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Sequence concepts at seismic and outcrop scale: the distinction between physical and conceptual stratigraphic surfaces

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Abstract

The sequence stratigraphic terms maximum flooding surface and downlap surface, as currently applied, are ambiguous. Examples of these intra-sequence surfaces are summarised from high frequency mid-Pleistocene sequences and from a Cretaceous–Recent seismic megasequence, both from New Zealand. At any one locality, a mid-Pleistocene sequence contains up to four stratal discontinuities, in ascending order: the sequence boundary, ravinement surface, local flooding surface and downlap surface. These physical surfaces, which occur in outcrop, are regionally diachronous and should be differentiated from theoretical isochronous horizons such as the time of maximum flooding (horizon corresponding to maximum shoreline transgression) and the time of peak eustatic or local relative sea-level (horizons corresponding to the highpoint of the eustatic and relative sea-level cycles, respectively). In seismic studies, the boundary between the transgressive and highstand systems tracts is usually located at the downlap surface. On the basis of a major thermo-tectonic sea-level cycle in the Canterbury Basin, it is shown that the downlap surface is not a single regional surface, and that the change in slope associated with toes of successive prograding clinoforms rises in stratigraphic height basinwards. The downlap surface therefore does not usually coincide with the maximum flooding horizon. In Plio–Pleistocene cyclothems, a discrete unit — the mid-cycle shellbed — straddles the contact between the transgressive and highstand systems tracts. This unit might be classified within its own systems tract (the condensed section systems tract; CSST). Alternatively, the position of the boundary between the transgressive and highstand systems tracts can remain unspecified or unknowable.

Keywords: sea level; sequence stratigraphy; eustasy; cyclothem

1. Introduction

Modern concepts of sequence stratigraphy grew out of the analysis of seismic reflection profiles of sedimentary basins during the 1960s and 1970s, particularly within the oil company EXXON. The first account of the principles and procedures of the method appeared in Payton (1977). Influential later treatments include those of Vail (1987), Vail and Sangree (1988), Van Wagoner et al. (1988, 1990), Wilgus et al. (1988) and Vail et al. (1991). These and other studies showed that unconformity-bound packets of sedimentary strata, termed sequences, occur on continental margins world wide. It was asserted also that global sea-level, or eustasy, was the controlling

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factor on the development of such sequences, and that a sea-level signature could be measured directly from seismic sections. The focus of much related research was therefore the derivation of what has become termed the global sea-level curve (Vail et al., 1977; Haq et al., 1987).

The technique of sequence stratigraphic analysis and the derivation of sea-level curves from that analysis are operations which are logically distinct from each other. Recognition of this distinction encourages the separation of description from inference, and thereby helps avoid confusion (Carter et al., 1991; Carter, 1998). The terms *sequence stratigraphic model* (SSM) and *global sea-level model* (GSM) are useful descriptors for the theories which underpin sequence analysis and the inferred sea-level curve, respectively. The present paper is concerned exclusively with the sequence stratigraphic model. The model is discussed in relationship to studies of Pleistocene cyclothems from Wanganui (New Zealand) deposited during known 5th (100 ky) and 6th (40 ky) order Milankovitch sea-level cycles, and of a Cretaceous to Recent, 1st order, 80 My long, thermo-tectonic cycle from the Canterbury Basin (New Zealand). It is probable that the insights gained are directly applicable to 4th and 3rd order cycles of the Vail type, but demonstrating that this is so continues to be hindered by our lack of independent knowledge of the pre-Plio–Pleistocene sea-level pattern.

2. The sequence stratigraphic model

The SSM (Fig. 1) is the result of a thought experiment aimed at answering the question: "What

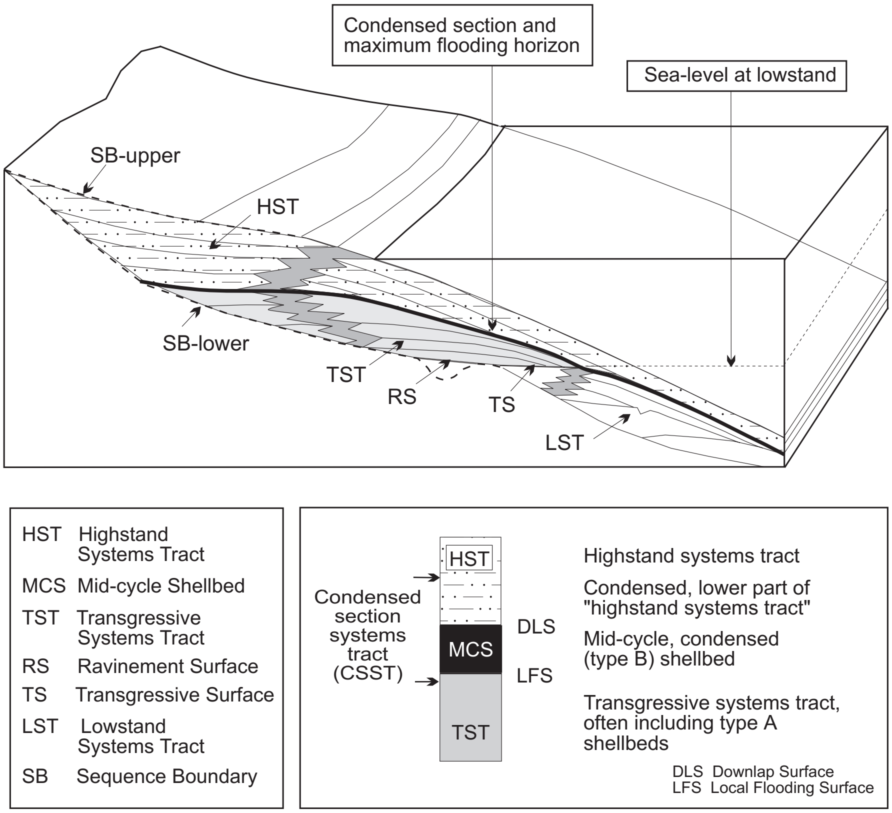


Fig. 1. The conventional sequence stratigraphic model at seismic scale (after Vail et al., 1991), which recognizes a mid-cycle condensed section and maximum flooding surface (= maximum flooding horizon). Inset (bottom right): outcrop scale summary of the mid-cycle condensed section, after Pleistocene examples described by Abbott and Carter (1994).

stratigraphic architecture results from sediment deposition during a single, sinusoidal cycle of sea-level change on a differentially subsiding continental margin?". The model is outlined in Carter et al., this volume. There is general agreement that the basis for the model is the existence of unconformity-bounded *sequences* which can usefully be subdivided into *systems tracts* bounded by important stratigraphic *surfaces*. There is, however, much less agreement regarding the ways in which particular systems tracts or surfaces are recognised or defined. Many sequence stratigraphic terms, for example 'downlap surface' and 'maximum flooding surface', carry theoretical overtones, even though they originated from real features which were observed on low-resolution seismic sections (e.g Payton, 1977). Such terms are therefore inherently ambiguous when applied to high-resolution seismic or outcrop data. The purpose of this paper is to discuss and help clarify these ambiguities.

2.1. Significance of the condensed section and mid-cycle shellbed

In the SSM, the locus of terrigenous deposition is displaced landward during the period of rapid relative sea-level rise and the supply of sediment offshore is therefore restricted at the time of maximum transgression. Slow pelagic to hemipelagic deposition results over much of the basin and a mid-cycle condensed section is developed. According to Haq et al. (1987), Van Wagoner et al. (1988) and Baum and Vail (1988), the condensed section encompasses both the top of the transgressive systems tract and the base of the overlying highstand systems tract. Abbott and Carter (1994) and Abbott (1997) have shown that a *mid-cycle shellbed* (MCS) marks the major part of the condensed section in Pleistocene 5th and 6th order sequences in the Wanganui Basin, New Zealand (Fig. 1, inset).

Seaward progradation of the HST across the sediment-starved, 'drowned' seafloor commences as the rate of relative sea-level rise decreases and/or the rate of sediment supply increases to fill the available accommodation. Sedimentation rates at the toe of HST prograding clinoforms therefore commonly remain low, and this part of the section constitutes a continuation of the condensed section (Baum and Vail, 1988 their fig. 13). The mid-cycle condensed section is of particular importance to stratigraphic correlation since it often provides an interval of increased planktonic and benthonic microfossil abundance within sequences, and thereby permits accurate age determination (Loutit et al., 1988). In addition, the condensed section has characteristics that make this interval easily recognizable in outcrop and in well logs, as well as on seismic profiles where it is marked by downlapping stratal terminations (Haq et al., 1987; Galloway, 1989). These characteristics include marine hardgrounds and other evidence of omission surfaces, calcareous sediments including shellbeds (Abbott and Carter, 1994), authigenic minerals such as glauconite, and high organic matter (Loutit et al., 1988). The condensed section has been used by Galloway (1989) as an alternative location for the sequence boundary, in part because of this ease of recognition.

2.2. Historical usage of the terms maximum flooding surface and downlap surface

Many of the concepts and terminology of sequence stratigraphy arose from the study of seismic profiles with a stratigraphic resolution of, at best, several tens of metres (e.g. Payton, 1977). Definitions of sequence stratigraphic terms for features associated with the transition from TST to HST, i.e. with the condensed section, have been correspondingly ambiguous. Confusion has arisen from practitioners adopting different interpretations of terms such as transgressive surface, maximum flooding surface, surface of maximum starvation and downlap surface. The application of sequence stratigraphy to high-resolution seismic and outcrop studies (e.g. Tokuhashi and Kondo, 1989; Embry, 1990; Kitamura and Kondo, 1990; Ito, 1992; Abbott and Carter, 1994; Naish and Kamp, 1997) has highlighted the need for a precise and uniform terminology. It is particularly important to distinguish clearly between the *theoretical chronostratigraphic horizons* of the SSM (Fig. 1) and *actual physical surfaces* which are observable in outcrop (Fig. 2).

Successive writers have treated the maximum flooding surface (MFS) in different ways. For instance, one possible view of the MFS is that it coincides with the time of inflection on the rising

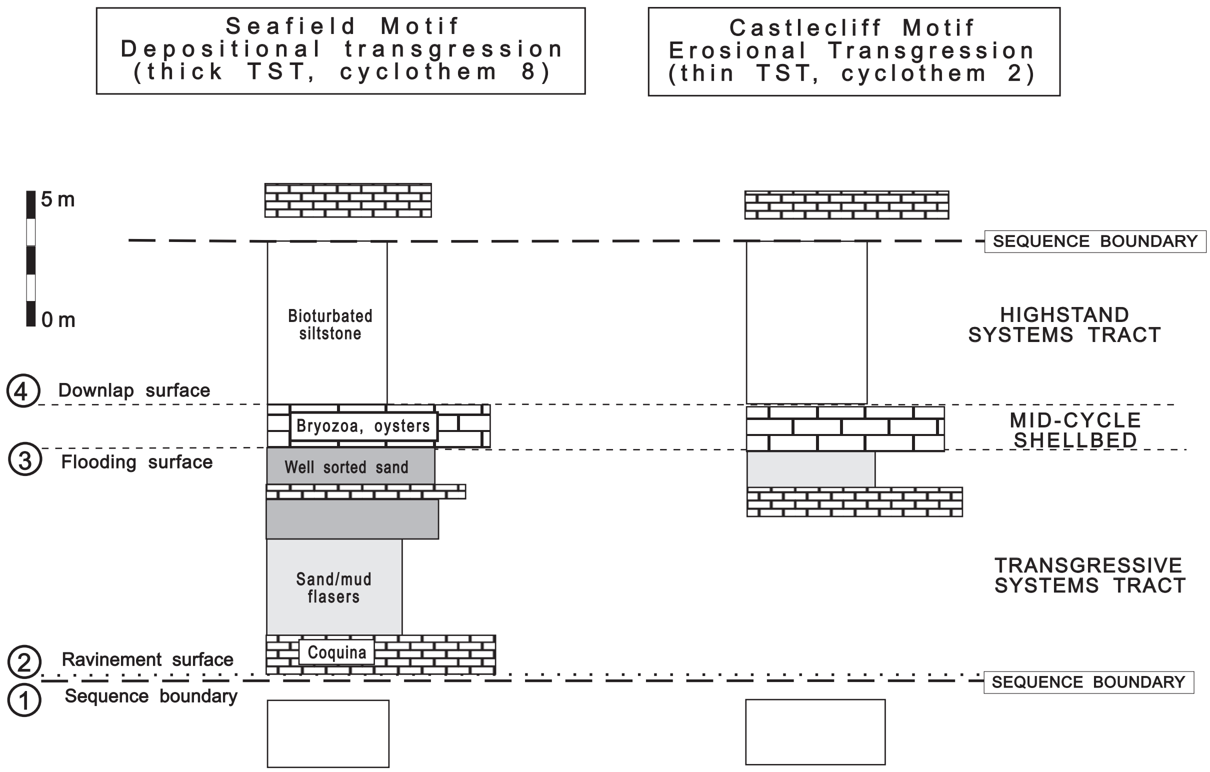


Fig. 2. Cyclothems from the mid-Pleistocene of Wanganui, New Zealand. Note that these cyclothems were deposited in highstand water depths of ca. 30–50 m, and do not display a maximum flooding 'surface'. Instead, a mid-cycle shellbed (MCS) is bounded above and below by a downlap surface (DLS) and a local flooding surface (LFS), respectively (after Carter et al., 1991).

limb of a sinusoidal eustatic curve; i.e. is located at the point of change from an increasing to a decreasing rate of sea-level rise, coincident with rapid shoreline transgression across the shelf (Vail and Sangree, 1988, p. 15). More commonly, however, writers have treated the MFS as the surface marking "the change from a retrogradational to an aggradational parasequence set" (Van Wagoner et al., 1988, p. 44), "the surface of maximum starvation (which) represents the interval of time of maximum landward extent of the condensed section" (Baum and Vail, 1988, p. 319), or implied its equivalence to the seismic downlap surface (Baum and Vail, 1988, p. 319; Loutit et al., 1988, fig. 9). Later still, the MFS has been described as "the physical boundary between the transgressive and highstand systems tract" (Vail et al., 1991, p. 625). The MFS is shown on many chronostratigraphic charts as a time horizon, and some authors have implied also that the boundary between the transgressive and highstand systems tracts is generated *at the time* of maximum transgression (Posamentier et al., 1988; Christie-Blick, 1991).

Seismic profiles commonly show seaward-prograding clinoform reflections within the highstand systems tract, which downlap onto underlying sediments, leading to use of the term *downlap surface* (DLS). Van Wagoner et al. (1988) followed conventional seismic stratigraphic practice in treating the DLS as equivalent to the transgressive/highstand systems tract boundary, and went on to equate the surface also with both the MFS and the change from a retrogradational to an aggradational reflector. The term DLS has also been applied to outcrop sections. For example, Loutit et al. (1988) treated the DLS as defining "a surface associated with condensed sections that formed during a period of nondeposition or extremely slow sedimentation", adding that, in outcrop, the DLS was often represented by an omission surface.

Clearly, many different concepts are here muddled. Confusion inevitably results, partly because of the mixing of interpretative and descriptive terms, and partly because of the very different scales of deep seismic and outcrop studies. The combination of observations from different parts of a sedimentary basin (in the dip direction) is a further source of ambiguity.

2.3. A more precise terminology for theoretical mid-cycle surfaces and related unconformities

Interchangeable use of DLS, MFS and time of maximum transgression may be acceptable at low-resolution seismic scale, but leads to confusion if applied to outcrop or high-resolution seismic data. At the scale of chronostratigraphic charts based on 3rd order cycles, 'surfaces' such as the MFS and DLS may be considered to form 'instantaneously' at the time of maximum transgression, but in fact flooding and downlap surfaces are diachronous across a basin at high-resolution.

In studies of mid-Pleistocene 5th and 6th order sequences, Abbott and Carter (1994), following Embry (1990), have recognized the occurrence of four significant physical surfaces within inner-mid shelf sequences (Fig. 2). These surfaces are:

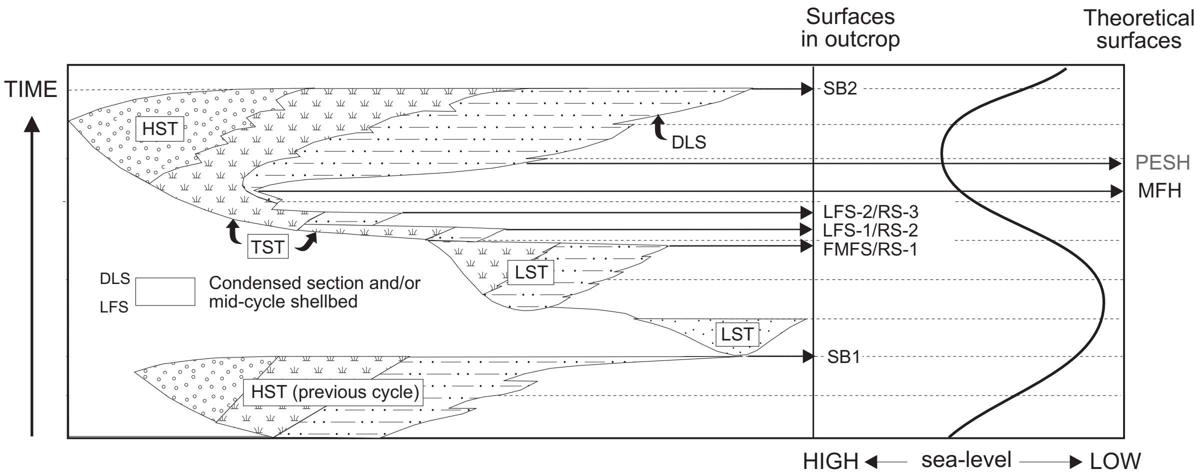
Upper sequence boundary		SB2
Highstand systems tract	HST	
Downlap surface		DLS
Mid-cycle shellbed	MCS	
Local flooding surface		LFS
Transgressive systems tract	TST	
Ravinement surface		RS
Lowstand systems tract	LST	
Lower sequence boundary		SB1

The RS is equivalent to the marine erosion surface of Thorne and Swift (1991) and the transgressive surface of erosion of Bhattarcharya (1993), and the LFS is equivalent to the submarine unconformity of Embry (1990), and part of the marine flooding surface of Van Wagoner et al. (1990) and Bhattarcharya (1993). The LFS at a particular location represents seafloor drowning and terrigenous sediment starvation, and is caused by rapid recession of the shoreline and its shore-connected sediment wedge.

In the sense used by Abbott and Carter (1994), the SB, RS, LFS and DLS each correspond to a physical sedimentary surface that can be located in the field. In some locations, depositional processes cause two or more surfaces to become superposed, as commonly are the RS and SB1. For the Wanganui Pleistocene shelf sequences, TST strata lie between the RS and the LFS, the MCS lies between the LFS and the DLS, and the HST occurs between the DLS and the overlying SB. Sediment between the LFS and DLS corresponds to the mid-cycle shellbed of Abbott and Carter (1994) (cf. also Kidwell, 1989), a discrete unit which spans the junction of the TST and HST, and in Pleistocene shelf examples comprises the main part of the condensed section (cf. Fig. 2).

In the Pleistocene examples described by Abbott and Carter (1994), the breaks associated with the SB, RS and LFS are sharp, often erosive and often bored or burrowed, i.e. these surfaces represent unconformities. In other, Pliocene, examples from New Zealand, TST sands may pass gradationally up into the MCS (Naish and Kamp, 1997), or the MCS may be absent altogether (Haywick et al., 1992), indicating that in these cases flooding took place more slowly, and/or the presence of a greater sediment supply. The contact above the MCS, interpreted as the DLS, is usually rapidly gradational, and probably represents a sedimentation rate change (from bypassing or an extremely low rate of terrigenous supply to a slightly higher rate of terrigenous supply) rather than an unconformity in the strict sense. As the transgressing shoreline moves across the shelf, marine erosion results in the development of successive RSs, above which may be developed thin (lagged) TST deposits. The 'regional RS' is therefore time transgressive. The SB itself is also a diachronous surface which takes time to form. However, and in distinction to the RS, LFS and DLS, time-lines never cross a sequence boundary, in the sense that all sediments above it are younger than all sediments below it (Nummedal and Swift, 1987).

In distinction to the *physical surfaces* just defined, each of which may be diachronous across a basin, it is useful to recognize also two important *theoretical isochronous horizons*, elements of each of which have been implicit in previous authors' use of the term maximum flooding surface (Fig. 3). From here on, we deliberately use the word horizon as a



Time-stratigraphic diagram of a sequence deposited during a single sinusoidal eustatic sea-level cycle. Note the *diachronous nature* of the major surfaces which provide the physical stratigraphic framework in each vertical section: the sequence boundaries (SB1, SB2), ravinement surfaces (RS1–3) and first marine and local flooding surfaces (FFS and LFS1–2), and downlap surfaces (DLS). In contrast, the maximum flooding horizon (MFH) and peak eustatic sea-level horizon (PESH) are *theoretical isochronous surfaces* which correspond, respectively, to the level of maximum landward advance of the shoreline and to the peak of the sea-level curve. Particular local flooding surfaces pass into ravinement surfaces near the basin margin.

pragmatic means of distinguishing these theoretical stratigraphic levels from the actual *outcrop surfaces* just described.

The *maximum flooding horizon* (MFH) is equivalent to the *maximum flooding surface* (MFS) of many previous writers. We define the MFH as the isochron within a sequence which corresponds to the moment of maximum flooding of the adjacent landmass (cf. Posamentier et al., 1988, p. 115; Thorne and Swift, 1991, p. 213). As such, the MFH (a) equates in time to the most landward position reached by the shoreline within a cycle; (b) lies close to the change from landward stepping parasequence sets to seaward prograding parasequence sets; (c) may precede the time of the peak eustatic sea-level in basins with a high rate of sediment supply, or follow the peak in basins where the subsidence rate exceeds the initial rate of eustatic fall; (d) will coincide with different isochrons on different cross-sections, depending upon varying rates of sediment supply and subsidence throughout a basin; and (e) is not usually marked by an unconformity in outcrop, where it may occur at any level within the mid-cycle condensed section, i.e. somewhere between the local flooding surface and a position low in the highstand systems tract.

The *peak eustatic sea-level horizon* (PESH) is the isochron within a sequence which corresponds to the eustatic sea-level highstand peak. As such, the PESH (a) may lie below, within or above the mid-cycle condensed section, depending upon local sediment supply and subsidence conditions; (b) will occur later in time than the MFH where rate of accommodation decrease caused by sediment supply exceeds accommodation generation caused by sea-level rise; (c) will occur earlier in time than the MFH when subsidence (accommodation generation) outstrips the rate of eustatic rise and early fall; (d) by definition corresponds to the same isochron at all locations within a basin; and (e) is not usually marked by an unconformity in outcrop, where it may occur at any level within or near the mid-cycle condensed section.

Both the MFH and PESH differ from the *peak relative sea-level horizon* (PRSH), which corresponds to the level of maximum palaeo-depth within a sequence at a particular location. The PRSH comprises a locatable stratigraphic level that lies at different horizons at different places within the basin, depending upon the local conditions of subsidence, sediment supply and eustasy. However, for the high frequency eustatic cycles of the Plio–Pleistocene, and given low subsidence rates, the PESH and PRSH may effectively coincide over wide areas of a basin (cf. Haywick and Henderson, 1991).

It should be stressed that the MFH, the PESH and the PRSH cannot be located by simple outcrop inspection since none of them necessarily correspond to any of the main physical surfaces distinguished in high-resolution sequence studies.

The MFH, and in some cases the PESH, will correspond with a physical RS/LFS only on the most inshore part of the shelf at the moment just before the TST/HST turnaround (cf. Larcombe and Carter, 1998). For all locations further offshore, the MFH and PESH will be separated from the LFS by a thin layer of mid-cycle condensed sediment, i.e. in many cases the two theoretical horizons will lie within the mid-cycle shellbed, becoming located higher above the LFS the further offshore the location (cf. Abbott and Carter, 1994, their fig. 11). In general, therefore, at offshore locations the MFH and PESH will lie close together at some level within the condensed section, which includes the uppermost TST, the MCS, and the lower part of the HST (Haywick and Henderson, 1991; Abbott and Carter, 1994).

2.4. Progradational paracycles in the TST, and the TST/HST turnaround

At any moment in a transgressive cycle the shoreline complex comprises three interlinked sediment prisms (Nummedal and Swift, 1987; Thorne and Swift, 1991), namely (Fig. 4):

Ravinement surface

  Beach/shoreface prism
Minor erosion surface 2

  Estuarine/lagoonal prism
Minor erosion surface 1

  Coastal plain prism
Lower sequence boundary

The minor erosion surfaces which punctuate such a succession may potentially be preserved in outcrop, associated, respectively, with an inner seaward-facing (MES-1) and outer landward-facing (MES-2) beach within a coastal estuary or lagoon [paralic shorefaces of Demarest and Kraft (1987); and inlet ravinement surfaces of Allen and Posamentier (1993)]. Wave-base erosion at these shorefaces may produce cross-bedding, concentration of coarser sediment and sometimes shell lags.

As such a sedimentary system migrates landwards, if it progresses steadily and remains largely closed — that is, reworks its sediment as it moves — it leaves behind on the shelf a ravinement surface overlain by only a thin TST [a situation termed erosional transgression by Demarest and Kraft (1987) and corresponding to 8 out of 10 of the Wanganui cyclothems, Fig. 2 right; Abbott and Carter, 1994]. However, should pauses occur during the transgression, or the sediment supply increase so that progradation temporarily occurs, a thicker TST in the form of one or more progradational parasequences will develop [depositional transgression of Demarest and Kraft (1987) corresponding to 2 out of 10 Wanganui cyclothems, Fig. 2 left; Holocene examples cited in Nummedal and Swift (1987)]. The formation and preservation of such parasequences depends largely upon the balance between the slope of the ravinement surface (=substrate), the rate of sea-level rise, the rate of sediment supply, and the energy of erosion of waves at the shoreface (Davis and Clifton, 1987; Cant, 1990; Thorne and Swift, 1991).

The preservation of progradational parasequences near the turn-around point of a sea-level cycle may lead to great complexity in recognizing the boundary between the TST and HST (Fig. 5; cf. Larcombe and Carter, 1998). At seismic scale, the Vail model locates the TST/HST contact at the change from landward-stepping (onlapping) reflectors to seaward prograding clinoform reflectors, a convention that we discussed earlier. At outcrop scale, however, the situation is more complex, for two reasons. First, internally progradational parasequences may occur anywhere within a TST which — at seismic scale — still shows landward-stepping geometry. Second, it may not always be possible to distinguish between the last parasequence of the TST and the first parasequence of the HST, since both are internally progradational (e.g. parasequences P^2 and P^3 of Fig. 5). Parasequences are bounded by some combination of SB–earlier RS–earlier LFS below, and later RS–later LFS above (Fig. 5B). The shoreline at the base of the first HST parasequence is by definition located landward of that at the top of the last TST parasequence, and the initiation of the HST parasequence therefore marks the time of maximum flooding (MFS) and youngest RS–LFS coincide at its base (RS^3–LFS^3 of Fig. 5). It is also conceivable, however, that a particular in-

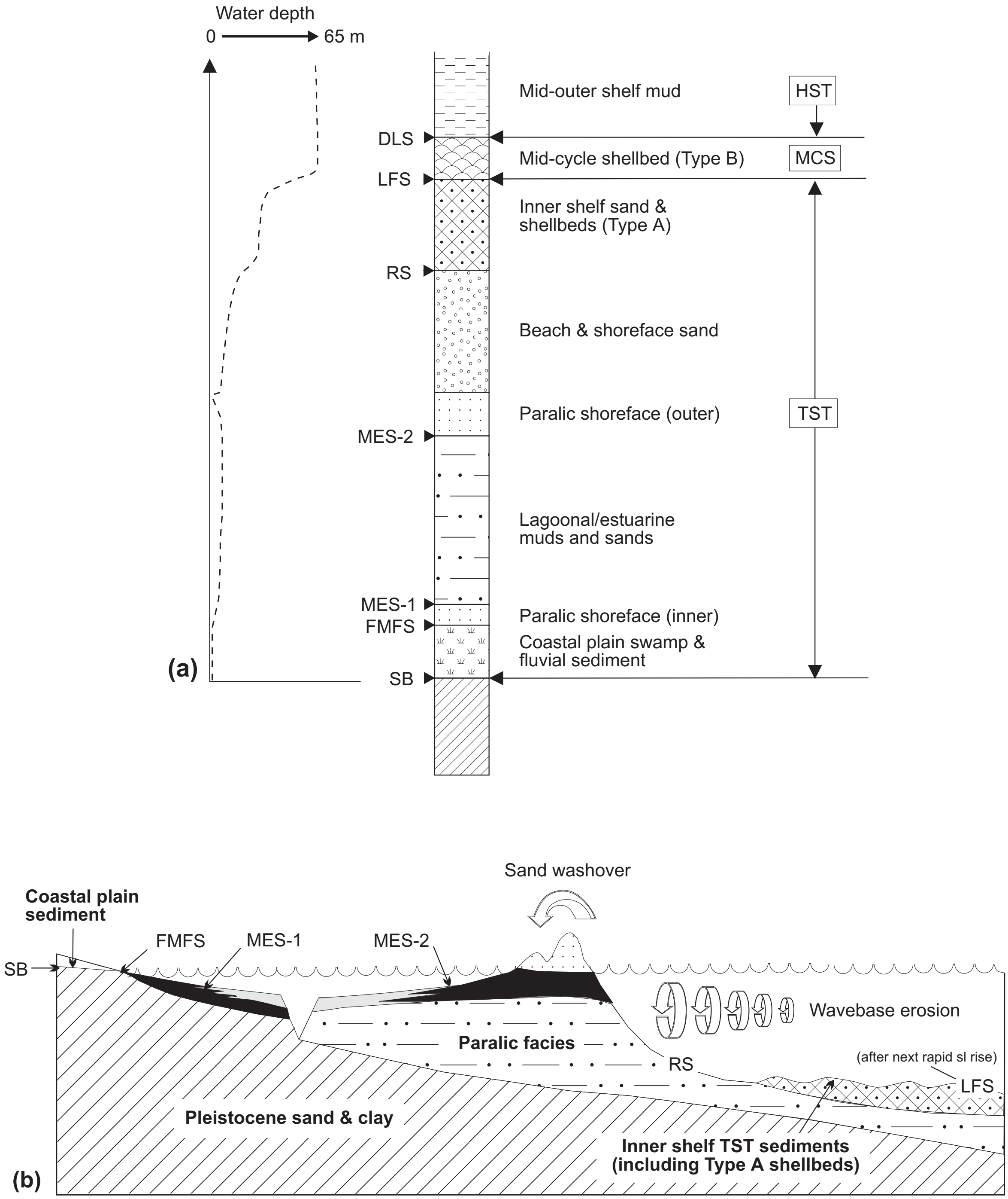


Fig. 4. (A) Homotaxial succession that will be left after the landward passage of the shoreline and inner shelf of (B). (B) Stratigraphic interpretation of a transgressing shoreline (for meaning of abbreviations, see text). After original diagrams by Swift (1976) and Demarest and Kraft (1987).

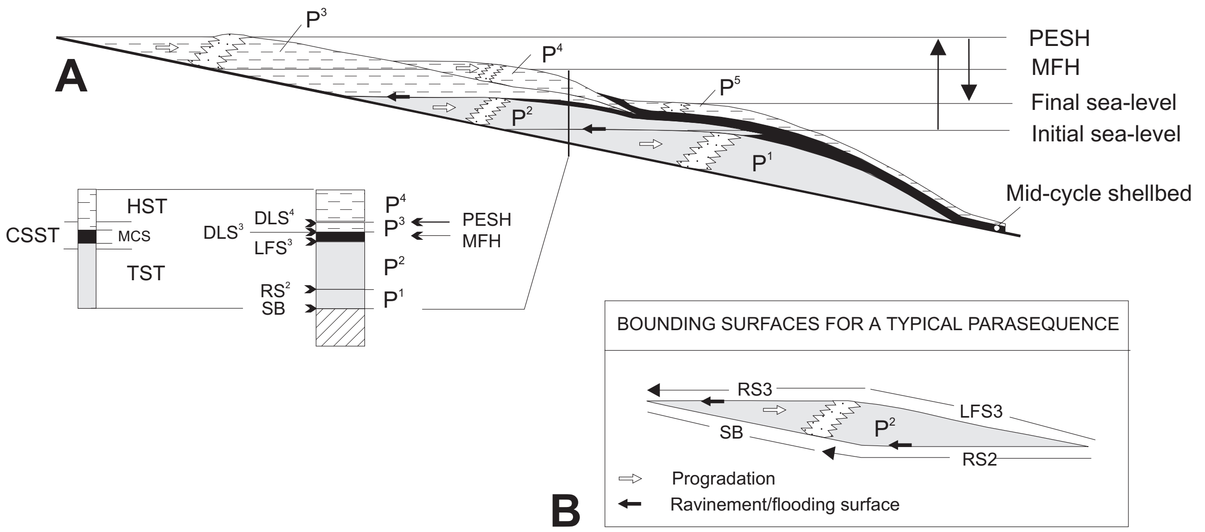


Fig. 5. (A) Detailed parasequence configuration near the point of turnaround of a transgressive and highstand systems tract, with (B) inset cartoon summarising the disposition of surfaces which bound a typical parasequence. The figure illustrates the impossibility of locating a basin-wide maximum flooding surface in outcrop. At landward locations, RS3/LFS3 lie at the boundary between TST and HST sediment. Further seaward, the equivalent chronostratigraphic horizon lies within the MCS, at a distance above LFS2 that is dependent on the rate of sedimentation within the condensed section. Though a flooding surface contemporaneous with LFS3 theoretically exists at more seaward locations, the prominent flooding physical surface at such outcrops is LSF2, which is an unrelated older surface WITHIN the TST. One solution to this dilemma is the recognition of a condensed section systems tract (CSST, left).

teraction of rates of sediment supply, subsidence and eustasy could cause the MFS to lie within a single parasequence, particularly if the deposition of that parasequence straddled the PESS.

2.5. The boundary between the transgressive and highstand systems tracts

Vail et al. (1991) (pp. 622–623) treated the boundaries between systems tracts as idealized isochronous surfaces which — though commonly coinciding with changes in seismic scale onlap/offlap pattern — nonetheless do not everywhere coincide with marked physical surfaces. Different, and inconsistent, definitions of systems tracts occur elsewhere in the literature. For instance, Van Wagoner et al. (1990) (p. 22) first accept an earlier definition of systems tracts as comprising “a linkage of contemporaneous depositional systems” (implying chronostratigraphic significance), but then (op. cit., p. 23) maintain that “lowstand and highstand (systems tracts) . . . do not indicate a period of time or position on a eustatic or relative cycle of sea-level”. However, Martinsen and Helland-Hansen (1994) are in no doubt that “in sequence-stratigraphic theory, specific stacking patters (which define systems tracts) are tied to specific sectors of the sea-level curve”. Thus ambiguity exists as to whether systems tracts are physical entities (analogous in that respect to lithostratigraphic formations), or are bounded by isochronous surfaces (and then analogous to chronostratigraphic stages). Van Wagoner (1996) has presented a detailed account of the way these two contrasting usages each grew out of the pioneering Exxon sequence studies. The ambiguity that attends the definition of systems tracts has been reinforced for us during the writing of this paper, in that each of the two referees argued strongly in favour of one of these two alternative usages!

Bewildering it may be, but stemming from this and earlier discussion, there are at least six alternative ways of defining the critical systems tract boundary between the TST and HST.

2.6. Option 1: Systems tracts as lithologic bodies, defined by their stratal geometry

If systems tracts are defined on the basis of their stratal geometry, then the boundaries which separate them should correspond to observable surfaces. In seismic studies, the turnaround from onlapping TST to offlapping HST strata corresponds to the DLS, which therefore marks the TST/HST junction (Van Wagoner, 1996). High-resolution outcrop studies (Abbott and Carter, 1994; Naish and Kamp, 1997) reveal that the DLS is marked by a sharp lithologic change between a mid-cycle shellbed ('condensed section') and overlying massive siltstone (basal 'HST').

2.6.1. Advantages

The pragmatist's solution; applicable after a fashion to both seismic and outcrop study.

2.6.2. Disadvantages

Inelegant when applied to high resolution studies; in particular, results in the incorrect classification of the mid-cycle shellbed as entirely TST.

2.7. Options 2–4: Systems tracts as chronostratigraphic bodies, bounded by isochrons related to the contemporary sea-level curve

If systems tracts are defined on the basis of their relationship to a contemporary sea-level curve, then three alternatives exist for the TST/HST boundary. The boundary could be defined as equivalent to the isochron of the MFH, the PESH, or the PRSH. In none of these cases would the boundary correspond to a physical surface across a basin, and detailed geochemical or faunal studies would generally be required to locate it in individual outcrop successions.

2.7.1. Advantages

The idealist's solution; logically consistent between outcrop and seismic, at least in principle.

2.7.2. Disadvantages

Largely impractical; requires detailed studies in outcrop, and is difficult to apply to seismic studies.

2.8. Option 5: Systems tracts as fuzzy sets, based on lithostratigraphy but in some cases allowing indeterminate boundaries

The systems tracts recognized from Plio–Pleistocene sequences in New Zealand each correspond to a distinctive set of lithologies, and they are separated by surfaces of recognizable significance in terms of inferred sea-level behaviour. The boundary between the TST and HST lies in the vicinity of the MCS, which accumulated during the late rise, the highstand peak and probably in some cases the early fall of sea-level. A clear TST is recognizable below the MCS, and an HST above. Therefore the boundary between these two systems tracts lies at some indeterminate level close or within the MCS, and the TST and HST have a fuzzy boundary in outcrop. However, because the MCS is generally <1 m thick, at seismic scale an apparently clear TST/HST contact will occur, separating onlapping TST below from prograding HST above.

2.8.1. Advantages

Does not force an interpretation onto observations that cannot sustain it.

2.8.2. Disadvantages

Intellectually unsatisfying to some.

2.9. Option 6: Introduction of a new mid-cycle systems tract, the condensed section systems tract

The MCS is a discrete lithologic unit which occurs between undoubted TST and HST, is usually bounded above and below by distinct boundaries (the DLS and LFS, respectively), and which can be interpreted in terms of sea-level control. It could therefore be elevated to systems tract status (e.g. Abbott and Carter, 1994). Though MCSs have not been widely described from other than Plio–Pleistocene strata, mid-cycle condensed sections are identified in most sequence studies, and the term condensed section systems tract (CSST) would therefore be appropriate.

2.9.1. Advantages

Provides a clear and generally unambiguous solution to the problem; neutral with respect to seismic application (since the CSST is generally too thin to be resolved).

2.9.2. Disadvantages

Proliferation of nomenclature; may be difficult to apply outside the Plio–Pleistocene and Permo–Carboniferous.

There is no obvious, or 'right', choice to make between these six alternative definitions of the TST/HST boundary, since each method of defining the contact can be justified from one point of view or another. Without doubt, however, the pragmatic solution of treating the DLS as the TST/HST contact (option 1 above) is currently widespread, especially in the petroleum exploration industry. Those who adopt such a usage need to be aware of the logical inconsistencies that it entails when applied in high resolution studies.

Because of the history in seismic studies of identifying the TST/HST boundary with parasequence geometry, where possible we prefer to treat systems tracts as bodies of strata bounded above and below by demonstrable sedimentologic discontinuities. These discontinuities are manifest on low-resolution seismic profiles as reflector discordances (e.g. onlapping reflectors in a transgressive systems tract, prograding clinoform reflectors in a highstand systems tract), and in outcrop as discernable surfaces (e.g. the sequence boundary and local flooding surface which bound the transgressive systems tract below and above, respectively). We therefore prefer either solution 6 above, and the recognition of a discrete condensed section systems tract (CSST), or solution 5, which allows an indeterminate boundary between the TST and HST.

3. The downlap surface in a seismic megasequence from the Canterbury Basin

As is evident from the earlier discussion, at the typical resolution of a multichannel seismic profile, the main sequence unconformities (SB, RS, LFS and DLS) and the two main theoretical horizons (MFH and PESH) may become coincident within a single reflector. From this stems the common practice of using the terms MFS (= MFH) and DLS interchangeably in some seismic studies. However, an example is given below, from the Canterbury Basin, New Zealand, where clear separation of these differing surfaces is achieved on seismic records, thus mirroring at a lower order of sea-level cycle the stratigraphic architecture previously only documented for 5th and 6th order Pleistocene sequences.

The Canterbury Basin, in eastern New Zealand (Fig. 6), exhibits a simple rift-drift stratigraphy developed since the late Cretaceous rifting associated with establishment of the mid-Pacific Rise. The sedimentary geometry revealed by multi-channel seismic profiles is analogous to that of the sequence stratigraphic model, but on the longer time scale of a first order thermo-tectonic relative sea-level cycle (Carter et al., 1991; Fulthorpe, 1991). Three distinct intervals can be recognized during which contrasting, large-scale sedimentary processes operated. Rift-fill and marine transgression occurred during the late Cretaceous and early Cenozoic, marked by onlapping reflectors (mega-TST). Maximum regional transgression occurred during the Oligocene, with the development of a basin-wide, condensed, greensand/limestone interval associated with regional paraconformity, the Marshall Paraconformity (Carter, 1985) (mega-condensed interval). Clinoform progradation and regression (mega-HST) occurred from the early Miocene, driven by sediment supply from an evolving Australian/Pacific plate boundary in the west. In this megasequence, the mid-cycle condensed interval lasted up to 15 my (mid-Oligocene to early Miocene) and encompasses the regional Marshall Paraconformity within it (Fulthorpe et al., 1996).

Seismic profiles from the centre of the Canterbury Basin demonstrate that downlap of mega-HST clinoforms occurs at progressively higher stratigraphic levels in the basinward direction, as successive clinoforms prograde over previously-deposited toe-of-clinoform sediment. The toe-of-clinoform sediment blanket represents the continuation of the condensed section into the basal HST, and there is therefore generally no single, regional surface of downlap (Fig. 7A). The point of downlap, i.e. the break in slope at the junction between any clinoform and its contemporaneous toe-of-slope sediment, rises offshore, as therefore does the stratigraphic level at which apparent downlap occurs.

However, the low resolution of most seismic profiles is such that the DLS often has the appearance of a real surface. Rudolph et al. (1989) investigated this geometry using a seismic model of the toe of a prograding slope. Their model showed that the apparent single downlap surface seen at seismic scale was an artefact, being the result of acoustic interference where foreslope beds thin below seismic resolution at clinoform toes (see also Thorne, 1992).

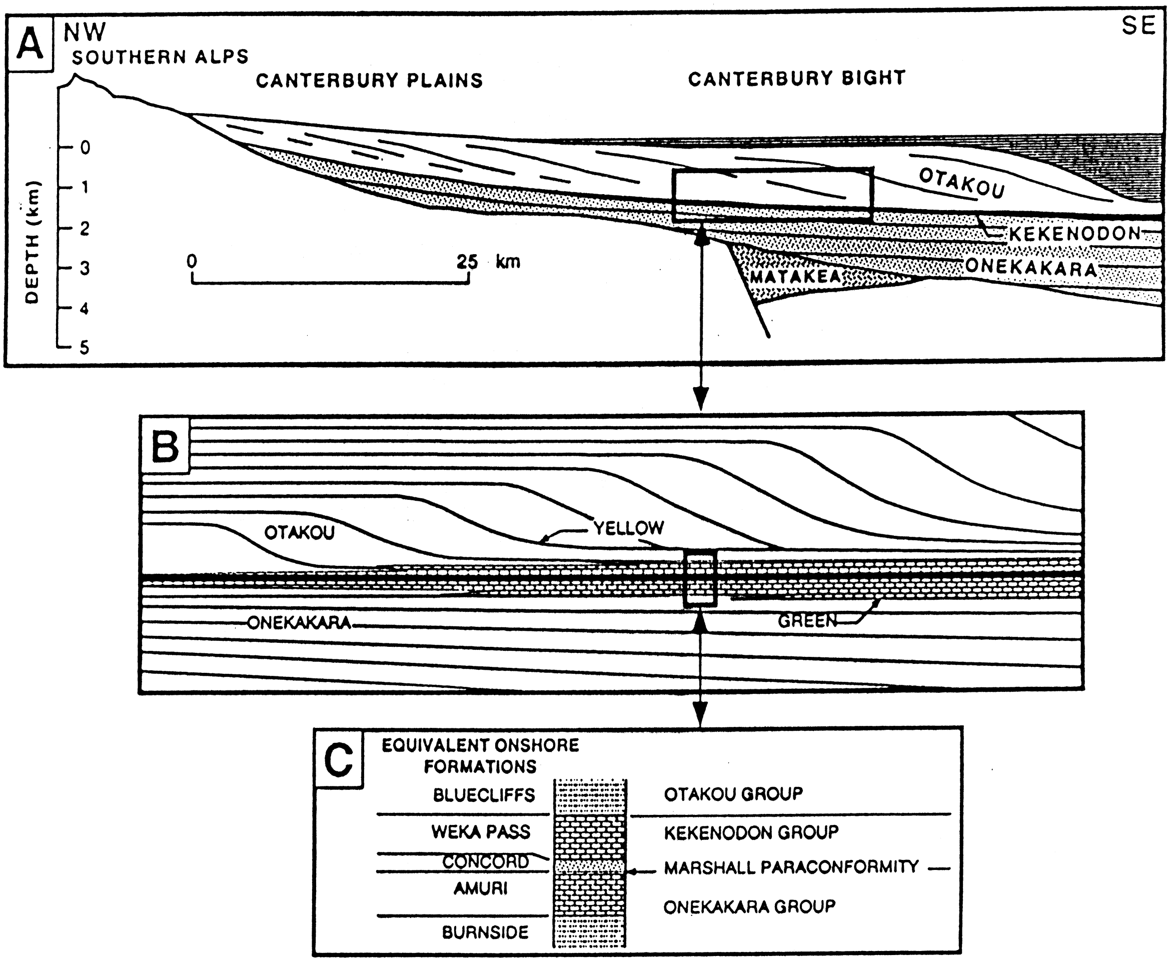


Fig. 6. Stratigraphic summary of the sedimentary megasequence which characterizes the late Cretaceous to Recent rifted margin of eastern South Island, New Zealand (after Fulthorpe et al., 1996).

Other profiles from the Canterbury Basin indicate, however, that a single regional DLS, which represents a stratigraphic discontinuity, can occur in special circumstances. These conditions are that the toe-of-clinoform sediment either not be deposited, or that sediment is removed or reworked in advance of the prograding clinoforms (Fig. 7B). Such a situation existed in some areas of the Canterbury Basin during the mid-Cenozoic, where current activity scoured a platform to a level within the Miocene and deposited the overlying sediment in large drifts (Fulthorpe and Carter, 1991). Downlap in these areas, therefore, occurs onto an omission surface which should be identifiable in outcrop regionally. In general, in the absence of evidence for current activity, a regional DLS that is a stratigraphic discontinuity — in the sense of time and toe-of-clinoform strata missing — should not be expected, and the point of clinoform downlap should normally rise basinwards.

The fact that seismic downlap may be an artefact does not imply the absence of a sharp lithological change in outcrop, as studies of mid-Pleistocene high-frequency cyclothems show (e.g. Abbott and Carter, 1994; Naish and Kamp, 1997). The outcrop studies of 5th and 6th order sequences display a physical surface (termed the downlap surface by Abbott and Carter, 1994) between prograding HST sediments and the underlying MCS. However, this

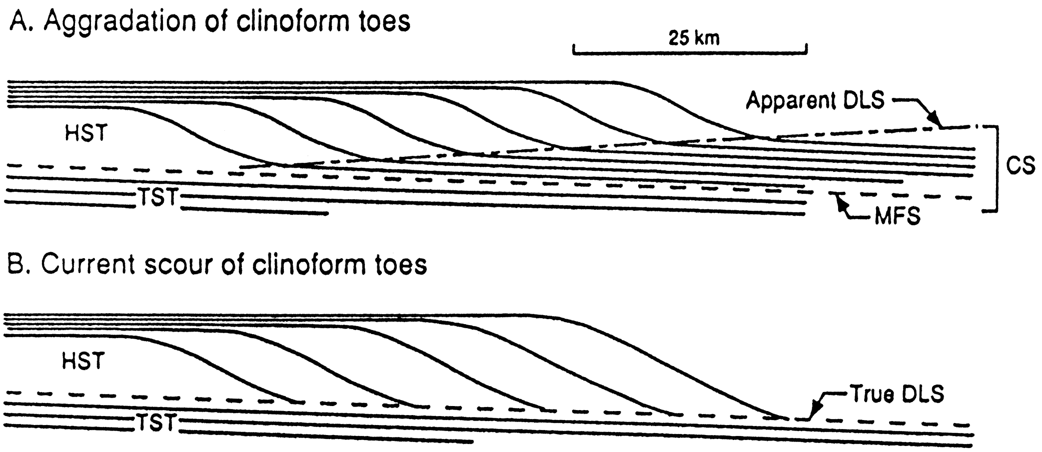


Fig. 7. Diagrams showing the distinction between (A) the apparent downlap surface which develops in conditions of steady sediment supply and deposition; and (B) a true downlap surface, which only develops in conditions of bottom-set sediment starvation or removal.

relatively sharp DLS represents the sedimentation rate change associated with clinoform progradation and does not correspond to a significant time break. As such, DLSs seen in different outcrops located across the basin will become younger in the direction of progradation (cf. Fig. 3).

We conclude that the tops of individual Pleistocene MCSs (i.e. DLSs) rise offshore in analogous fashion to the clinoform toes of the Canterbury Basin megasequence, and that the uppermost mid-cycle surface recognizable in outcrop represents a sedimentation-rate change associated with clinoform progradation rather than marking a true omission surface. Indeed, the upper part of each MCS itself may be expected to represent the most offshore manifestation of toe-of-clinoform strata which are ultimately continuous with the clinoform foresets themselves (cf. Larcombe and Carter, 1998).

4. Summary

(1) Four significant surfaces are associated with mid-Pleistocene, 5th and 6th order, inner shelf sequences from the Wanganui Basin, each of which can be identified in outcrop. In ascending order these surfaces are the sequence boundary (SB), the ravinement surface (RS), the local flooding surface (LFS) and the downlap surface (DLS).

(2) The maximum flooding horizon (MFH) is defined as the theoretical chronostratigraphic level which coincides with the maximum landward transgression of the shoreline. In general, neither any local flooding surface (LFS) nor any downlap surface (DLS) necessarily corresponds to the MFH, except that the youngest LFS and the MFH coincide at the point of maximum transgression of the shoreline. Therefore, the MFH is not generally represented by a physical surface in outcrop, and may lie at different levels on different basin cross-sections, corresponding to regional variations in rate of subsidence and sediment supply.

(3) The terms peak eustatic sea-level horizon (PESH) and peak relative sea-level horizon (PRSH) are introduced for the chronostratigraphic horizons coincident with the highpoint of sea-level within a eustatic or local relative sea-level cycle, respectively. The PESH or PRSH do not necessarily coincide with the MFH, nor with any particular LFS or DLS.

(4) The pragmatic boundary adopted between the TST and the HST for seismic and regional studies is the DLS. For high resolution outcrop studies, however, a new condensed section systems tract (CSST) is recognized. Alternatively, the TST and HST may be allowed to have an indeterminate boundary.

(5) A seismic megasequence of 80 My duration from the Canterbury Basin contains internal surfaces analogous to the DLSs of the mid-Pleistocene sequences. However, a single, basin-wide DLS does not occur. Rather, each successive clinoform reflector

of the mega-HST progrades over successively higher bottomset horizons. In seismic data sets where a single, sharp DLS occurs, it is therefore a result of either (a) low resolution data; or (b) non-deposition or current erosion of toe-of-slope clinoforms.

(6) Sequence stratigraphic interpretations are enhanced by the maintenance of a clear distinction between *physical surfaces observed in the field* (sequence boundary, ravinement surface, local flooding surface, downlap surface) and *conceptual isochronous horizons* (maximum flooding horizon, peak eustatic sea-level horizon, peak relative sea-level horizon).

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