta basin contain no fewer than 10 sequence boundaries in an interval that is only 90-270m thick (Plint 2000). These surfaces have been mapped in outcrop and well logs over an area of ~80,000km^2. 4) The principles are applicable in every depositional and tectonic setting, in deposits of any age (from the Holocene to Archean); in seismic reflection, Compressed High Intensity Radar Pulse (CHIRP) sonar, ground-penetrating radar, downhole logs and cores, as well as outcrop; and at scales of meters to hundreds of kilometers (e.g., Grotzinger et al. 1989; Mitchum and Van Wagoner 1991; Underhill 1991; García-Mondéjar and Fernández-Mendiola 1993; Van Wagoner 1995; Tinker 1998; Plint 2000; Sharp et al. 2000; Tesson et al. 2000; Christie-Blick et al. 2002; Jiang et al. 2002; Møller and Anthony 2003; Pekar et al. 2003; Posamentier 2004; Rabineau et al. 2005; Nordfjord et al. 2006).

Limitations

Sequence stratigraphy is also subject to some important limitations. Confident interpretation typically requires a lot of data. Seismic data are expensive, and their interpretation is both time-consuming and susceptible to shortcuts. Errors related to autotracking on a workstation, for example, are easy to propagate across a dataset, in some cases hooking together portions of closely spaced but unrelated surfaces (e.g., Poulson et al. 1998). The stratigraphic interpretation of downhole logs depends on wells or boreholes being in sufficiently close proximity (and comparable in terms of vintage and acquisition parameters) that log character varies only subtly from one location to another. Studies of the caliber of Plint (2000) in the Alberta basin take years to complete, and are generally possible at regional scale only in "mature" sedimentary basins peppered with wells. Outcrop-based interpretations similarly require numerous measured sections, and the mapping of physical surfaces at a resolution that challenges the patience of most stratigraphers. Compare, for example, the level of stratigraphic documentation provided by Van Wagoner (1995) with that supporting conflicting interpretations of Yoshida et al. (1996), Yoshida et al. (1998), Willis (2000), Yoshida (2000), McLaurin and Steel (2000), McLaurin and Steel (2001) and Yoshida et al. (2001) in the Book Cliffs of Utah.

Stratal geometry and the systematic arrangement of associated facies so elegantly portrayed in the sequence stratigraphic model or "slug diagram" are more complex and variable in practice, and at high resolution. Surfaces terminate against or merge with other surfaces, in some cases in such a bewildering array that sequence boundaries are interpreted with difficulty (e.g., within some contemporary shelf and slope deposits, and more generally in channelized fluvial deposits; Shanley and McCabe 1994; Trincardi and Correggiari 2000; Lu and Fulthorpe 2004). The mapping of sequence boundaries is problematic also in uniform facies and where strata are generally concordant. As a practical matter, therefore, time resolution tends to scale inversely with the physical dimensions of available data.

A preoccupation in the literature with the division of successions into systems tracts (or facies tracts) is unfortunate, first because interpretations are commonly subjective or at least poorly documented, and second because more interesting questions about how discontinuities develop or even how they are traced are rarely asked. Sequences are typically incomplete at a local scale, in some cases or at some locations dominated by transgressive elements (e.g., Christie-Blick et al. 1995; Nummedal and Molenaar 1995; Kidwell 1997), and in others by progradation (e.g., Van Wagoner 1995; Plint 2000; Pekar et al. 2003). The transition from transgression to regression is not necessarily easy to recognize at a sequence scale, even when both intervals are present, owing to complexities in higher order stratigraphic cyclicity or to the preservation of too few cycles (e.g., parasequences) for stacking patterns to be determined.

The lowstand concept is especially problematic both in deep-water settings (more on that below) and as widely applied to relatively thin, coarse-grained and/or nonmarine sediments resting on a sequence boundary (e.g., Baum and Vail 1988; Van Wagoner 1995; and subsequent papers by numerous authors). Such deposits commonly constitute a lithosome that is both inherently diachronous and, at a larger scale, associated with overall transgression (Christie-Blick and Driscoll 1995). Evidence for a decrease in paleowater depth across a sequence boundary, therefore does not by itself imply lowstand sedimentation. The lowstand systems tract is defined observationally as a stratigraphic unit onlapping a sequence boundary, and characterized internally and at sequence scale by overall progradation and shoaling of facies (Van Wagoner et al. 1988).

In other outcrop examples, stratigraphic elements claimed as lowstands are indeed progradational, but contiguous with and questionably distinguishable from underlying highstand deposits (e.g., Posamentier and Chamberlain 1993; Ainsworth and Pattison 1994; Mellere and Steel 1995; Pattison 1995; Mellere and Steel 2000; Posamentier and Morris 2000). The difficulty in both cases is that interpretations appear to be driven primarily by expectations rather than by what is actually observed.

While the lowstand is the single if generally doubtful stratigraphic element that distinguishes sequences from transgressive-regressive (T-R) cycles of classical stratigraphy (Johnson et al. 1985; Embry 1988, 1995), and sequence boundaries in some cases coincide at least locally with prominent flooding surfaces, sequences are nonetheless not T-R cycles. This is because they are defined on the basis of geometry and facies, and not on the basis of facies alone. The literature, however, is replete with examples of minor or "type 2 sequence boundaries" (Van Wagoner et al. 1988), discontinuities that are in many cases marine flooding surfaces lacking incised valleys or other convincing evidence for subaerial degradation. In some examples, a sequence boundary is in fact present, though at a lower stratigraphic level (with incised valleys; e.g., Lindsay 1987). More commonly, evidence for the existence of a *bona fide* sequence boundary is conspicuously absent (e.g., Montañez and Osleger 1993; MacNaughton et al. 1997).

We make this point because it is clear that the bio-chrono-sequence stratigraphic charts of Hardenbol et al. (1998) are strongly influenced by the earlier global synthesis of Haq at al. (1987), in which nearly 60% of Mesozoic-Cenozoic sequence boundaries are said to be type 2 boundaries, and they incorporate nearly twice as many surfaces (Miall and Miall 2001). We suspect therefore that at least some of the less prominent "sequence boundaries" portrayed in those charts are instead flooding surfaces, particularly in deposits of Mesozoic age. Although such discontinuities are undoubtedly useful in local stratigraphic interpretation, the distinction is important because the eustatic paradigm depends in part on being able to make the case for allocyclicity (an origin external to the sedimentary basin). Shoreline position, and hence the development of T-R cycles, is highly sensitive to changes in sediment supply.

None of this is an argument against the sequence stratigraphic approach. Indeed, broadly conceived, sequence stratigraphy is arguably the best framework for stratigraphic interpretation. Our point is that results are inevitably uneven, and subject to practical limitations.

CHALLENGES FOR CHRONOSTRATIGRAPHY

If sequence stratigraphy is accepted as providing a useful context for stratigraphic interpretation, an important issue that needs to be addressed is what role if any it ought to play in chronostratigraphy and global correlation. We draw attention here to three challenges for the construction of global biochrono-sequence stratigraphic charts (Haq et al. 1987; International Commission on Stratigraphy 2007): 1) non-trivial disagreement about the criteria by which sequence boundaries are recognized and mapped, with implications for both the manner in which surfaces develop and their timing; 2) non-eustatic origins for at least some, and perhaps many sequence boundaries; and 3) diachrony of interpreted surfaces.

Mapping and Development of Sequence Boundaries

A host of geometrical, facies-based, biostratigraphic and other criteria allow sequence boundaries to be recognized and mapped with confidence at up-dip locations (see above). Difficulties arise in tracing those surfaces to more conformable marine successions where ages are generally established, and especially in intracratonic and other ramp settings, where sequence boundaries are more or less concordant with overlying and underlying strata for long distances. One of the fundamental insights of seismic and sequence stratigraphy, as the field emerged in the late 1970s and early 1980s, was the practical and conceptual value of defining boundaries primarily on the basis of stratal (and reflection) geometry, thereby delineating relatively conformable successions of "genetically related strata" (the "sequences" between the boundaries; Mitchum 1977). According to that view, and it is a practice that we have adopted in diverse geological settings over the past quarter century, the sequence boundary lies everywhere above offlapping and/or erosionally truncated strata, and below onlapping strata (Vail 1987; Van Wagoner et al. 1990; Christie-Blick 1991). That is not necessarily easy to determine, particularly where onlap against a clinoform (fossil depositional slope) is some distance from the most basinward offlap, or at high resolution in some shelf and ramp settings (e.g., Hunt and Tucker 1992, 1995; Ainsworth and Pattison 1994; Kolla et al. 1995; Mellere and Steel 2000; Posamentier and Morris 2000). Large mis-ties commonly arise in seismic reflection data when a sequence boundary is traced too low (down a clinoform that, in fact, offlaps the boundary) or too high (along an onlapping element rather than beneath all onlapping strata).

Beyond such practical difficulties, which can normally be resolved with enough data of sufficient resolution, we face two important conceptual issues. First, it is widely assumed that slope and rise sedimentation at continental margins is as strongly influenced by sea-level change as nearshore and shelf sedimentation (Haq 1991; Posamentier et al. 1991; Emery and Myers 1996; Posamentier and Allen 1999; Posamentier and Kolla 2003). This is a logical corollary of the eustatic paradigm. Sediment accumulates preferentially in deep water when continental shelves and platforms are subaerially exposed; and mass wasting in slope and rise settings is assumed to indicate sea-level lowering and shelf exposure, whether or not independent evidence exists for either. However, studies at three quite different continental margins suggest that sedimentation in shelf and off-shelf settings may not be as closely linked as generally supposed.

Ocean Drilling Program Leg 155 showed that late Pleistocene sediments of the Amazon submarine fan consist of channel-levée deposits interleaved with sand-rich sheets (Hiscott et al. 1997). The latter do not represent "basin-floor fans" overlying a corresponding series of sequence boundaries, the conventional sequence stratigraphic interpretation of such sediments (e.g., Haq et al. 1987; Vail 1987; Mutti and Normark 1991; Posamentier et al. 1991), but channel avulsion at upfan sites (Hiscott et al. 1997). The Amazon fan's youngest levée complex, deposited entirely during oxygen isotope stages 4 to 2 (Piper et al. 1997), consists of at least 10 laterally shingled channel-levée units and many more sand-rich sheets (Damuth et al. 1983; Manley and Flood 1988; Hiscott et al. 1997). While all of the sedimentation took place during a span of < 55 ky of generally lowered sea level (Thompson and Goldstein 2006), stratigraphic details bear little relation to the sea-level curve.

The Fuji basin, a salt-withdrawal minibasin located immediately seaward of the shelf-slope break, offshore Louisiana (Gulf of Mexico), includes at least 10 mass transport complexes in its late Pleistocene to Holocene fill (< ~470 ka, and ~45% by volume; A.S. Madof, unpublished data). Like the sand sheets of the Amazon fan, these too would conventionally be regarded as individual lowstand deposits. However, the abundance of such complexes compared with the dominant orbitally forced ~100 ky sea-level cycles (Miller et al. 2005a) and geometric evidence for radial flow into the depocenter (vs derivation primarily from the upper slope) suggest that mass failure was triggered by salt motion rather than by eustasy. Details of this study are currently being prepared for publication elsewhere.

Another variant of off-shelf stratigraphy is illustrated by middle Miocene through Holocene sedimentation in the Canterbury basin, eastern offshore South Island, New Zealand. The continental margin there is dominated by current-deposited sediment drifts that nucleated in water depths of 300-750 m, and migrated towards the shelf (Fulthorpe and Carter 1991; Lu et al. 2003; Carter et al. 2004a; Carter et al. 2004b; Lu and Fulthorpe 2004). While the sediment was ultimately derived from the adjacent microcontinent, and is punctuated by unconformities at a timescale of several million years to ~100 ky (Lu and Fulthorpe 2004), its physical stratigraphy was strongly influenced by variations in the strength and trajectory of contour-hugging ocean currents, and not simply by the rise and fall of sea level.

Whether or not sequence stratigraphic nomenclature is applicable in these and other deep-water settings (and we're doubtful that it is in the absence of a clear connection with shelf stratigraphy), our key point is that stratigraphic discontinuities develop in off-shelf environments for a host of reasons, besides direct eustatic forcing. So their existence is of limited use in global correlation without broader context.

A second conceptual issue is whether sequences ought to be defined and mapped on the basis of geometric criteria, though in a conceptually consistent way (our view), or according to some perception of sea-level change (e.g., Posamentier and Allen 1999). While individual workers are at liberty to define stratigraphic units any way they please (e.g., Embry 1988, 1995; Galloway 1989; Hunt and Tucker 1992; Kolla et al. 1995; Naish and Kamp 1997; Plint and Nummedal 2000), at stake is more than an inconsequential debate about terminology. Rather, it is our understanding of how sedimentation responds to various phenomena (including sea-level change), how discontinuities arise, and specifically how surfaces are traced and therefore dated in basinal settings.

It is still widely assumed that sequence boundaries develop more or less instantaneously as "relative sea level begins to fall," when sea level is falling most rapidly or as sea level drops below the shelf edge (to pick just three popular but obviously different ideas; e.g., Posamentier et al. 1988; Van Wagoner et al. 1988; Vail et al. 1991; Posamentier and Allen 1999; Posamentier and Morris 2000; Coe 2003; Catuneanu 2006). The concept of relative sea-level change, which dates back to the early years of seismic stratigraphy (Vail et al. 1977), makes sense at a qualitative level. The space available for sediment to accumulate is influenced by vertical motions of both the crust and sea level. So, it is argued, all possible origins of sequence boundaries can be accommodated by considering changes in sea level relative to a subsiding sedimentary basin; and headward erosion from a subaerially exposed shelf edge accounts for both the origin and timing of incised valleys.

The main problem with these firmly entrenched ideas has been appreciated for more than 20 years: they're circular and not consistent with available data (Christie-Blick and Mountain 1989; Christie-Blick 1991; Christie-Blick and Driscoll 1995; Pekar et al. 2001; Pekar et al. 2003). Relative sea-level change cannot be rigorously defined or independently measured in subsiding sedimentary basins in the now generally accepted manner suggested by Posamentier et al. (1988), and it must vary spatially as well as temporally owing to differential subsidence and associated lateral variations in sediment accumulation, compaction and loading. For these reasons, and because sediment bypassing characterizes some marine settings as well as many nonmarine ones (Christie-Blick et al. 2002; Pekar et al. 2003), the relative sea level concept in fact provides no explanation for the onset of bypassing and/or erosion at any location or for the timing of sequence boundaries. And though headward erosion is a fine concept for understanding knickpoint migration and landscape evolution at short timescales, evidence in hand indicates that in subsiding sedimentary basins, sequence boundaries and their associated incised valleys develop over a finite interval of geological time during highstand progradation (Christie-Blick 1991; Christie-Blick and Driscoll 1995; Morton and Suter 1996; Plint and Nummedal 2000; Pekar et al. 2003).

Quantitative analysis of the New Jersey Oligocene, one of the few studies in which precise constraints are available for timing, facies and (most important) eustatic variations, demonstrates that highstand progradation (the stratigraphic element) in each sequence continued to the low stand (two words) of sea level (Kominz and Pekar 2001; Pekar and Kominz 2001; Pekar et al. 2001; Pekar et al., 2003). The systematic delay in the anticipated timing of sequence boundaries (by almost half a cycle; cf. Christie-Blick et al. 1992), and the corresponding absence of lowstand systems tracts at a location for which the rate of eustatic change was as much as an order of magnitude greater than the local rate of tectonic subsidence, is inconsistent with the relative sea level concept. The documented timing is thought to relate instead to a wave climate on the shallow shelf that was sufficiently active during sea-level falls that the advancing shoreline was generally unable to catch up with the prograding shallow shelf edge. Point sources and hence lowstand units failed to develop. So renewed onlap at the adjacent shelf slope (and the conventional age of each sequence boundary) in this case corresponds not with a relative sea-level fall, but with the onset of eustatic rise.

In light of such results, a fallback position is to claim that the timing of a relative sea-level fall can be recognized stratigraphically, even if the concept itself defies rigorous definition, on the basis of evidence for sediment bypassing (so-called forced regression) and the development of offlap (Posamentier et al. 1992; Posamentier and Allen 1999). However, the concept of a sequence boundary then needs to be changed radically in order to preserve the supposed relationship between sequence boundaries and the onset of relative sea-level falls. According to Posamentier and Allen (1999), a sequence boundary corresponds not with a geometrically well defined offlap surface but with the onset of bypassing at a hypothetical clinoform that traces basinward beneath all offlapping strata. Apart from the impracticality of partitioning bypassing from subsequent erosion, and hence identifying the appropriate clinoform, this interpretation is at odds with the most basic principle of sequence stratigraphy: the supremacy of stratal geometry and associated discontinuities in interpreting the stratigraphic record. It is also apparently based upon a fundamental misunderstanding of the time-stratigraphic significance of unconformities (Posamentier and Allen 1999, p. 46): "Inherent in these contrasting definitions is the question of whether the sequence boundary represents a surface that forms at a specific point in time, and therefore represents a chronostratigraphically significant surface. We will discuss below that placing the sequence boundary at the top of sediments deposited during relative sea-level fall implies that *the sequence boundary is, in fact, the unconformity surface* itself (a surface that can form over long periods of time), thereby eliminating any chronostratigraphic significance of the sequence boundary." (The italics are ours.)

In case these considerations seem a little far-fetched, we should recall that the ICS's Working Group on Sequence Stratigraphy expended seven years (1995-2002) on not reaching a consensus definition of the word sequence (Berggren et al. 2001; Christie-Blick 2001; Posamentier 2001; Salvador 2001). That discussion, which involved some of the most influential individuals in this field, hung up in large measure over the issue of whether sequences are interpretive in the limited sense advocated in this essay or purely descriptive entities, with the latter involving no conceptual rationale for either the recognition or the tracing of boundaries. Our colleague, Jan Hardenbol was among the most outspoken advocates for a non-interpretive definition akin to that of Mitchum (1977), a minority view in the working group that was nonetheless endorsed by most present and former representatives of the Exxon school (Salvador 2001). The obvious inconsistency between this view and numerous publications by the same authors was never adequately addressed (compare, for example, Posamentier and Allen 1999 and Posamentier 2001). If the sequence concept is extended to submarine erosion surfaces without a direct or even conceptual connection with subaerial degradation (e.g., Schlager 1991; Posamentier 2001), and if the criteria for mapping sequence boundaries are arbitrary (akin to lithostratigraphy), or at least unspecified (Hardenbol et al. 1998, p. 3), how can we even begin to consider whether unconformities are synchronous at the scale of European basins, let alone globally?

Non-Eustatic Origins

Among important advances in sequence stratigraphy over the past decade have been improvements in the dating of sequence boundaries (in the sense advocated here), in the measurement of amplitudes of sea-level change based on backstripping approaches at continental margins, and in the calibration of the deep-sea oxygen isotopic record (Miller et al. 1998; Kominz and Pekar 2001; Pekar and Kominz 2001; Pekar et al. 2002; John et al. 2004; Miller et al. 2005a; Pekar and Christie-Blick 2006; Pekar and Christie-Blick in press). It is now generally agreed that eustasy was an important driver of sedimentary cyclicity at least since the development of large ice sheets in the early Oligocene, and during earlier ice ages (Miller et al. 1998; Crowell 1999). Eustasy arguably played a role also during times of limited glaciation such as the Jurassic, Cretaceous and early Paleogene (Frakes and Francis 1988; Frakes et al. 1992; Jacobs and Sahagian 1995; Stoll and Schrag 1996; Miller et al. 1998; Miller et al. 1999; Price 1999; Gale et al. 2002; Miller et al. 2003; Immenhauser 2005; Miller et al. 2005b; Pekar et al. 2005). Nonetheless, the paucity of evidence for glacial ice through much of the Mesozoic (Frakes et al. 1992; Markwick and Rowley 1998; Crowell 1999; Price 1999) and during spans such as the Cambrian for which a low-latitude location of East Antarctica precludes concealment of glacial deposits beneath the modern ice sheet (Scotese 2007), suggests that glacio-eustasy may not have influenced sedimentation in the geological past as strongly as it has during the past few tens of millions of years. Since sequence boundaries are now known not to develop instantaneously or to require large and rapid sea-level changes, an issue that arises is whether some and perhaps many unconformities relate to essentially non-eustatic phenomena (Christie-Blick and Driscoll 1995).

High-resolution stratigraphic studies in tectonically active basins demonstrate the development of stratigraphic growth at timescales well within the Milankovitch range (10^4-10^6 y; e.g., Rosales et al. 1994; Plint 2000; Saurborn et al. 2000; Sharp et al. 2000; Mortimer et al. 2005). If stratigraphic geometry in such basins is fundamentally tectonic at that resolution, we infer that the boundaries between units may be of tectonic origin also, rather than only "tectonically enhanced" (e.g., Vail et al. 1984; Vail et al. 1991), with length scales ranging from local (individual structures) to hundreds of kilometers (flexural deformation in foreland basins; Christie-Blick and Driscoll 1995; Catuneanu 2006). Our purpose here is not to embark on a discussion of tectonic phenomena, and there are many. It is to recognize that most basins are tectonically active (even some so-called passive continental margins), and that serious exploration of these phenomena has been mostly side-tracked by uncritical acceptance of the eustatic paradigm thinly veiled as relative sea-level change.

Diachrony

The bedrock assumption that stratigraphic discontinuities have time-stratigraphic significance is not universally correct. Surfaces related to the propagation of faults and the growth of associated folds are expected to be diachronous at the timescale of the deformation, as well as only locally developed (e.g., Weldon 1984; Medwedeff 1989; Christie-Blick et al. 1990; Quebral et al. 1996; Gawthorpe et al. 1997; Sharp et al. 2000). Diachrony also characterizes discontinuities associated with the development of sediment drifts at continent margins (Christie-Blick et al. 1990; Lu et al. 2003; Lu and Fulthorpe 2004), and it is undoubtedly the case that surfaces of eustatic origin are more generally associated with leads and lags, independent of the criteria adopted for mapping (Christie-Blick 1991). Compare, for example, terrigenous sequences of the New Jersey Oligocene with a hypothetical carbonate platform at which widespread subaerial exposure would have been engendered by even a small lowering of sea level (a potential range in sequence boundary timing of nearly one half of a cycle). While the debate about how sequence boundaries ought to be traced is informed in part by similar considerations, with some preferring definitions that minimize implied diachrony (e.g., Hunt and Tucker 1992, 1995; Kolla et al. 1995; Posamentier and Allen 1999), we think that it is better to recognize that objective mapping based on stratal geometry makes some level of diachrony unavoidable. In that case, and at some scale, unconformities pass laterally not into correlative conformities, but into correlative intervals. Such considerations begin to be important as the resolution of the geological timescale improves at a global scale.

IMPLICATIONS

The present status of sequence stratigraphy in chronostratigraphy therefore appears to be as follows. A compelling case can be made for interpretive sequence stratigraphy. It is what most sequence stratigraphers do in practice even as some argue for non-genetic terminology. However, the quality of published interpretations is highly uneven, and we are some distance from a consensus about how sequence boundaries ought to be traced seaward and hence dated in basinal settings. While age control has improved markedly since the publication of Haq et al. (1987), through the integration of numerous outcrop studies, the release of proprietary data, and targeted drilling under the auspices of the Ocean Drilling Program (and now the Integrated Ocean Drilling Program), uncertainties persist primarily because sampling of well defined sequence boundaries is rarely possible at correlative conformities, and well dated successions are not necessarily closely connected to physical stratigraphy. Unconformities are not universally of eustatic origin, and those that are due to sea-level change are not likely to be synchronous at the level that has generally been assumed (e.g., Loutit 1992). Bio-chrono-sequence stratigraphic charts, as they now exist, are misleading because they imply a level of confidence in dating that cannot be sustained and because they assume global significance for most local data (e.g., Christie-Blick et al. 1988; Gradstein et al. 1988; Christie-Blick et al. 1990; Miall 1991, 1992, 1993, 1994; Miall and Miall 2001). Little incentive exists to challenge such schemes. So many sequences are included in syntheses that it is invariably possible to correlate local stratigraphy to a "global" chart (Miall 1992), and indeed to use the latter to sharpen the calibration of the former. Existing syntheses are incrementally and uncritically updated to incorporate new data (cf. Vail et al. 1977; Haq et al. 1987; Hardenbol et al. 1998); and the local absence of supposedly global features is invariably attributed to tectonic suppression, lack of expression in preserved facies, or inadequate resolution.

So what should we do? The most objective approach would be to regard all sequence stratigraphic interpretations as local or regional. The geometrical basis for interpretations ought to be appropriately documented, along with the rationale for relating that geometry to age control (with uncertainties). Schemes based primarily on facies interpretation of isolated measured sections or well logs are at best doubtful, and fraught with the potential for circularity. The stratigraphic record includes plenty of proxies for global signals, based for example on evolutionary biology, changes in magnetopolarity, secular changes in marine isotopes, and cyclicity of various kinds related to orbital forcing. There is some evidence that eustatically modulated sequences, and not just T-R cycles, may develop at orbital timescales (e.g., Naish and Kamp 1997; Carter et al. 1999; Saul et al. 1999; Gale et al. 2002; Rabineau et al. 2005; Gale et al. 2006), though more commonly they do not, and most of the cited examples can themselves be debated. We think that the prospects are nonetheless excellent for perfecting an astrochronological timescale, at least for the Mesozoic and Cenozoic, and perhaps into the Paleozoic (Berger et al. 1992; Bond et al. 1993; de Boer and Smith 1994; House and Gale 1995; Olsen and Kent 1999; Hinnov 2000; Pälike et al. 2007; see Miall and Miall 2004 for a different view). We also endorse continued research in quantifying the timing and amplitudes of sea-level change (with specified uncertainties), particularly for the Cenozoic, and integrating passive-margin backstripping in a sequence stratigraphic context with the much higher resolution deep-sea oxygen isotopic record (e.g., Kominz and Pekar 2001; Pekar and Kominz 2001; Pekar et al. 2002; Miller et al. 2005a; Pekar and Christie-Blick in press). Global sequence stratigraphic/cycle charts, however, were always a fudge, and they aren't going to help much in chronostratigraphy at the resolution that is now needed.

ACKNOWLEDGMENTS

We thank Kari Bassett and Ashton Embry for comments on the manuscript, and numerous colleagues for discussions over the years that have helped shape the authors' views. Christie-Blick acknowledges protracted email correspondence with members of the Working Group on Sequence Stratigraphy (International Commission on Stratigraphy, 1995-2002), along with participants in the Hedberg Research Conference on Sequence Stratigraphic and Allostratigraphic Principles and Concepts (2001) and the Penrose Conference on Chronostratigraphy: Beyond the Global Standard Stratotype and Point (2006). Our recent sequence stratigraphic studies have been supported by National Science Foundation grant OCE 01-19019 (Christie-Blick and Pekar), and by Compagnie Générale de Géophysique, Paradigm and summer internships with Chevron (Madof). Christie-Blick thanks the Department of Geological Sciences at the University of Canterbury, New Zealand, for hospitality during his 2006-07 sabbatical leave. Lamont-Doherty Earth Observatory Contribution Number 7028.

REFERENCES

AINSWORTH, R. B. and PATTISON, S. A. J., 1994. Where have all the lowstands gone? Evidence for attached lowstand systems tracts in the Western Interior of North America. *Geology,* 22: 415-418.

ANADÓN, P., CABRERA, L., COLOMBO, F., MARZO, M. and RIBA, O., 1986. Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro basin margins (NE Spain). In: Allen, P. A., and Homewood, P., Eds., *Foreland basins.* International Association of Sedimetologists Special Publication 8:259-271.

AUBRY, M.-P., 1995. From chronology to stratigraphy: interpreting the lower and middle Eocene stratigraphic record in the Atlantic Ocean. In: Berggren, W. A., Kent, D. V., Aubry, M.-P., and Hardenbol, J., Eds., *Geochronology, time scales and global stratigraphic correlation*, 213-274. SEPM (Society for Sedimentary Geology) Special Publication 54.

AUBRY, M.-P., BERGGREN, W. A., VAN COUVERING, J. A. and STEININGER, F., 1999. Problems in chronostratigraphy: stages, series, unit and boundary stratotypes, global stratotype section and point and tarnished golden spikes. *Earth-Science Reviews,* 46:99-148.

BAUM, G. R. and VAIL, P. R., 1988. Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic basins. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 309-327. Society of Economic Paleontologists and Mineralogists Special Publication 42.

BERGER, A., LOUTRE, M. F. and LASKAR, J., 1992. Stability of the astronomical frequencies over the Earth's history for paleoclimate studies. *Science,* 255:560-566.

BERGGREN, W. A., CHRISTIE-BLICK, N., AUBRY, M.-P., CARTER, R. M., HALLAM, A., MILLER, K. G., OWEN, D. E., VAN COUVERING, J. A. and WATKINS, J. S., 2001. A proposed bipartite sequence stratigraphic nomenclature. *Hedberg Research Conference* (*Sequence stratigraphic and allostratigraphic principles and concepts, Program and Abstracts Volume*, 16-17. Dallas, Texas: American Association of Petroleum Geologists.

BOND, G. C., DEVLIN, W. J., KOMINZ, M. A., BEAVAN, J. and MCMANUS, J., 1993. Evidence of astronomical forcing of the Earth's climate in Cretaceous and Cambrian times. *Tectonophysics,* 222: 295-315.

CARTER, R. M., ABBOTT, S. T. and NAISH, T. R., 1999. Plio-Pleistocene cyclothems from Wanganui basin, New Zealand: type locality for an astrochronologic time-scale, or template for recognizing ancient glacio-eustasy? *Philosophical Transactions of Royal Society of London,* A, 357: 1861-1872.

CARTER, R. M., FULTHORPE, C. S. and LU, H., 2004b. Canterbury Drifts at Ocean Drilling Program Site 1119, New Zealand: climatic modulation of southwest Pacific intermediate water flows since 3.9 Ma. *Geology,* 32: 1005–1008.

CARTER, R. M., McCAVE, I. N. and CARTER, L., 2004a. Leg 181 synthesis: fronts, flows, drifts, volcanoes, and the evolution of the southwestern gateway to the Pacific Ocean, eastern New Zealand. In: Richter, C., Ed., *Proceedings of Ocean Drilling Program, Scientific Results,* 181 [Online]: http://www-odp.tamu.edu/publications/181_SR/synth/synth.htm.

CASTELLTORT, S., GUILLOCHEAU, F., ROBIN, C., ROUBY, D., NALPAS, T., LAFONT, F. and ESCHARD, R., 2003. Fold control on the stratigraphic record: a quantified sequence stratigraphic study of the Pico del Aguila anticline in the south-western Pyrenees (Spain). *Basin Research,* 15:527-551.

CATUNEANU, O., 2006, *Principles of sequence stratigraphy.* Elsevier: Amsterdam, 375 pp.

CHRISTIE-BLICK, N., 1982. Pre-Pleistocene glaciation on Earth: Implications for climatic history of Mars. *Icarus,* 50: 423-443.

——— 1991. Onlap, offlap, and the origin of unconformity-bounded depositional sequences. *Marine Geology,* 97: 35-56.

———, 2001. A personal perspective on sequence stratigraphic nomenclature. *Hedberg Research Conference (Sequence stratigraphic and allostratigraphic principles and concepts), Program and Abstracts Volume*, 20-21. Dallas, Texas: American Association of Petroleum Geologists.

CHRISTIE-BLICK, N. and DRISCOLL, N. W., 1995. Sequence stratigraphy. *Annual Review of Earth and Planetary Sciences,* 23:451-478.

CHRISTIE-BLICK, N. and MOUNTAIN, G. S., 1989. A model for development of unconformity-bounded depositional sequences, with implications for sequence-stratigraphic record of sea-level fluctuations. *28th International Geological Congress.* Washington, D.C., Abstracts Volume 1:1-291 to 1-292.

CHRISTIE-BLICK, N., DYSON, I. A. and VON DER BORCH, C. C., 1995. Sequence stratigraphy and the interpretation of Neoproterozoic earth history. *Precambrian Research,* 73:3-26.

CHRISTIE-BLICK, N., MILLER, K. G., MOUNTAIN, G. S., DRISCOLL, N. W., REYNOLDS, D. J. and STECKLER, M. S., 1992. Sequence stratigraphy and sea-level change: examples from the Atlantic margins of the U.S. and Canada. *Geological Society of London, Marine Studies Group (The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region).* Edinburgh, UK.

CHRISTIE-BLICK, N., MOUNTAIN, G. S., and MILLER, K. G., 1988. Sea level history. *Science,* 241:596.

———, 1990. Seismic stratigraphic record of sea-level change. In: *Sea-Level Change*, 116-140. Studies in Geophysics, Washington, D.C., National Academy Press.

CHRISTIE-BLICK, N., MOUNTAIN, G. S., GHOSH, A., MCHUGH, C. M. G., PEKAR, S. F. and SCHOCK, S. G., 2002. New insights on late Pleistocene sedimentation at the New Jersey margin based on Chirp sonar profiles and vibracores. *EOS, Transactions, American Geophysical Union,* 83(47), Abstract OS71C-0298.

CHRISTIE-BLICK, N., WILLIAMS, G. E. and GOSTIN, V. A., 2001. Discussion on mantle plume uplift in the sedimentary record: origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia. *Journal of Geological Society of London,* 158: 573-576.

COE, A. L., Ed., 2003. *The sedimentary record of sea-level change.* Cambridge: Cambridge University Press, 288 pp.

CROSS, T. A. and LESSENGER, M. A., 1988. Seismic stratigraphy. *Annual Review of Earth and Planetary Sciences,* 16:319-354.

CROWELL, J. C., 1999. *Pre-Mesozoic ice ages: their bearing on understanding the climate system.* Geological Society of America Memoir 192, 106 pp.

DAMUTH, J. E., FLOOD, R. D., PIRMEZ, C. and MANLEY, P. L., 1995. Architectural elements and depositional processes of Amazon deep sea fan imaged by long-range side-scan sonar (GLORIA), bathymetric swath-mapping (SeaBEAM), high-resolution seismic, and piston-core data. In: Pickering, K. T., Hiscott, R. N., Kenyon, N. H., Ricci Lucchi, F., and Smith, R. D. A., Eds., *Atlas of Deep Water Environments: Architectural Style in Turbidite Systems*, 105-121. London: Chapman and Hall.

DAMUTH, J. E., KOWSMANN, R. O., FLOOD, R. D., BELDERSON, R. H. and GORINI, M. A., 1983. Age relationships of distributary channels on Amazon deep-sea fan: implications for fan growth pattern. *Geology,* 11:470-473.

DE BOER, P. L. and SMITH, D. G., 1994. Orbital forcing and cyclic sequences. In: de Boer, P. L., and Smith, D. G., Eds., *Orbital forcing and cyclic sequences*, 1-14. International Association of Sedimentologists Special Publication 19.

DE GRACIANSKY, P.-C., HARDENBOL, J., JACQUIN, T. and VAIL, P. R., Eds., 1998. *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins.* SEPM (Society for Sedimentary Geology) Special Publication 60, 786 pp.

DRISCOLL, N. W., HOGG, J. R., CHRISTIE-BLICK, N. and KARNER, G. D., 1995. Extensional tectonics in the Jeanne d'Arc basin, offshore Newfoundland: implications for the timing of break-up between Grand Banks and Iberia. In: Scrutton, R. A., Stoker, M. S., Shimmield, G. B. and Tudhope, A. W., Eds., *The tectonics, sedimentation and palaeoceanography of the North Atlantic region*, 1-28. Geological Society of London Special Publication 90.

EBERLI, G. P., ANSELMETTI, F. S., KROON, D., SATO, T. and WRIGHT, J. D., 2002. The chronostratigraphic significance of seismic reflections along the Bahamas Transect. *Marine Geology,* 185: 1-17.

EMBRY, A. F., 1988. Triassic sea-level changes: Evidence from the Canadian Arctic archipelago. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 249-259. Society of Economic Paleontologists and Mineralogists Special Publication 42.

———, 1995. Sequence boundaries and sequence hierarchies: problems and proposals. In: Steel, R. J., Felt, V. L., Johannessen, E. P. and Mathiu, C., Eds., *Sequence stratigraphy on the northwest European margin*, 1-11. Amsterdam, Elsevier: Norwegian Petroleum Society Special Publication 5.

EMERY, D. and MYERS, K. J., Eds., 1996. *Sequence stratigraphy.* Oxford: Blackwell Science, 297 pp.

FORD, M., WILLIAMS, E. A., ARTONI, A., VERGÉS, J. and HARDY, S., 1997. Progressive evolution of a fault-related fold pair from growth strata geometries, Sant Llorenç de Morunys, SE Pyrenees. *Journal of Structural Geology,* 19: 413-441.

FRAKES, L. A. and FRANCIS, J. E., 1988. A guide to Phanerozoic cold polar climates from high-latitude ice-rafting in the Cretaceous. *Nature,* 333: 547-549.

FRAKES, L. A., FRANCIS, J. E. and SYKTUS, J. I., 1992. *Climate modes of the Phanerozoic.* Cambridge: Cambridge University Press, 274 pp.

FULTHORPE, C. S., and CARTER, R. M., 1991. Continental-shelf progradation by sediment-drift accretion. *Geological Society of America Bulletin,* 103: 300-309.

GALE, A. S., HARDENBOL, J., HATHWAY, B., KENNEDY, W. J., YOUNG, J. R. and PHANSALKAR, V., 2002. Global correlation of Cenomanian (Upper Cretaceous) sequences: evidence for Milankovitch control on sea level. *Geology,* 30: 291–294.

GALE, A. S., HUGGETT, J. M., PÄLIKE, H., LAURIE, E., HAILWOOD, E. A. and HARDENBOL, J., 2006. Correlation of Eocene–Oligocene marine and continental records: orbital cyclicity, magnetostratigraphy and sequence stratigraphy of the Solent Group, Isle of Wight, UK. *Journal of Geological Society of London,* 163: 401-415.

GALLOWAY, W. E., 1989. Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. *American Association of Petroleum Geologists Bulletin,* 73: 125-142.

GARCÍA-MONDÉJAR, J. and FERNÁNDEZ-MENDIOLA, P. A., 1993. Sequence stratigraphy and systems tracts of a mixed carbonate-siliciclastic platform-basin setting: the Albian of Lunada and Soba, northern Spain. *American Association of Petroleum Geologists Bulletin,* 77: 245-275.

GAWTHORPE, R. L., SHARP, I., UNDERHILL, J. R. and GUPTA, S., 1997. Linked sequence stratigraphic and structural evolution of propagating normal faults. *Geology,* 25:795-798.

GILES, K. A. and LAWTON, T. F., 2002. Halokinetic sequence stratigraphy adjacent to the El Papalote diapir, northeastern Mexico. *Association of Petroleum Geologists Bulletin,* 86:823-840.

GRADSTEIN, F. M., AGTERBERG, F. P., AUBREY, M.-P., BERGGREN, W. A., FLYNN, J. J., HEWITT, R., KENT, D. V., KLITGORD, K. D., MILLER, K. G., OBRADOVITCH, J., OGG, J. G., PROTHERO, D. R. and WESTERMAN, G. E. G., 1988. Sea level history. *Science,* 241:599-601.

GROTZINGER, J. P., ADAMS, R. D., MCCORMICK, D. S. and MYROW, P., 1989. Sequence stratigraphy, correlations between Wopmay orogen and Kilohigok basin, and further investigations of the Bear Creek Group (Goulburn Supergroup), District of Mackenzie, N.W.T. *Geological Survey of Canada Paper* 89-1C:107-119.

HAMPSON, G. J., 2000. Discontinuity surfaces, clinoforms, and facies architecture in a wave-dominated, shoreface-shelf parasequence. *Journal of Sedimentary Research,* 70: 325-340.

HAQ, B. U., 1991. Sequence stratigraphy, sea-level change, and significance for the deep sea. In: Macdonald, D. I. M., Ed., *Sedimentation, tectonics and eustasy. Sea-level changes at active margins*, 3-39. International Association of Sedimentologists Special Publication 12.

HAQ, B. U., HARDENBOL, J. and VAIL, P. R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science,* 235: 1156-1167.

HARDENBOL, J., THIERRY, J., FARLEY, M. B., JACQUIN, T., DE GRACIANSKY, P.-C. and VAIL, P. R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: de Graciansky, P.-C., Hardenbol, J., Jacquin, T., and Vail, P. R., Eds., *Mesozoic and Cenozoic sequence stratigraphy of European basins*, 3-13. Tulsa: SEPM (Society for Sedimentary Geology) Special Publication 60.

HINNOV, L. A., 2000. New perspectives on orbitally forced stratigraphy. *Annual Review of Earth and Planetary Sciences,* 28: 419-475.

HISCOTT, R. N., PIRMEZ, C. and FLOOD, R. D., 1997. Amazon submarine fan drilling: a big step forward for deep-sea fan models. *Geoscience Canada,* 24: 13-24.

HOUSE, M. R. and GALE, A. S., Eds., 1995. *Orbital forcing timescales and cyclostratigraphy.* Geological Society of London Special Publication 85, 210 pp.

HUNT, D. and TUCKER, M. E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. *Sedimentary Geology,* 81:1-9.

HUNT, D. and TUCKER, M. E., 1995. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall – reply. *Sedimentary Geology,* 95:147-160.

IMMENHAUSER, A., 2005. High-rate sea-level change during the Mesozoic: New approaches to an old problem. *Sedimentary Geology,* 175: 277-296.

INTERNATIONAL COMMISSION ON STRATIGRAPHY, 2007, Interactive geologic time scale and bio-chrono-sequence stratigraphy charts: http://www.stratigraphy.org/.

JACOBS, D. K. and SAHAGIAN, D. L., 1995. Milankovitch fluctuations in sea level and recent trends in sea-level change: ice may not always be the answer. In: Haq, B. U., Ed., *Sequence stratigraphy and depositional response to eustatic, tectonic and climatic forcing*, 329-366. Dordrecht, Netherlands: Kluwer Academic Publishers.

JIANG GANQING, CHRISTIE-BLICK, N., KAUFMAN, A. J., BANERJEE, D. M. and RAI, V., 2002. Sequence stratigraphy of the Neoproterozoic Infra Krol Formation and Krol Group, Lesser Himalaya, India. *Journal of Sedimentary Research,* 72: 524-543.

JOHN, C. M., KARNER, G. D. and MUTTI, M., 2004. $\delta^{18}O$ and Marion Plateau backstripping: combining two approaches to constrain late middle Miocene eustatic amplitude. *Geology,* 32: 829–832.

JOHNSON, J. G., KLAPPER, G. and SANDBERG, C. A., 1985. Devonian eustatic fluctuations in Euramerica. *Geological Society of America Bulletin,* 96: 567-587.

KENNARD, J. M., SOUTHGATE, P. N., JACKSON, M. J., O'BRIEN, P. E., CHRISTIE-BLICK, N., HOLMES, A. E. and SARG, J. F., 1992. New sequence perspective on the Devonian reef complex and the Frasnian-Famennian boundary, Canning basin, Australia. *Geology,* 20: 1135-1138.

KIDWELL, S. M., 1997. Anatomy of extremely thin marine sequences landward of a passive-margin hinge zone: Neogene Calvert Cliffs succession, Maryland, U.S.A. *Journal of Sedimentary Research,* 67: 322-340.

KOLLA, V., POSAMENTIER, H. W. and EICHENSEER, H., 1995. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall – discussion. *Sedimentary Geology,* 95: 139-145.

KOMINZ, M. A. and PEKAR, S. F., 2001. Oligocene eustasy from two-dimensional sequence stratigraphic backstripping. *Geological Society of America Bulletin,* 113: 291-304.

LINDSAY, J. F., 1987. Sequence stratigraphy and depositional controls in Late Proterozoic-Early Cambrian sediments of Amadeus basin, central Australia. *American Association of Petroleum Geologists Bulletin,* 71: 1387-1403.

LOUTIT, T. S., Ed., 1992. Sea-Level Working Group. *JOIDES Journal,* 18(3): 28-36.

LOUTIT, T. S., HARDENBOL, J., VAIL, P. R. and BAUM, G. R., 1988. Condensed sections: The key to age determinations and correlation of continental margin sequences. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 183-213. Society of Economic Paleontologists and Mineralogists Special Publication 42.

LU, H. and FULTHORPE, C. S., 2004. Controls on sequence stratigraphy of a middle Miocene–Holocene, current-swept, passive margin: offshore Canterbury Basin, New Zealand. *Geological Society of America Bulletin,* 116: 1345-1366.

LU, H., FULTHORPE, C. S. and MANN, P., 2003. Three-dimensional architecture of shelf-building sediment drifts in the offshore Canterbury Basin, New Zealand. *Marine Geology,* 193: 19-47.

MacNAUGHTON, R. B., DALRYMPLE, R. W. and NARBONNE, G. M., 1997. Multiple orders of relative sea-level change in an earliest Cambrian passive-margin succession, Mackenzie Mountains, northwestern Canada. *Journal of Sedimentary Research,* 67: 622-637.

MANLEY, P. L. and FLOOD, R. D., 1988. Cyclic sediment deposition within Amazon deep-sea fan. *American Association of Petroleum Geologists Bulletin,* 72: 912–925.

MARKWICK, P. J. and ROWLEY, D. B., 1998. The geological evidence for Triassic to Pleistocene glaciations: implications for eustasy. In: Pindell, J. L. and Drake, C. L., Eds., *Paleogeographic evolution and non-glacial eustasy, northern South America*, 17-43. SEPM (Society for Sedimentary Geology), Special Publication 58.

McLAURIN, B. and STEEL, R., 2001. Fourth-order nonmarine to marine sequences, middle Castlegate Formation, Book Cliffs, Utah: Reply. *Geology,* 29: 188.

McLAURIN, B. T. and STEEL, R. J., 2000, Fourth-order nonmarine to marine sequences, middle Castlegate Formation, Book Cliffs, Utah. *Geology,* 28: 359-362.

MEDWEDEFF, D. A., 1989. Growth fault-bend folding at southeast Lost Hills, San Joaquin Valley, California. *American Association of Petroleum Geologists Bulletin,* 73: 54-67.

MELLERE, D. and STEEL, R., 2000. Style contrast between forced regressive and lowstand/transgressive wedges in the Campanian of south-central Wyoming. In: Hunt, D. and Gawthorpe, R. L., Eds., *Sedimentary responses to forced regressions*, 141-162. Geological Society of London Special Publication 172.

———, 1995. Variability of lowstand wedges and their distinction from forced-regressive wedges in the Mesaverde Group, southeast Wyoming. *Geology,* 23: 803-806.

MIALL, A. D., 1991. Stratigraphic sequences and their chronostratigraphic correlation. *Journal of Sedimentary Petrology,* 61: 497-505.

———, 1992. Exxon global cycle chart: an event for every occasion?: *Geology,* 20: 787-790.

———, 1993. Exxon global cycle chart: an event for every occasion?: Reply. *Geology,* 21: 284-285.

———, 1994. Sequence stratigraphy and chronostratigraphy: problems of definition and precision in correlation, and their implications for global eustasy. *Geoscience Canada,* 21: 1-26.

MIALL, A. D. and MIALL, C. E., 2001. Sequence stratigraphy as a scientific enterprise: the evolution and persistence of conflicting paradigms. *Earth-Science Reviews,* 54: 321-348.

———, 2004. Empiricism and model-building in stratigraphy: around the hermeneutic circle in the pursuit of stratigraphic correlation. *Stratigraphy,* 1: 27-46.

MILLER, K. G., BARRERA, E., OLSSON, R. K., SUGARMAN, P. J. and SAVIN, S. M., 1999. Does ice drive early Maastrichtian eustasy? *Geology,* 27: 783-786.

MILLER, K. G., KOMINZ, M. A., BROWNING, J. V., WRIGHT, J. D., MOUNTAIN, G. S., KATZ, M. E., SUGARMAN, P. J., CRAMER, B. S., CHRISTIE-BLICK, N. and PEKAR, S. F., 2005a. The Phanerozoic record of global sea-level change. *Science,* 310:1293-1298.

MILLER, K. G., MOUNTAIN, G. S., BROWNING, J. V., KOMINZ, M., SUGARMAN, P. J., CHRISTIE-BLICK, N., KATZ, M. E. and WRIGHT, J. D., 1998. Cenozoic global sea level, sequences, and the New Jersey Transect: results from coastal plain and continental slope drilling. *Reviews of Geophysics,* 36: 569-601.

MILLER, K. G., MOUNTAIN, G. S., THE LEG 150 SHIPBOARD PARTY and MEMBERS OF THE NEW JERSEY COASTAL PLAIN DRILLING PROJECT, 1996. Drilling and dating New Jersey Oligocene-Miocene sequences: ice volume, global sea level, and Exxon records. *Science,* 271: 1092-1095.

MILLER, K. G., SUGARMAN, P. J., BROWNING, J. V., KOMINZ, M. A., HERNÁNDEZ, J. C., OLSSON, R. K., WRIGHT, J. D., FEIGENSON, M. D. and VAN SICKEL, W., 2003. Late Cretaceous chronology of large, rapid sea-level changes: glacioeustasy during the greenhouse world. *Geology,* 31: 585–588.

MILLER, K. G., WRIGHT, J. D. and BROWNING, J. V., 2005b. Visions of ice sheets in a greenhouse world. *Marine Geology,* 217: 215-231.

MITCHUM, R. M., JR., 1977. Seismic stratigraphy and global changes of sea level, part 11: Glossary of terms used in seismic stratigraphy. In: Payton, C. E., Ed., *Seismic stratigraphy – applications to hydrocarbon exploration*, 205-212. American Association of Petroleum Geologists Memoir 26.

MITCHUM, R. M., JR. and VAN WAGONER, J. C., 1991. High-frequency sequences and their stacking patterns: sequence-stratigraphic evidence of high-frequency eustatic cycles. *Sedimentary Geology,* 70:131-160.

MØLLER, I. and ANTHONY, D., 2003. A GPR study of sedimentary structures within a transgressive coastal barrier along the Danish North Sea coast. In: Bristow, C. S. and Jol, H. M., Eds., *Ground penetrating radar in sediments*, 55-65. Geological Society of London Special Publication 211.

MONTAÑEZ, I. P. and OSLEGER, D. A., 1993. Parasequence stacking patterns, third-order accommodation events, and sequence stratigraphy of Middle to Upper Cambrian platform carbonates, Bonanza King Formation, southern Great Basin. In: Loucks, R. G. and Sarg, J. F., Eds., *Carbonate sequence stratigraphy*, 305-326. American Association of Petroleum Geologists Memoir 57.

MORTIMER, E., GUPTA, S. and COWIE, P., 2005. Clinoform nucleation and growth in coarse-grained deltas, Loreto basin, Baja California Sur, Mexico: a response to episodic accelerations in fault displacement. *Basin Research,* 17: 337-359.

MORTON, R. A. and SUTER, J. R., 1996. Sequence stratigraphy and composition of late Quaternary shelf-margin deltas, northern Gulf of Mexico. *American Association of Petroleum Geologists Bulletin,* 80: 505-530.

MUTTI, E. and NORMARK, W. R., 1991. An integrated approach to the study of turbidite systems. In: Weimer, P. and Link, M. H., Eds., *Seismic facies and sedimentary processes of submarine fans and turbidite systems,* 75-107. New York: Springer-Verlag,.

NAISH, T. and KAMP, P. J. J., 1997. Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui basin, New Zealand: a case for the regressive systems tract. *Geological Society of America Bulletin,* 109:978-999.

NORDFJORD, S., GOFF, J. A., AUSTIN, J. A., JR. and GULICK, S. P. S., 2006. Seismic facies of incised-valley fills, New Jersey continental shelf: implications for erosion and preservation processes acting during latest Pleistocene-Holocene transgression. *Journal of Sedimentary Research,* 76: 1284-1303.

NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE, 2005. North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin,* 89: 1547-1591.

NUMMEDAL, D. and MOLENAAR, C. M., 1995. Sequence stratigraphy of ramp-setting strand plain successions: the Gallup Sandstone, New Mexico. In: Van Wagoner, J. C. and Bertram, G. T., Eds., *Sequence stratigraphy of foreland basin deposits. Outcrop and subsurface examples from the Cretaceous of North America*, 277-310. American Association of Petroleum Geologists Memoir 64.

OLSEN, P. and KENT, D. V., 1999. Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the Early Mesozoic time-scale and the longterm behaviour of the planets. *Philosophical Transactions of Royal Society of London,* A, 357: 1761-1786.

PÄLIKE, H., NORRIS, R. D., HERRLE, J. O., WILSON, P. A., COXALL, H. K., LEAR, C. H., SHACKLETON, N. J., TRIPATI, A. K. and WADE, B. S., 2007. The heartbeat of the Oligocene climate system. *Science,* 314: 1894-1898.

PATTISON, S. A. J., 1995. Sequence stratigraphic significance of sharp-based lowstand shoreface deposits, Kenilworth Member, Book Cliffs, Utah. *American Association of Petroleum Geologists Bulletin,* 79: 444-462.

PEKAR, S. F., HUCKS, A., FULLER, M. and LI, S., 2005, Glacioeustatic changes in the early and middle Eocene (51-42 Ma): Shallow-water stratigraphy from ODP Leg 189 Site 1171 (South Tasman Rise) and deep-sea $\delta^{18}O$ records. *Geological Society of America Bulletin,* 117: 1081-1093.

PEKAR, S. F. and CHRISTIE-BLICK, N., 2006. Linking pCO_2 estimates and oceanographic and Antarctic climate records for the early icehouse world (34-16 Ma). *Geological Society of America, Abstracts with Programs,* 38(7):50.

———, in press. Resolving apparent conflicts between oceanographic and Antarctic climate records and evidence for a decrease in pCO_2 during the Oligocene through early Miocene (34-16 Ma). *Palaeogeography, Palaeoclimatology, Palaeoecology.*

PEKAR, S. F. and KOMINZ, M. A., 2001. Two-dimensional paleoslope modeling: a new method for estimating water depths for benthic foraminiferal biofacies and paleoshelf margins. *Journal of Sedimentary Research,* 71: 608-620.

PEKAR, S. F., CHRISTIE-BLICK, N., KOMINZ, M. A. and MILLER, K. G., 2001. Evaluating the stratigraphic response to eustasy from Oligocene strata in New Jersey. *Geology,* 29: 55-58.

———, 2002. Calibration between eustatic estimates from backstripping and oxygen isotopic records for the Oligocene. *Geology,* 30:903-906.

PEKAR, S. F., CHRISTIE-BLICK, N., MILLER, K. G. and KOMINZ, M. A., 2003. Quantitative constraints on the origin of stratigraphic architecture at passive continental margins: Oligocene sedimentation in New Jersey, U.S.A. *Journal of Sedimentary Research,* 73: 227-243.

PIPER, D. J. W., FLOOD, R. D., CISOWSKI, S., HALL, F., MANLEY, P. L., MASLIN, M., MIKKELSEN, N. and SHOWERS, W., 1997. Synthesis of stratigraphic correlations of the Amazon Fan. In: Flood, R. D., Piper, D. J. W., Klaus, A. and Peterson, L. C., Eds., *Proceedings of Ocean Drilling Program, Scientific Results,* volume 155: 595-609. College Station, Texas: Ocean Drilling Program.

PLINT, A. G., 1988. Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea level. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 357-370. Society of Economic Paleontologists and Mineralogists Special Publication 42.

———, 2000. Sequence stratigraphy and paleogeography of a Cenomanian deltaic complex: the Dunvegan and lower Kaskapau formations in subsurface and outcrop, Alberta and British Columbia. *Bulletin of Canadian Petroleum Geology,* 48: 43-79.

PLINT, A. G. and NUMMEDAL, D., 2000. The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: Hunt, D. and Gawthorpe, R. L., Eds., *Sedimentary responses to forced regressions*, 1-17. Geological Society of London Special Publication 172.

POBLET, J., MUÑOZ, J. A., TRAVÉ, A. and SERRA-KIEL, J., 1998. Quantifying the kinematics of detachment folds using three-dimensional geometry: application to the Mediano anticline (Pyrenees, Spain). *Geological Society of America Bulletin,* 110: 111-125.

POSAMENTIER, H. W., 2001. Ruminations on sequence terminology with specific reference to "sequence" and sequence boundary types. *Hedberg Research Conference (Sequence stratigraphic and allostratigraphic principles and concepts) Program and Abstracts Volume,* 39-40. Dallas, Texas: American Association of Petroleum Geologists.

———, 2004. Seismic geomorphology: imaging elements of depositional systems from shelf to deep basin using 3D seismic data: implications for exploration and development. In: Davies, R. J., Cartwright, J. A., Stewart, S. A., Lappin, M., and Underhill, J. R., Eds., *3D seismic technology: application to the exploration of sedimentary basins*, 11-24. Geological Society of London Memoir 29.

POSAMENTIER, H. W., ALLEN, G. P., JAMES, D. P. and TESSON, M., 1992. Forced regressions in a sequence stratigraphic framework: concepts, examples, and exploration significance. *American Association of Petroleum Geologists Bulletin,* 76: 1687-1709.

POSAMENTIER, H. W. and ALLEN, G. P., 1999. *Siliciclastic sequence stratigraphy – concepts and applications. S*EPM (Society for Sedimentary Geology) Concepts in Sedimentology and Paleontology 7, 210 pp.

POSAMENTIER, H. W. and CHAMBERLAIN, C. J., 1993. Sequence-stratigraphic analysis of Viking Formation lowstand beach deposits at Joarcam Field, Alberta, Canada. In: Posamentier, H. W., Summerhayes, C. P., Haq, B. U. and Allen, G. P., Eds., *Sequence stratigraphy and facies associations*, 469-485. International Association of Sedimentologists Special Publication 18.

POSAMENTIER, H. W. and KOLLA, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research,* 73:367-388.

POSAMENTIER, H. W. and MORRIS, W. R., 2000. Aspects of the stratal architecture of forced regressive deposits. In: Hunt, D. and Gawthorpe, R. L., Eds., *Sedimentary responses to forced regressions*, 19-46. Geological Society of London Special Publication 172.

POSAMENTIER, H. W., ERSKINE, R. D. and MITCHUM, R. M., JR., 1991. Submarine fan deposition in a sequence stratigraphic framework. In: Weimer, P. and Link, M. H., Eds., *Seismic facies and sedimentary processes of submarine fans and turbidite systems*, 127-136. New York: Springer-Verlag.

POSAMENTIER, H. W., JERVEY, M. T. and VAIL, P. R., 1988. Eustatic controls on clastic deposition I – conceptual framework. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 109-124. Society of Economic Paleontologists and Mineralogists Special Publication 42.

POULSON, C. J., FLEMINGS, P. B., ROBINSON, R. A. J. and METZGER, J. M., 1998. Three-dimensional stratigraphic evolution of the Miocene Baltimore Canyon region: implications for eustatic interpretations and the systems tract model. *Geological Society of America Bulletin,* 110: 1105-1122.

PRICE, G. D., 1999. The evidence and implications of polar ice during the Mesozoic. *Earth-Science Reviews,* 48: 183–210.

QUEBRAL, R. D., PUBELLIER, M. and RANGIN, C., 1996. The onset of movement on the Philippine fault in eastern Mindanao: a transition from a collision to a strike-slip environment. *Tectonics,* 15: 713-726.

RABINEAU, M., BERNÉ, S., ASLANIAN, D., OLIVET, J.-L., JOSEPH, P., GUILLOCHEAU, F., BOURILLET, J.-F., LEDREZEN, E. and GRANJEON, D., 2005. Sedimentary sequences in the Gulf of Lion: a record of 100,000 years climatic cycles. *Marine and Petroleum Geology,* 22: 775-804.

RIBA, O., 1976. Syntectonic unconformities of the Alto Cardener, Spanish Pyrenees: a genetic interpretation. *Sedimentary Geology,* 15: 213-233.

ROSALES, I., FERNÁNDEZ-MENDIOLA, P. A. and GARCÍA-MONDÉJAR, J., 1994. Carbonate depositional sequence development on active fault blocks: the Albian in the Castro-Urdiales area, northern Spain. *Sedimentology,* 41: 861-882.

SALVADOR, A., 2001. Review of the concept of and recommended terminology for unconformity-related units. *Hedberg Research Conference (Sequence stratigraphic and allostratigraphic principles and concepts) Program and Abstracts Volume,* 46-47. Dallas, Texas: American Association of Petroleum Geologists.

SARG, J. F., 1988. Carbonate sequence stratigraphy. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 155-181. Society of Economic Paleontologists and Mineralogists Special Publication 42.

SAUL, G., NAISH, T. R., ABBOTT, S. T. and CARTER, R. M., 1999. Sedimentary cyclicity in the marine Pliocene–Pleistocene of the Wanganui basin (New Zealand): sequence stratigraphic motifs characteristic of the past 2.5 m.y. *Geological Society of America Bulletin,* 111: 524– 537.

SAURBORN, M. J., KARNER, G. D., CHRISTIE-BLICK, N., PLINT, A. G. and SCHOLZ, C. H., 2000. Accommodation changes in Upper Cretaceous sediments of the Alberta foreland basin: implications for the role of changes in in-plane force on unconformity development. *Geological Society of America, Abstracts with Programs,* 32:A102.

SCHLAGER, W., 1989. Drowning unconformities on carbonate platforms. In: Crevello, P. D., Wilson, J. L., Sarg, J. F. and Read, J. F., Eds., *Controls on carbonate platform and basin development*, 15-25. Society of Economic Mineralogists and Paleontologists Special Publication 44.

———, 1991. Depositional bias and environmental change – important factors in sequence stratigraphy. *Sedimentary Geology,* 70: 109-130.

———, 1999. Type 3 sequence boundaries. In: Harris, P. M., Saller, A. H. and Simo, J. A., Eds., *Advances in carbonate sequence stratigraphy: application to reservoirs, outcrops and models*, 35-45. SEPM (Society for Sedimentary Geology) Special Publication 63.

SCHLAGER, W. and CAMBER, O., 1986. Submarine slope angles, drowning unconformities, and self-erosion of limestone escarpments. *Geology,* 14: 762-765.

SCOTESE, C. R., 2007. Paleomap Project: http://www.scotese.com/earth.htm.

SHANLEY, K. W. and MCCABE, P. J., 1994. Perspectives on the sequence stratigraphy of continental strata. *American Association of Petroleum Geologists Bulletin,* 78: 544-568.

SHARP, I. R., GAWTHORPE, R. L., UNDERHILL, J. R. AND GUPTA, S., 2000. Fault-propagation folding in extensional settings: Examples of structural style and synrift sedimentary response from the Suez rift, Sinai, Egypt. *Geological Society of America Bulletin,* 112: 1877–1899.

SLOSS, L. L., 1963. Sequences in the cratonic interior of North America. *Geological Society of America Bulletin,* 74: 93-113.

———, 1988, Forty years of sequence stratigraphy. *Geological Society of America Bulletin,* 100: 1661-1665.

SLOSS, L. L., KRUMBEIN, W. C. and DAPPLES, E. C., 1949. Integrated facies analysis. In: Longwell, C. R., Ed., *Sedimentary facies in geologic history,* 91-124. Geological Society of America Memoir 39.

SONNENFELD, M. D. and CROSS, T. A., 1993. Volumetric partitioning and facies differentiation within the Permian Upper San Andres Formation of Last Chance Canyon, Guadalupe Mountains, New Mexico. In: Loucks, R. G. and Sarg, J. F., Eds., *Carbonate sequence stratigraphy*, 435-474. American Association of Petroleum Geologists Memoir 57.

STOLL, H. M. and SCHRAG, D. P., 1996. Evidence for glacial control of rapid sea level changes in the Early Cretaceous. *Science,* 272: 1771-1774.

SUPPE, J., SÀBAT, F., MUÑOZ, J. A., POBLET, J., ROCA, E. and VERGÉS, J., 1997. Bed-by-bed fold growth by kink-band migration: Sant Llorenç de Morunys, eastern Pyrenees. *Journal of Structural Geology,* 19: 443-461.

TESSON, M., POSAMENTIER, H. W. and GENSOUS, B., 2000. Stratigraphic organization of late Pleistocene deposits of the western part of the Golfe du Lion shelf (Languedoc shelf), western Mediterranean Sea, using high-resolution seismic and core data. *American Association of Petroleum Geologists Bulletin,* 84: 119–150.

THOMPSON, W. G. and GOLDSTEIN, S. L., 2006. A radiometric calibration of the SPECMAP timescale. *Quaternary Science Reviews,* 25: 3207-3215.

TINKER, S. W., 1998. Shelf-to-basin facies distributions and sequence stratigraphy of a steep-rimmed carbonate margin: Capitan depositional system, McKittrick Canyon, New Mexico and Texas. *Journal of Sedimentary Research,* 68: 1146-1174.

TRINCARDI, F. AND CORREGGIARI, A., 2000. Quaternary forced regression deposits in the Adriatic basin and the record of composite sea-level cycles. In: Hunt, D. and Gawthorpe, R. L., Eds., *Sedimentary responses to forced regressions*, 245-269. Geological Society of London Special Publication 172.

UNDERHILL, J. R., 1991. Controls on late Jurassic seismic sequences, Inner Moray Firth, UK North Sea: a critical test of a key segment of Exxon's original global cycle chart. *Basin Research,* 3:79-98.

VAIL, P. R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy. Part I: Seismic stratigraphy interpretation procedure. In: Bally, A. W., Ed., *Atlas of seismic stratigraphy.* American Association of Petroleum Geologists Studies in Geology 27(1):1-10.

———, 1992. The evolution of seismic stratigraphy and the global sea-level curve. In: Dott, R. H., Jr., Ed., *The historical ups and downs of a major geological concept*, 83-91. Geological Society of America Memoir 180.

VAIL, P. R., AUDEMARD, F., BOWMAN, S. A., EISNER, P. N. and PEREZ-CRUZ, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology – an overview. In: Einsele, G., Ricken, W. and Seilacher, A., Eds., *Cycles and events in stratigraphy*, 617-659. Berlin: Springer-Verlag.

VAIL, P. R., HARDENBOL, J. and TODD, R. G., 1984. Jurassic unconformities, chronostratigraphy, and sea-level changes from seismic stratigraphy and biostratigraphy. In: Schlee, J. S., Ed., *Interregional unconformities and hydrocarbon accumulation,* 129-144. American Association of Petroleum Geologists Memoir 36.

VAIL, P. R., MICHUM, R. M., JR., TODD, R. G., WIDMIER, J. M., THOMPSON, S., III, SANGREE, J. B., BUBB, J. N. and HAT-

LELID, W. G., 1977. Seismic stratigraphy and global changes of sea level. In: Payton, C. E., Ed., *Seismic stratigraphy – applications to hydrocarbon exploration*, 49-212. American Association of Petroleum Geologists Memoir 26.

VAN WAGONER, J. C., 1995. Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. In: Van Wagoner, J. C. and Bertram, G.T., Eds., *Sequence stratigraphy of foreland basin deposits. Outcrop and subsurface examples from the Cretaceous of North America,* 137-223. American Association of Petroleum Geologists Memoir 64.

VAN WAGONER, J. C., MITCHUM, R. M., CAMPION, K. M. and RAHMANIAN, V. D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. American Association of Petroleum Geologists Methods in Exploration Series, 7, 55 pp.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M., VAIL, P. R., SARG, J. F., LOUTIT, T. S. and HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C. K., Hastings, B. S., Kendall, C. G. St. C., Posamentier, H. W., Ross, C. A. and Van Wagoner, J. C., Eds., *Sea-level changes: an integrated approach*, 39-45. Society of Economic Paleontologists and Mineralogists Special Publication 42.

WELDON, R. J., 1984. Implications of the age and distribution of the Late Cenozoic stratigraphy in Cajon Pass, southern California. In: Hester, R. L. and Hallinger, D. E., Eds., *San Andreas fault – Cajon Pass to Wrightwood*, 9-15. American Association of Petroleum Geologists, Pacific Section, volume and guidebook 55.

WHEELER, H. E., 1958. Time-stratigraphy. *American Association of Petroleum Geologists Bulletin,* 42: 1047-1063.

WILLIS, A., 2000. Tectonic control of nested sequence architecture in the Sego Sandstone, Neslen Formation and Upper Castlegate Sandstone (Upper Cretaceous), Sevier foreland basin, Utah, USA. *Sedimentary Geology,* 136: 277-317.

YOSHIDA, S., 2000. Sequence and facies architecture of the upper Blackhawk Formation and the lower Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah, USA. *Sedimentary Geology,* 136: 239-276.

YOSHIDA, S., MIALL, A. D. and WILLIS, A., 1998. Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A.: Discussion. *American Association of Petroleum Geologists Bulletin,* 82: 1596-1606.

YOSHIDA, S., WILLIS, A. and MIALL, A., 2001. Fourth-order nonmarine to marine sequences, middle Castlegate Formation, Book Cliffs, Utah: Comment. *Geology,* 29: 187-188.

YOSHIDA, S., WILLIS, A. and MIALL, A.D., 1996. Tectonic control of nested sequence architecture in the Castlegate Sandstone (Upper Cretaceous), Book Cliffs, Utah. *Journal of Sedimentary Research,* 66: 737-748.