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Two models: global sea-level change and sequence stratigraphic architecture

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Abstract

Two different conceptual models underlie the application of sequence stratigraphy by Exxon stratigraphers and later researchers. One, the global sea-level model (GSM), relates to presumed sea-level behaviour through time; the other, the sequence stratigraphic model (SSM), relates to the stratigraphic record produced during a single cycle of sea-level change. Though the two models are inter-related they are logically distinct, and it is important to test them separately. A summary is presented of the nature of the two models, and of the nomenclature that is used in their description. It is concluded (a) that the global sea-level model comprises an assembly of local relative sea-level events which are widely recognisable within their parent sedimentary basin; and (b) that the sequence stratigraphic model is robust, and its application is therefore an insightful way to approach the interpretation of sedimentary rocks.

Keywords: sequence stratigraphy; global sea level; sea-level change

1. Introduction

The discipline of sequence stratigraphy had its origin in the comprehensive monograph of Payton (1977), which first published the results of the extensive in-house stratigraphic studies by Peter Vail and his colleagues within Exxon petroleum company. The Vail group drew their insights from the analysis of seismic profiles available to them as part of Exxon's worldwide exploration efforts. Two quite distinct but intertwined paradigms were encompassed by Payton's original publication, and persisted in later summaries by Exxon researchers (e.g. Haq et al., 1987; Posamentier and Vail, 1988; Van Wagoner et al., 1988; Vail et al., 1991; Van Wagoner, 1995). The recognition of *unconformity-bounded sequences* was predicated upon the belief that sequence deposition was controlled by sea-level fluctuations, leading to the concept of systems tracts and the development of what later writers have termed the *sequence stratigraphic model* (SSM). At the same time, it was asserted that an accurate sea-level history could be reconstructed from sequence analysis, leading to the concept of a global sea-level curve, or *global sea-level model* (GSM), which could be applied to the interpretation of continental margin strata worldwide (Vail et al., 1977; Haq et al., 1987).

Much sequence stratigraphic literature fails to distinguish adequately between the SSM and the GSM, to the great detriment of clarity of discussion. Prior recognition of the distinction is in fact fundamental

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Table 1
Commonly used sequence stratigraphic terms, with abbreviations (after Carter et al., 1991; Abbott and Carter, 1994)

Conceptual models	
GSM	Global sea-level model
SSM	Sequence stratigraphic model
Physical surfaces	
SB	Sequence boundary
RS	Ravinement surface
LFS	Local flooding surface
DLS	Downlap surface
Theoretical horizons	
MFH	Maximum flooding horizon
PESH	Peak eustatic sea-level horizon
PRSH	Peak relative sea-level horizon
PB	Parasequence boundary
Systems tracts	
LST	Lowstand systems tract
TST	Transgressive systems tract
CSST	Condensed section systems tract
HST	Highstand systems tract
RST	Regressive systems tract
FRST	Forced regressive systems tract
Shellbeds	
Type C	Barnea/Glossofungites (SB)
Type A	Cross-bedded, coquina (TST)
Type B	In situ, muddy matrix (MCS)
MCS	Mid-cycle (condensed) shellbed
Clinoform features	
SB	Shelf-break
DSB	Depositional shoreline break
CBP	Clinoform breakpoint

to making adequate tests of either model (Carter et al., 1991). This paper provides a summary of the two models, and of contemporary sequence stratigraphic terminology, as a background for the studies of Plio–Pleistocene strata which comprise most of the papers in this special volume. However, the sequence terminology contained in Table 1 represents a personal summation, and the authors of individual chapters have been left free to utilise alternative terms, some more conventional, some less so, where they wished.

2. The global sea-level model

The first model corresponds to the global sea-level model (GSM; Fig. 1), as initially published by Vail et al. (1977) and later modified by Haq et al. (1987). This 'global' curve was derived primarily from the analysis of seismic profiles in terms of unconformity-bound sequences, using techniques explained in Payton (1977), Vail et al. (1991) and Miall (1996). In essence, the GSM curve comprises a prediction (or retrodiction) of the behaviour of eustatic sea-level through time, derived from a globally averaged coastal onlap chart. The GSM is alternatively named the 'global cycle chart' (e.g. Payton, 1977; Miall, 1996).

The GSM displays systematic patterns of sea-level variation at different wavelengths (= timespans; Table 2) (Fulthorpe, 1991). Thus Vail et al. (1977) recognized first, second and third order cycles with timespans ranging between many tens of millions of years for first order cycles to a few million years for third order cycles. Fifth (100 kyr, eccentricity), 6th (41 kyr, tilt) and 7th (20 kyr, precession) order Milankovitch cycles of the Plio–Pleistocene are not usually depicted as part of the Exxon global curve. They are, however, well documented in Plio–Pleistocene oceanic piston-cores and ODP cores, especially those analysed in terms of the standard oxygen isotope stages (e.g. Shackleton and Opdyke, 1973, 1976; Williams et al., 1988; Ruddiman et al., 1989; Raymo et al., 1989; Tiedemann et al., 1994). More recently, 40 kyr (6th order) climatic cyclicity has been recognized back as far as the Oligocene (Zachos et al., 1997). It is, however, not yet clear to what extent this cyclicity was accompanied by matching eustatic sea-level changes prior to about the middle Pliocene.

Compelling evidence exists from both oxygen isotope data, and from studies of modern continental shelf sediments, that the late Cenozoic glacio-eustatic 5th order sea-level cycles typically exceeded 100 m in amplitude. Fourth order cycles were absent from the original GSM (Vail et al., 1977). However, 4th order cycles were later depicted over the early Eocene part of the Haq et al. (1987) version, and were claimed to be widespread through the stratigraphic column by Van Wagoner and Mitchum (1989). Other studies have identified a stratigraphic signature appropriate to 4th order cycles in Eocene and mid-Miocene onland outcrops (Plint, 1988; Kidwell, 1984), and in mid–late Miocene offshore seismic profiles (Fulthorpe and Carter, 1989).

Table 2
The fundamental orders of Phanerozoic sea-level cycle (after Fulthorpe, 1991)

Order	Time-span	Magnitude	Dominant cause	Described by
1st	100 million plus	up to 500 m	Ocean-basin volume changes	Pitman (1978); Kominz (1984)
2nd	5–100 million	up to 5000 m	Thermotectonic subsidence	Vail et al. (1977); Watts (1982, 1989); Carter et al. (1998)
3rd	1–5 million	up to 200 m?	Eustasy/tectonics	Vail et al. (1977); Haq et al. (1987)
4th	0.3–0.6 million	up to 30 m?	Eustasy/tectonics	Kidwell (1984); Plint (1988); Fulthorpe and Carter (1989); Haq et al. (1987); Van Wagoner and Mitchum (1989)
5th	ca. 100 thousand	100–130 m	Glacio-eustasy (eccentricity)	Emiliani (1955); Shackleton and Opdyke (1973, 1976)
6th	ca. 40 thousand	30–100 m	Glacio-eustasy (tilt)	Williams et al. (1988); Abbott and Carter (1994)
7th	ca. 20 thousand	up to ca. 50 m	Glacio-eustasy (precession)	Hays et al. (1976); Tiedemann et al. (1994)
infra-7th	<20 thousand	up to ca. 30 m	Eustasy-sediment supply	Boyd et al. (1988); Anderson and Thomas (1989)

In contrast to 5th and 3rd order cycles, which, respectively, have known and claimed amplitudes of at least 100 m each, 4th order cycles seem to be of much smaller amplitude — at most a few tens of metres, and perhaps as little as a few metres. It is, therefore, apparent that the effects of 4th order cycles will generally only be conspicuous in outcrop in shallow-water basin-margin facies such as those described by Kidwell (1984) and Plint (1988).

2.1. Tests of the GSM

Three fundamental problems are inherent in the current sea-level model:

(1) The precision of the best available means of stratigraphic correlation is inadequate for distinguishing between stratigraphically adjacent sequences worldwide. For example, the resolving power of the most widely used correlation tool throughout the Cenozoic, micropalaeontology, is generally no better than 1 Myr and often much worse (Miller and Kent, 1987; Miall, 1991). Though better discrimination, down to 0.1 Myr, is attainable using biostratigraphy combined with other modern tools such as tephrochronology or magnetochronology (Miller, 1990), such refined techniques are not routinely applied in the great majority of the petroleum exploration studies which form the basis for the current GSM.

For large parts of the Cretaceous and Cenozoic, the GSM predicts the occurrence of a sequence boundary (= global eustatic fall) about every 0.5–3 million years. Given that 1–2 Myr is the minimum uncertainty attached to most real geological correlations, simple statistical analysis shows that the correlations which will always exist between different sections in such circumstances are largely meaningless (Miall, 1992).

(2) The pattern of coastal onlap inferred from seismic profiles, and which is used as the basis for determining the amplitude of the cycles of the ‘global’ sea-level curve, is rarely able to be shown to be a response to eustatic, as opposed to local relative, sea-level rise. (Though Plio–Pleistocene and Permo–Carboniferous strata form obvious exceptions to this generalisation, they only comprise a small part of the time period covered by the current GSM; cf. Fig. 1.) There is of course, a long history of dispute in stratigraphy on precisely this point, i.e. the relative degree to which tectonics or eustasy is the dominant control on ancient, cyclic successions (e.g. Dott, 1992; Dennison and Ettensohn, 1994; Witzke et al., 1996). However, and as Watts (1982, 1989) argued theoretically, and Saul et al. (1998) have confirmed with Plio–Pleistocene examples, it is indisputable that patterns of sedimentary onlap with periodicities of 10^5–10^6 years have tectonic causes within many sedimentary basins. These tectonic cycles result in cycles of local relative sea-level change which overlap precisely in timespan with the 5th through 3rd order cycles of sequence stratigraphy (cf. Table 2). The discussion above, and Table 2, show that the amplitudes of the different orders of sea-level cycle do not form a simple, nested ‘Russian doll’ set, “whereby the SSM applies at any level and the sequence at that level is viewed as forming from a large number of finer sequences of the next higher order” (Carter et al., 1991, p. 45). Given that the present GSM comprises a pastiche of sea-level cycles at all levels between 5th and 2nd order, it is unclear how

such a chart can be derived in systematic fashion, since each larger cycle could be expected to destroy, or at least to dramatically modify, the effects of any smaller scale (lower order) cycles that it subsumes (cf. Drummond and Wilkinson, 1996).

The existence of these problems make it extremely difficult to test the validity of the GSM, not least because mismatches with the established curve can be (and often are) dismissed as due to 'local effects' in the particular basin being studied. In this respect, Tipper (1993) has contributed a thought-provoking analysis of the importance of using tests designed to falsify, rather than to support, the global cycle chart. A number of independent tests of the global universality of the events represented on the Exxon cycle chart have in fact been attempted (e.g. Hubbard et al., 1985a,b; Hubbard, 1988; Carter et al., 1991; Underhill, 1991; Aubry, 1991, 1995). Perhaps not surprisingly, all these authors report significant mismatches between their stratigraphic data and the current GSM (e.g. Fig. 2), i.e. their results falsify one or more parts of the model.

More recently, an ocean drilling transect across the New Jersey continental margin has established that a good match exists between the established mid–late Cenozoic cycle chart and the unconformities and sequences established by the drilling (Miller and Sugarman, 1995; Pekar and Miller, 1996). Such results may seem encouraging, but they need to be tempered by remembering that data from north Atlantic continental margins formed an important input into the derivation of the original 'global' chart. It is for that reason that the current GSM is probably incapable of being tested properly by any amount of further investigation of northern hemisphere margins. Rather, demonstrating the universality or not of the GSM requires investigations in far field southern hemisphere sites, and that whilst bearing in mind the fundamental limitations imposed by the accuracy of current correlation techniques (point 1 above).

With these and other problems in mind, Miall (1996), p. 281) recently concluded that "the Exxon methods . . . are seriously flawed", and that "current chronostratigraphic dating techniques do not permit the level of accuracy and precision claimed for the global cycle charts that have been published by Peter Vail and his former Exxon colleagues". More optimistically, and bearing in mind the positive local results from the New Jersey study of Miller and Sugarman (1995) and Pekar and Miller (1996), perhaps "the Exxon 'Global' sea-level curve, in general, represents a patchwork through time of many different local relative sea-level curves" (Carter et al., 1991, p. 59).

3. The sequence stratigraphic model

The Exxon sequence stratigraphic model (SSM) summarises the idealised stratigraphic architecture of sediment deposited during a single sea-level cycle. An alternative model proposed by Galloway (1989) (after Frazier, 1974) has similar architecture to the original Exxon model, but locates the sequence boundaries along the 'maximum flooding surface' corresponding to successive sea-level highs, rather than along subaerial unconformities corresponding to successive sea-level lows. The difference is largely conceptual, and Galloway's model has not been widely adopted in the literature. SSMs therefore are the result of thought experiments aimed at answering the question: "What stratigraphic architecture results from sediment deposition during a single, sinusoidal cycle of sea-level change on a differentially subsiding continental margin?" The answer was initially formulated as a qualitative model (Fig. 3), though, more recently, many computer-based models have also been created (e.g. Aigner et al., 1990; Lawrence et al., 1990; Franseen et al., 1991; Reynolds et al., 1991; Flemings and Grotzinger, 1996). However, the simple qualitative SSM remains useful and continues to receive wide application despite these later advances.

The Exxon SSM characterises the sediments deposited during a single cycle of eustatic sea-level as belonging to three main, geometrically separate bodies of sediment termed *systems tracts* (Fig. 3; Table 1) (e.g. Vail et al., 1991). The *lowstand systems tract* (LST) comprises sediment deposited at and around a sea-level lowstand, typically but not necessarily when the shoreline is located below the shelf-break. The *transgressive systems tract* (TST) is deposited during the rising part of the relative sea-level cycle, when rapid shoreline transgression occurs, and the *highstand systems tract* (HST) is deposited mostly during and shortly after a sea-level cycle peak. Abbott and

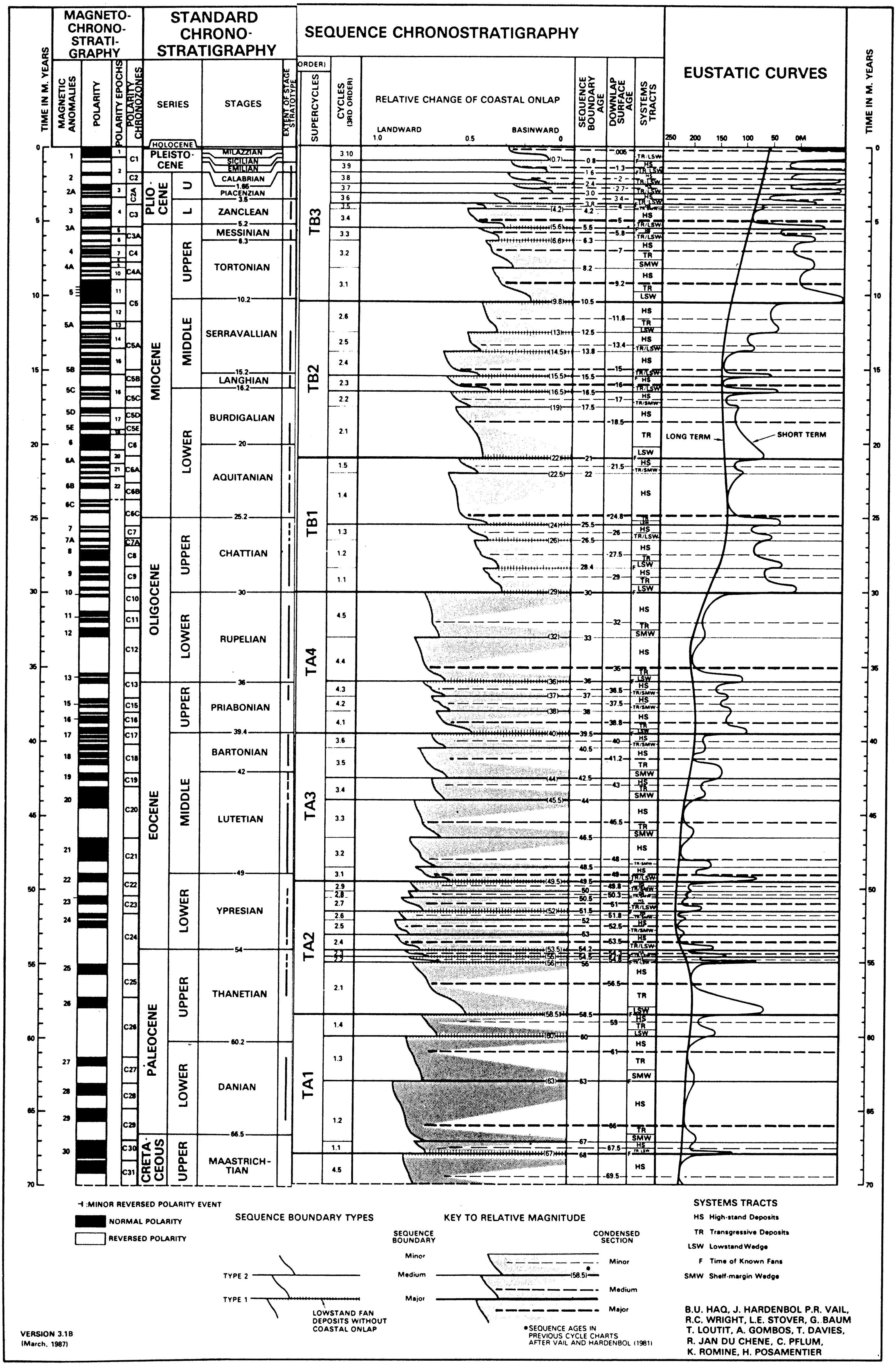

Fig. 1. Global Sea-level model for the Cenozoic (after Haq et al., 1987).

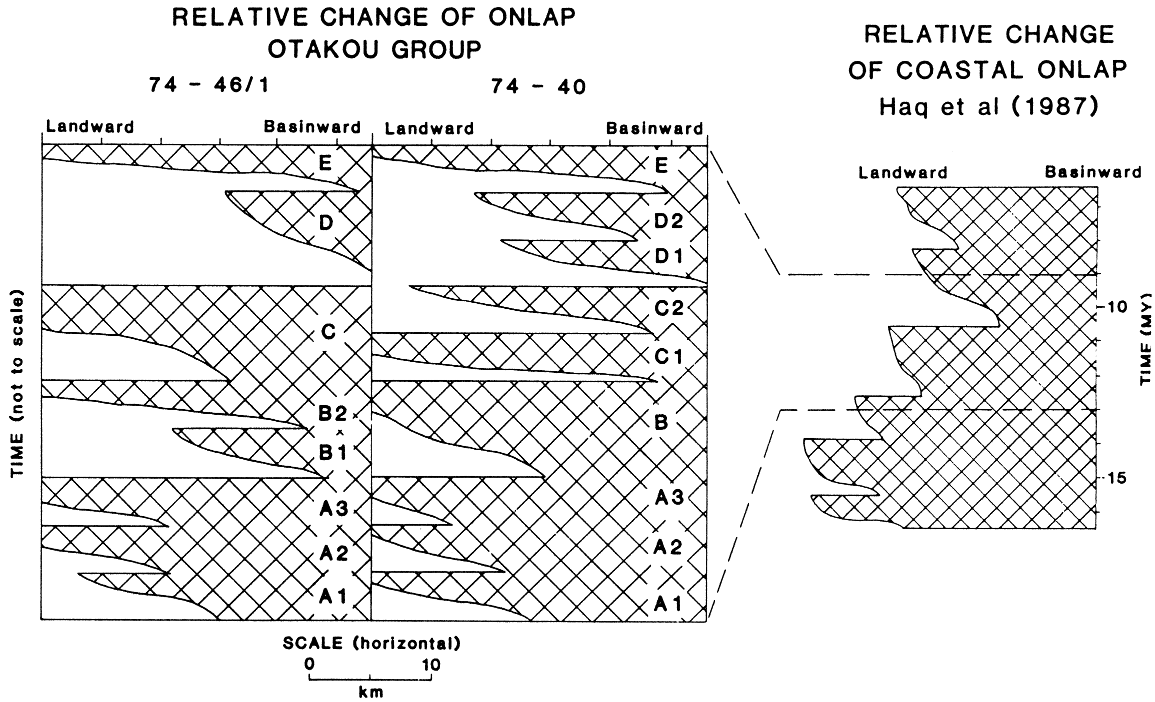

Fig. 2. Comparison of relative change of onlap (= sea-level change) for two closely spaced parallel seismic lines in the Canterbury Basin, New Zealand, with approximate correlation to the mid–late Miocene part of the global sea-level model of Haq et al. (1987). Note the different patterns of onlap for the two lines, and the poor correlation of either with the GSM (after Carter et al., 1991, fig. 4).

Carter (1994) have shown from outcrop studies that a *mid-cycle (condensed) shellbed* marks the transition between the TST and HST in mid-Pleistocene sequences from Wanganui, New Zealand.

In the original manifestation of the SSM, no sediment is deposited on the shelf during most of the falling part of the sea-level cycle, because that is generally a time of erosion. However, given the right balance of rate of relative sea-level fall and rate of supply of sediment, deposition may occur on the shelf during falling sea-level (Hunt and Tucker, 1992, 1995; Posamentier et al., 1992; Kolla et al., 1995; Naish and Kamp, 1997). A *forced regressive systems tract* (FRST; Hunt and Tucker, 1992; falling stage systems tract of Hart and Long, 1996) is recognized when conditions are such that sediments deposited under falling sea-level are bounded below by a *regressive surface of erosion* (RSE; Plint, 1988; Hart and Long, 1996), whereas the term *regressive systems tract* (RST; Naish and Kamp, 1997) applies when regressive deposits shoal gradationally upwards from shelf into shoreface facies and no RSE is present. The ‘shelf-margin systems tract’ (SMST) of Vail et al. (1991) is just a variety of lowstand systems tract produced by a sea-level lowering of insufficient magnitude to have displaced the lowstand shoreline below the contemporary shelf-edge break. In essence, the RST, FRST, SMST and LST occupy theoretically different but overlapping positions on the falling and lowstand parts of an idealised sea-level curve.

In the traditional sequence model, the three main systems tracts (LST, TST and HST) are punctuated by a number of significant stratigraphic surfaces (Fig. 3, Table 1). In ascending outcrop order, these surfaces include:

(1) the *lower sequence boundary* (SB1; a *subaerial unconformity* located landward of the lowstand shoreline, and the lower boundary of the TST, and a *correlative conformity* seaward of the lowstand shoreline, and lower boundary of the LST);

(2) the *transgressive surface* (TS; upper surface of the LST, later renamed the *top lowstand surface* by

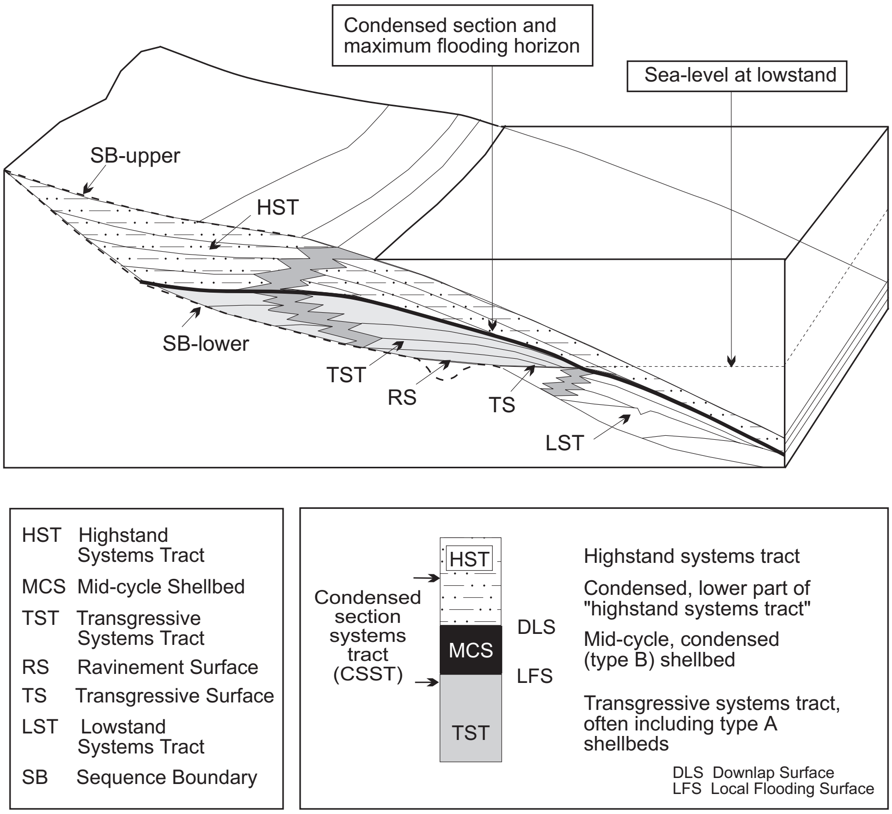

Fig. 3. The conventional sequence stratigraphic model at seismic scale (after Vail and Sangree, 1988), which recognizes a mid-cycle condensed section and maximum flooding surface (= maximum flooding horizon). Inset (bottom right): summary of outcrop scale features of the mid-cycle condensed section, after Pleistocene examples described by Abbott and Carter (1994).

Vail et al., 1991), which passes shorewards into the lowest *ravinement surface* (RS; often superposed on the sequence boundary over much of the transgressed shelf, but preserved as a discrete surface at the base of the TST above the fill of incised fluvial or estuarine channels);

(3) the *maximum flooding surface* (MFS; located near the boundary between the TST and HST);

(4) the *downlap surface* (DLS; located at the base of a seaward downlapping HST); and

(5) the *upper sequence boundary* (SB2). Abbott and Carter (1994) have shown that the MFS is not marked in outcrop by an identifiable surface, i.e. it is a conceptual horizon (cf. also Carter et al., 1998, this volume). Where RSTs or FRSTs are present, alternative arguments can be made for locating the upper sequence boundary either below (Posamentier et al., 1992) or above (Hunt and Tucker, 1992; Van Wagoner, 1995) the RST/FRST and any contiguous LST basin floor fan. I follow Naish and Kamp (1997) in preferring the latter option.

3.1. Tests of the SSM

Though it was developed from an analysis of Exxon 3rd order cycles, it has become apparent that the Exxon SSM is applicable to sediments deposited during any scale of sea-level cycle between the 1st and infra-7th orders inclusive (Carter et al., 1991). Studies in California (Hunter et al., 1984; Clifton et al., 1988), New Zealand (Abbott and Carter, 1994, 1997; Abbott, 1997a,b, 1998a,b; Naish and Kamp, 1997; Saul et al., 1998) and Japan (Tokuhashi and Kondo, 1989; Kitamura, 1991; Ito, 1992; Ito and Katsura, 1992; Kitamura et al., 1994) have demonstrated that the SSM applies particularly well to cyclothemic sediments of Pleistocene age, laid down under the influence of known glacio-eustatic sea-level perturbations.

The Exxon SSM has thus passed the test of comparison with the actual unconformity-bounded sequences that were deposited under the influence of changing eustatic sea-levels during the Plio–Pleistocene. It is therefore an extremely robust paradigm with which to approach the interpretation of sedimentary rocks, as exemplified also by its successful application across the entire Precambrian to Recent stratigraphic spectrum (see, for example, monographs by Berg and Woolverton, 1985; Van Wagoner et al., 1990, 1991; Loucks and Sarg, 1993; Posamentier et al., 1993; Weimer and Posamentier, 1993; Van Wagoner and Bertram, 1995; Van Wagoner et al., 1996; and the extensive literature cited by Miall, 1996). Nonetheless, the application of the SSM to either seismic or field sections is an act of interpretation, not description. Thus a sequence stratigraphic study and systems tract designations should always be in addition to, not serve as a substitute for, the conventional lithostratigraphic and facies description of sedimentary rocks.

4. Summary

The discipline of sequence stratigraphy is primarily concerned with the description of unconformity-bounded packages of strata termed sequences, and with understanding the geological controls which control the deposition of sequences, especially with respect to changing sea-levels. The discipline encompasses two distinct and fundamental paradigms, or models.

(1) The global sea-level model (GSM) comprises a predicted 'global' sea-level curve for the Phanerozoic, derived from the worldwide study of onlap patterns exhibited by stratigraphic sequences. In actual fact, the GSM probably comprises an assembly of local relative sea-level events which were controlled at least as much by tectonics as they were by eustasy. Some such, but not all, sea-level events may have significance beyond the basin or continental margin from which they were first described, and some may indeed even be global. The trick, and it is not easy, is telling which is which.

(2) The sequence stratigraphic model (SSM) comprises a prediction of the stratigraphic architecture which is produced during a single cycle of sea-level change. The SSM corresponds well with the patterns of sedimentary facies changes which occur within the glacio-eustatic cyclothems of the Plio–Pleistocene. It is therefore a robust interpretative tool which can be applied with profit to sedimentary strata of all ages and types.

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