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Transgressive coastal systems (1st part): barrier migration processes and geometric principles

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ABSTRACT - Coastal processes during transgression have been explored through morpho-kinematic simulations using the Shoreface Translation Model (STM). Our STM experiments show that the landward migration of coastal system is controlled by the rate of sea level rise (SLR), the rate of sediment supply (Vs), the shelf slope (α), and the morphology of the coastal profile (M). Additionally, the geometric relationships between shoreface and plane of translation govern three kinematic modes of coastal barrier migration: (1) roll-over, (2) hybrid, (3) encroachment. Each mode exhibits differences along the coastal profile in relation to zones of erosion (cut) and redeposition (fill) and to the consequent sediment exchanges across the profile (from the cut to the fill). Each mode produces distinctive facies architectures and specific stratigraphic position of the shoreface-ravinement surface. Environmental conditions (rates of sea-level rise, sediment supply (±), barrier morphology) and kinematic modes both control stratal preservation. Transgressive roll-over, in particular, occurs on gently sloping shelves and involves erosion along the entire shoreface and landward sediment redeposition (by overwash and tidal inlet processes). Three different types of roll-over are possible depending on the conditions of sediment supply (Vs) to the coastal cell: neutral roll-over (*Vs*=0 m^3), which produces no effect on the shelf; depositional roll-over (*Vs* >0) and erosional (*Vs*<0) roll-over, which modify the shelf through stratal preservation and erosion, respectively. These differences are quantified in simulations by tracking parameters that principally relate to the trajectory of a 'neutral point' (maximum depth of shoreface erosion). The shoreface-ravinement defines the trajectory in all the transgressions and in principle is preserved in the rock record, making it a much more useful tracking point than the shoreline trajectory analysed in other studies. Coastal migration in all kinematic modes includes state-dependent inertial effects, experimentally well evident when, after a perturbation, the drivers (SLR, *Vs*, *α*, *M*) are maintained constant for a long interval of time. Kinematic inertia appears as progressive geometric self-adjustments of the barrier until it acquires a shape that is stable under prevailing conditions (constant drivers). At this stage (kinematic equilibrium), which is unlikely ever to be attained in nature, simulated transgressions finally evolve with processes and geological products that remain invariant. Kinematic inertia is likely to be an additional factor that governs the real transgressions under most circumstances.

KEY WORDS: coastal system, sea level rise, barrier migration, kinematic models

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INTRODUCTION

This study explores the mechanisms involved in landward migration of siliciclastic coastal systems during phases of sea-level rise. Geometric relationships between certain physical elements of the coastal system, notably the morphological profile of the coastal barrier and the paleo-topography upon which the transgression occurs, form the basis of several attempts in the past to explain the processes and modalities of barrier migration (Leatherman, 1983; Boyd and Penland, 1984; Belknap and Kraft, 1985; Roy et al., 1994; Niedoroda et al., 1995). This task is approached here using simulated transgressions derived from the Shoreface Translation Model (STM), a program which, provided with given environmental conditions as input data, returns kinematic data and morpho-stratigraphic images of coastal evolution displayed at discrete temporal intervals along a section of coastline (Cowell et al., 1995). The STM has permitted the exploration of various types of transgression, and the identification of significant kinematics and stratigraphic features which may be explained by geometric rules. Salient principles deriving from hundreds of experiments are introduced here using didactic examples that, even if they do not contain the typical complexities in nature, permit the isolation of individual controlling factors. The principles are common to all transgressions within the limiting conditions defined through available tests, specified herein.

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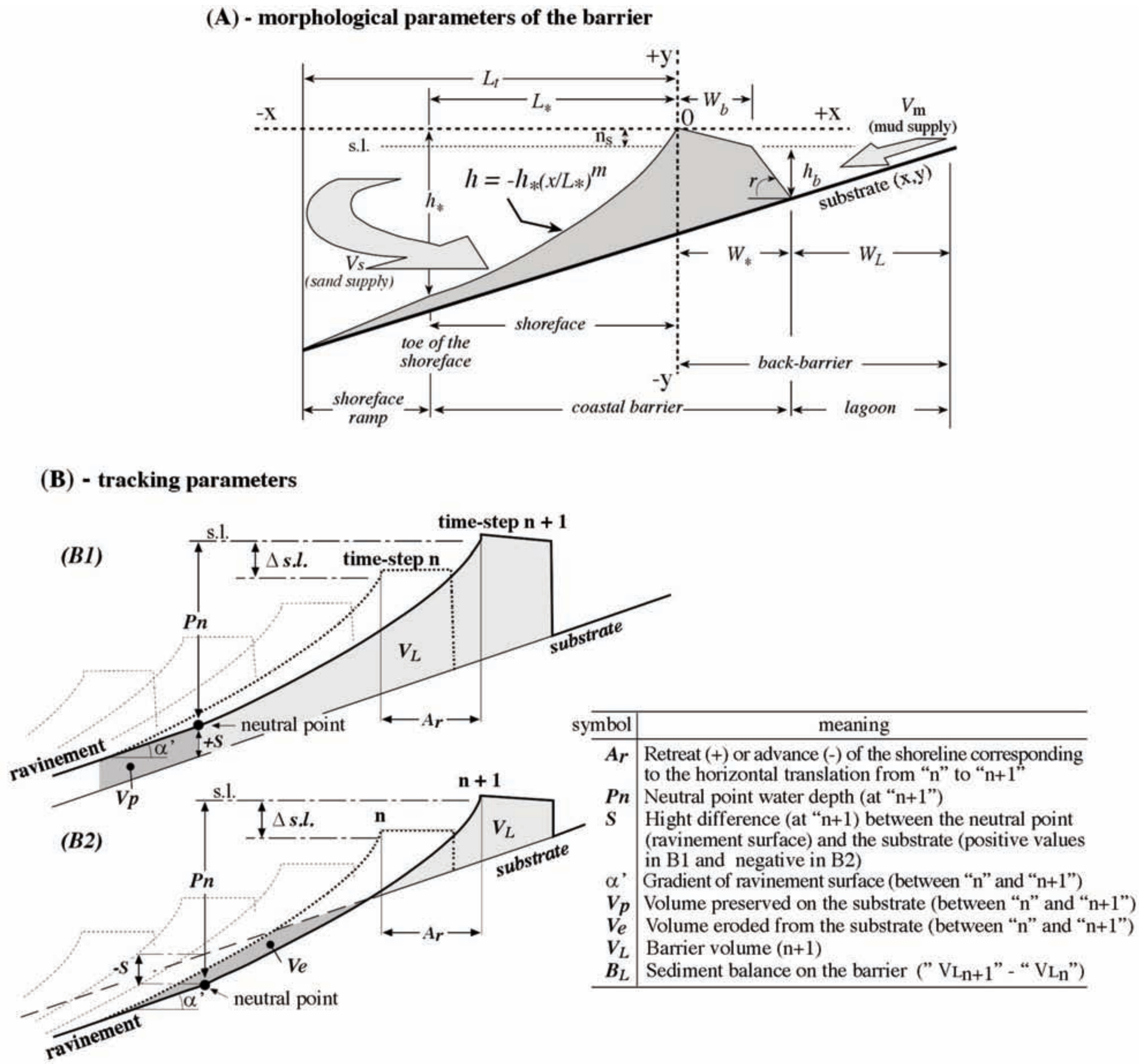
SHOREFACE TRANSLATION MODEL

For a given sea level rise (SLR), sediment supply (±), shelf (or substrate) topography and land-sea coastal profile, the Shoreface Translation Model generates the resulting coastal changes in morphology. When the process is repeated for a number of time steps, the model simulates kinematics of the morpho-stratigraphic evolution over the total time period. The STM has been used in the past in theoretical studies, in coastal-change predictions and in the reproduction of stratigraphic sections to deduce their formative processes (Tarantola, 1987; Roy et al., 1994; Cowell et al., 1999; Dillenburgh et al., 2000; Cowell and Kench, 2001; Kench and Cowell, 2001; Cowell et al., 2003a; 2003b).

In terms of input data, the program requires three groups of parameters that define the geometric elements of the dynamic littoral morphology (Fig. 1A), the initial topography and substrata of the seabed and land surface, and the prevailing boundary conditions accompanying the



symbol	meaning
Ar	Retreat (+) or advance (-) of the shoreline corresponding to the horizontal translation from "n" to "n+1"
Pn	Neutral point water depth (at "n+1")
S	Hight difference (at "n+1) between the neutral point (ravinement surface) and the substrate (positive values in B1 and negative in B2)
α'	Gradient of ravinement surface (between "n" and "n+1")
Vp	Volume preserved on the substrate (between "n" and "n+1")
Ve	Volume eroded from the substrate (between "n" and "n+1")
V_L	Barrier volume (n+1)
B_L	Sediment balance on the barrier (" V_{Ln+1}" - " V_{Ln}")

Fig. 1 - State variables and tracking parameters. (A) Morphological parameters used in the STM to represent the coastal complex (see text for explanation of variables). (B) Tracking parameters calculated at each time-step during the simulations.

transgression (Cowell and Roy, 1988). The boundary conditions include the sea-level rise and net volumes of sediment entering or exiting the coastal cell due to longshore drift of sand and fine material supplied to the lagoon (V_s and V_m respectively: Fig. 1A). The transgression takes place within a Cartesian system representing an alongshore-averaged cross section perpendicular to the general trend of the coastline (Fig. 1A). Ancillary software was developed for this study to extract, from the STM at every step, synthetic data that in principle correspond to quantities that can be observed in field data, in seismic records and in sediment cores. These data, referred to herein as *tracking parameters*, comprise the coordinates and dimensions of the morphological elements, the amount of sediment transferred landward or seaward by the transgression, and stratigraphic measures (Fig. 1B).

The STM results are based on a mass-balance principle which governs the erosion and deposition (repeated at each time step) as a function of the imposed conditions (the three groups of parameters referred to above). Such a principle assumes that the sedimentary mass must necessarily be conserved during barrier migration, and that any variations to the sediment mass along the two dimensional profile are due to external gains and losses, such as those due to the action of longshore drift.

Three elementary applications of this principle are illustrated in Fig. 2, simulating transgressions in (A) closed coastal systems or balanced systems with equal import and export of sediment ($V_s = 0$ m3); (B) open coastal systems with net sediment input ($V_s > 0$); and (C) open coastal systems with net sediment losses ($V_s < 0$). Solutions for the barrier translation in the three cases are obtained by satisfying the following sediment-balance conditions: (A) volume balance between eroded (cut) and redeposited sediment (fill); (B) an excess fill equal to the sediment input retained by the barrier ($+V_s$); and (C) a fill reduction equal to sediment loss ($-V_s$). More intuitively, the solution involves raising the barrier by the SLR increment, and then moving it horizontally land-

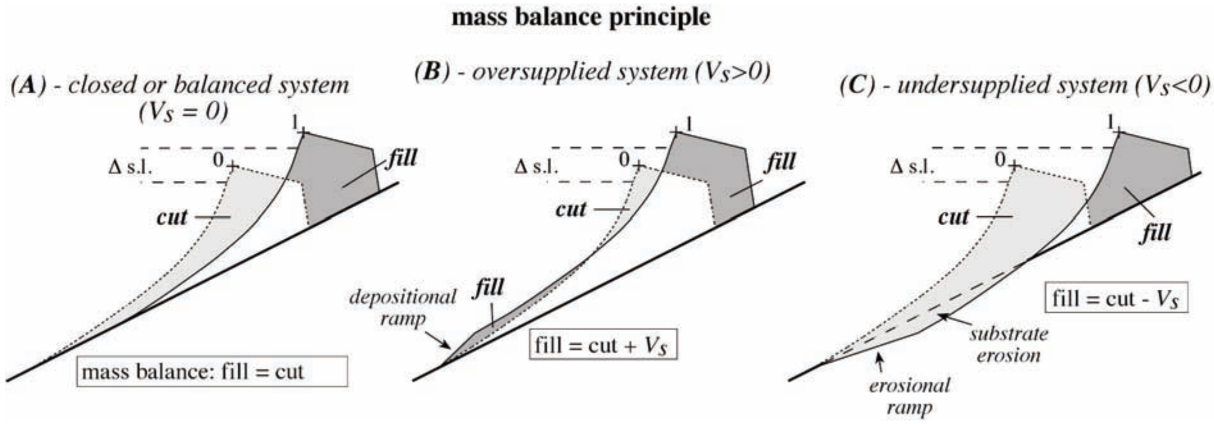


Fig. 2 - Idealised illustrations of the "principle of mass balance" that govern the kinematics of coastal barriers in response to increments of sea level under three different conditions of sediment supply: (A) closed or zero supply; (B) oversupplied; (C) undersupplied.

wards until the cut-fill balances referred to above are achieved. This operation is executed automatically using the continuity equation for sediment transport (Cowell et al., 1992; 1995). The entire program is "built" around this equation, taking into account the three parameter-groups that allow its application to varied environmental conditions. The absence of preconceived concepts of coastal dynamics ensures the clear and free interpretation of the STM results.

METHODS

This study was undertaken in three stages: (1) an experimental stage aimed at identifying the links between geometric evidence and transgressive processes; (2) the verification of such links under different environmental conditions, with the additional aim of defining requirements for their validity; (3) a reasoned synthesis of what emerged from the numerical experiments through conceptual analysis of representative examples. The first two stages involved examining hundreds of simulations that characterised different transgressive conditions. Examples were selected for discussion based on their ranked utility in facilitating explanations in terms of cause and effect. Generally, such cases represent idealised reference conditions free from complexities typical of most natural transgressions. Their value as reference cases exists because they manifest behaviour, evident in the tracking parameters, common to all transgressions. Behaviour in specific cases differs only by degree as conditions vary, providing these conditions remain within limits specified herein.

The reference cases involve morphologically identical barriers, unaltered in time, in which choice of parameters has been guided by measurements taken from actual coastal barriers from the regions of Tuscany and Latium in Italy (CNR-MURST, 1997), and by high resolution seismic data from late-Quaternary transgressive deposits in Italy (Tortora, 1989; Chiocci et al., 1991; Chiocci and La Monica, 1996; Tortora, 1996b; Tortora et al., 2001; Chiocci et al., 2004). The principal morphologic-parameter values used were L_*=1150 m, h_*=12 m, W_*=300 m, m=0.68 (refer to Fig.1A); the latter value represents the form of the shoreface in equilibrium conditions (Dean, 1991). These values are suited to intermediate-type beaches in the Mediterranean area (Short, 1979).

The examples adopt substrates (antecedent topography) that conform to Italian continental-shelf slopes (0.3°-0.7°; except in the Adriatic Sea) and, to reduce complexity, all were of a constant gradient. Increments of SLR at 1 m per time-step were applied, and the sediment flux (V_S) was mostly maintained constant over time (except for simulations related to Figs 6 and 9), with ratios V_S/SLR that generally conform to Holocene transgressions. Littoral systems with lagoonal sedimentation and mud-rich shelves giving rise to condensed successions were avoided. The environment considered was therefore strictly littoral (Fig. 1), and the results obtained from the simulations are thus limited to such environments. Each time-step, if compared to the average rate of SLR during the last transgression (about 8.5mm/a from 18,000 to 6,000 yrs BP; Fleming et al., 1998; Milne et al., 2005), would correspond to 118 years (Figs 3, 7 and 8), 150 years (Fig. 6) and 84 years (Fig. 9).

The STM geological sections were examined in terms of physical stratigraphy, considering the repetition (at every step) of the morphological outline bounding the littoral sediment body. These bounding outlines appear in the synthetic stratigraphic record as a succession of depositional surfaces. These surfaces have been utilised to distinguish different deposits and key surfaces, and to identify geometric rules that link sedimentary processes to mechanisms of barrier migration.

BARRIER MIGRATION

Migration of the coastal system occurs through sediment dynamics which regenerate the barrier, forcing it to move progressively landwards (Leatherman, 1983; Cowell and Thom, 1994). Such dynamics operate according to three modes of accommodation-governed behaviour that depend on geometric relationships between the submarine beach (the shoreface) and the paleo-topography (Pilkey et al., 1993; Niedoroda et al., 1995; Storms et al., 2002; Stolper et al., 2005; Wolinsky and Murray, 2009). This is illustrated in Fig. 3 (A, B, C) where, for an elementary increase in sea level, an invariant shoreface profile is translated across substrates of varying gradient. The kinematics are shown in the superposition of the two morphological profiles of the barrier (steps 0 and 1), from which it emerges that the translative process involves eroded sediment masses (cut) and redeposited sediment masses (fill), necessarily connected by transport systems directed from the cut to the fill zones.

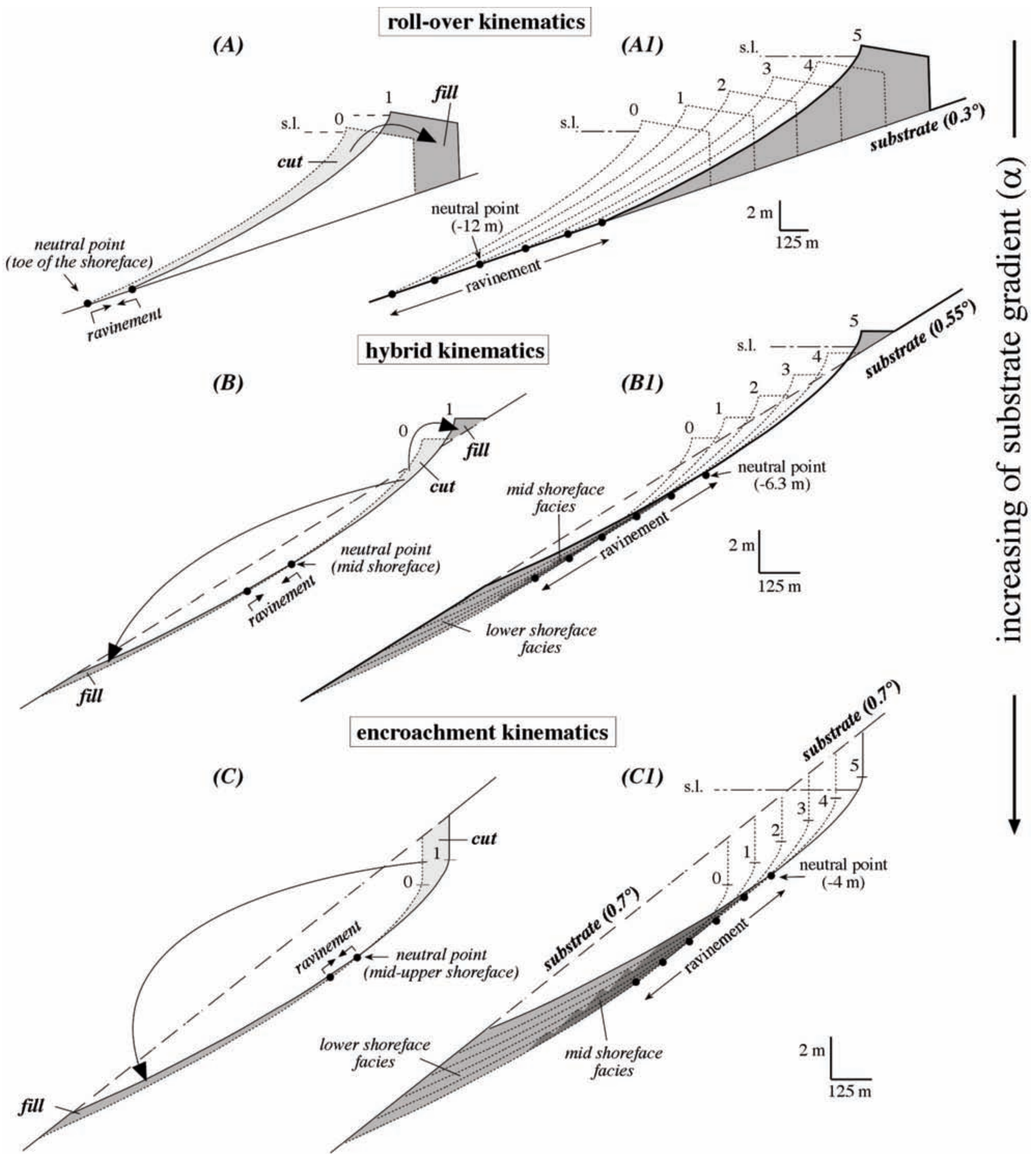


Fig. 3 - The three modes of coastal evolution during the sea level rise for different illustrative conditions of the ravinement:shoreface gradient ratio (eq.1): (A) barrier roll-over; (B) hybrid translation; (C) encroachment (Cowell et al., 1995). The left-hand panel shows the fundamental geometric relationships between the shoreface and the substrate governing coastal accommodation and resulting sediment redistribution processes (arrows indicate sediment dispersal - cut to fill). Points in black indicate position of the "neutral point", translation of which produces a ravinement surface. The right-hand panel shows distinctive stratigraphic architectures produced after multiple steps of each mode. Parameter values are the same for each mode ($V_S = 0$, $V_f = 0$, $L^* = 1150$ m, $h^* = 12$ m, defined in Fig. 1); only the substrate slope differs and consequently the gradient (α') of the ravinement surface.

In case A (Fig. 3), erosion involves the entire shoreface (cut). Sediments from this source are redeposited on the back-barrier area (fill) through a transport exclusively directed landwards. In B the transport is divergent, with the cut zone lying between the two peripheral areas of fill. The erosion derives from the translation of the upper-mid segment of the shoreface, while the lower segment is depositional and gives rise to a sediment body which may be isolated on the continental shelf. Case C differs from B due to the more pronounced coastal erosion and absence of landward redeposition. Extending the evolution by several time-steps, the three types of migration produce different stratigraphic effects even under identical environmental conditions of sea-level rise, sediment supply, and energy regime (Fig. 3A1, B1 and C1).

These three modes are termed (Cowell et al., 1995) *roll-over*, *hybrid*, and *encroachment* modes. The zones of cut and fill, and the transport path which connects them, may be interpreted as the work of one or more littoral dispersal systems (Swift et al., 1991), which typically include a sediment source (cut region), transit zones and zones of final deposition (fill). In nature, systems which are dispersive in a landward direction (Fig. 3A1 and B1) involve overwash, tidal-flood-delta and aeolian processes, while those in a seaward direction (Fig. 3B1 and C1) involve redeposition on the lower shoreface (Wolinsky and Murray, 2009), generally assumed for retreating modern beaches (Bruun, 1962).

The erosion associated to barrier migration generates a ravinement surface, traced by the lower extremity of the eroded segment of the shoreface (lower limit of cut). This extreme limit of the cut, here defined as the *neutral point*, is located at the toe of the shoreface in rollover (Fig. 3A) and in a more coastal position in the other two kinematic modes (Fig. 3B and C): closest to shore for encroachment. The ravinement surface records the neutral-point trajectory during a transgression (Fig. 3).

Further geometric features are shown by the examples in Fig. 4 that involve two well-supplied coastal systems (V_S=1100 m^3 per time-step) which respectively evolve by roll-over (case A) and encroachment/transitional to hybrid (B) modes. In A, migration of the barrier involves only the sediment mass above the neutral point. The barrier therefore consists of (see step 30 for reference) an upper migrating portion and a lower portion that is static and preserved on the shelf as the upper portion of the coastal system moves landwards. The derived deposit (DL, steps 0-29) is comparable to an inland-dispersal-systems deposit (Swift et al., 1991) in as much as it includes sedimentary products (or what remains of them) of the original landward dispersal systems (fill in Fig. 3A). This deposit is generally composed of diverse coastal facies (washover, flood tide delta, sometimes mobile dunes) which cannot be resolved individually in the STM schemes. The ravinement surface, bordering the facies from above, identifies the true plane on which the barrier has migrated; in fact the substrate acts only as a support for the fill redeposited behind the barrier.

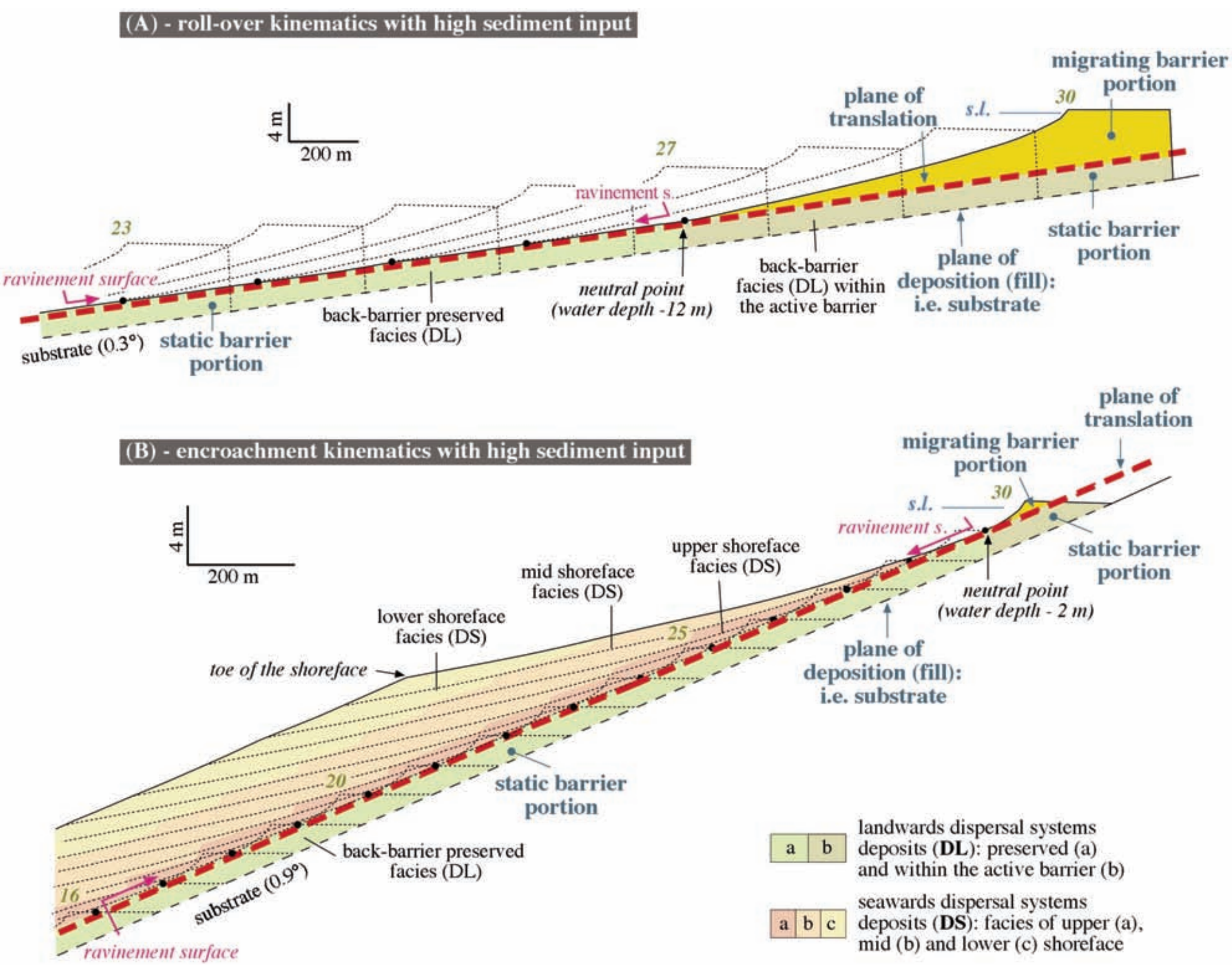


Fig. 4 - Transgression with high rates of sediment supply (V_S = 1100 m^3 per step) over land surfaces of different gradients: (A) sufficiently low gradient surface to permit barrier roll-over; (B) steeper land surface causing near encroachment. Deposit DL is truncated by the shoreface-ravinement (the plane along which the littoral sediment body migrates). Deposits DL and DS form respectively by sediment transported in landward and seaward directions (Fig. 3: A, C). The back-barrier facies DL typically includes washover and flood tidal delta sediments, while DS exclusively comprises shoreface facies.

In the simulation of Fig. 4B, the littoral deposit is divided into a migrating portion and a static portion, both abandoned as preserved deposits on the shelf. The latter unit (DL) supports the former (DS) which forms from a seaward dispersive system, comprising facies in a retrogradational setting, indicated in Fig. 4B as the lower, middle and upper shoreface. The DL and DS deposits are separated by a ravinement surface, and they belong to the dispersive systems defined as conjugated (Swift et al., 1991; Tortora, 1996a). The ravinement surface records, in both examples, the true plane of translation and the trajectory of the barrier during migration. The shoreface-ravinement defines the trajectory in all the transgressions and in principle is preserved in the rock record, making it a much more useful tracking point than the shoreline trajectory analysed in other studies (Helland-Hansen and Martinsen, 1996; Cattaneo and Steel, 2003; Wolinsky and Murray, 2009). Shoreface-ravinement and shoreline trajectories are based on the same concepts.

The conditions governing the three kinematic modes of migration (Fig. 3) are defined in this study as geometrically dependent upon: (1) the gradient (α') of the plane of translation (ravinement surface: Fig. 4), which is the result of the environmental parameters that control the evolution (substrate slope, sediment supply, sea level rise, barrier morphology); (2) the steepness (β) of the shoreface; and (3) its concavity related to the parameter *m* in Fig. 1A, well known from Dean (1991). The kinematic domain for each mode varies with *m* in relation to ravinement:shoreface gradient ratio, $\gamma = \tan\alpha'/\tan\beta$:

$$\begin{aligned}&\text{roll-over mode } 0 < \gamma \le m\\ &\text{hybrid mode } m < \gamma < 1 \qquad (1)\\ &\text{encroachment mode } \gamma \ge 1\end{aligned}$$

Encroachment mode occurs only on translation planes with gradient equal to or greater than the shoreface slope ($\gamma \ge 1$), while the other two modes ($\gamma < 1$) are also dependent on *m*, with the premise that the hybrid type does not occur for convex profiles of the shoreface ($m > 1$). Numerical intervals of equation (1) are represented graphically in Fig. 5 for $m = 0.68$ (the equilibrium profile of Dean, 1991).

The roll-over, hybrid and encroachment modes correspond respectively to the evolutionary models widely cited in the literature as the generalised Bruun rule (Dean and Maurmeyer, 1983), the Swift model (Swift et al., 1991), and the standard Bruun rule (Bruun, 1962; Schwartz, 1967). Therefore these models should each apply under the different conditions respectively specified in equation (1).

Roll-over and encroachment modes are end-members of a vast spectrum of possibilities covered in the middle by the hybrid mode. The dynamics of migration are therefore as numerous and blurred as the range of possible geometric relationships between the shoreface and the plane of translation. Each type of migration exhibits a specific position of the neutral point and therefore specific extents of the erosive (cut) and depositional (fill) segments of the shoreface. The erosion and deposition potential of the shoreface during transgression depends on the extent of these two segments, and is respectively maximised during roll-over (the whole shoreface is erosive) and in encroachment (all, or almost all, depositional). In the following, the focus is on roll-over transgressions for several reasons. We are interested in large-scale transgressions typically associated with major eustatic fluctuations, of

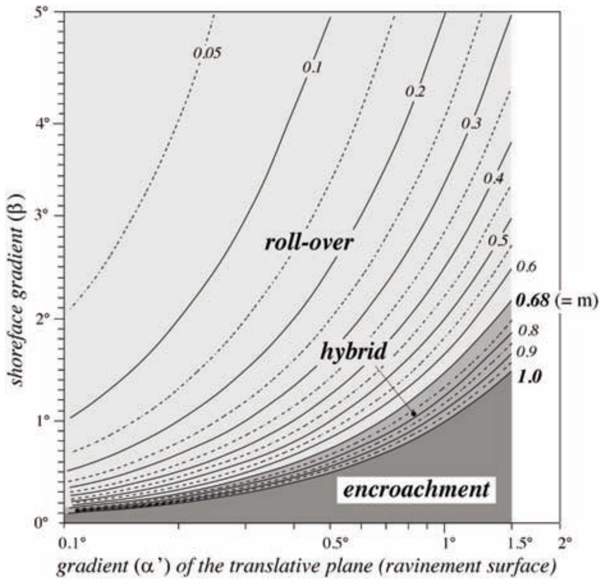


Fig. 5 - Gradient ratios (ravinement:shoreface γ-isolines) defining limits of the three modes of accommodation-governed behaviour (see Fig. 3) as a function of the shoreface-ravinement slope α'), shoreface slope (β) and shoreface concavity (*m*): cf, m = 0.68 (Dean, 1991).

primary relevance to the geological record. On this scale, the slope of most continental-shelf surfaces, subject to transgression, is much less than associate shoreface slopes, and shoreface convexity typical of wave-dominated conditions. Therefore we infer that conditions conducive to barrier roll-over ($0 < \gamma \le m$) are likely to be more prevalent.

ROLL-OVER TRANSGRESSIONS

Sediment balance

The coastal sediment balance can be explained as the volumetric variation of the barrier over time (from the toe of the shoreface to the inland barrier closure). This balance depends on (1) the prevailing sediment import or export ($\pm V_s$) in the coastal cell due to the alongshore sand drift (lateral dynamics), and (2) the sediment exchange between the barrier and the shelf (dynamics along the profile). The barrier-shelf exchange can result in sediment losses when portions of the barrier are preserved (V_p) and abandoned on the shelf (Fig. 1B1; DL in Fig. 4), or in sediment gains when the substrate is eroded (V_e) in supplying the coast (Fig. 1B2). Stratal preservation or substrate erosion typically occurs in oversupplied ($V_s > 0$) or undersupplied ($V_s < 0$) coasts (Fig. 2), with the additional control of the other drivers if transgression evolves under variable conditions (Tortora et al., 2009; in this volume). The balance depends definitively on how the transgression allocates the available sediment with respect to the shelf-littoral boundary. The sedimentary balance (B_L) for the barrier volume, may be expressed in a generic temporal interval 0-*n*, involving *n* time steps, as

$$B_L = \sum_0^n (\pm V_s + V_e - V_p) \qquad (2)$$

The example in Fig. 6 shows the control exerted by the transgression over the barrier sedimentary balance, B_L. The simulation involves a depositional roll-over which, driven by variable rates of SLR and by constant sand inputs over time

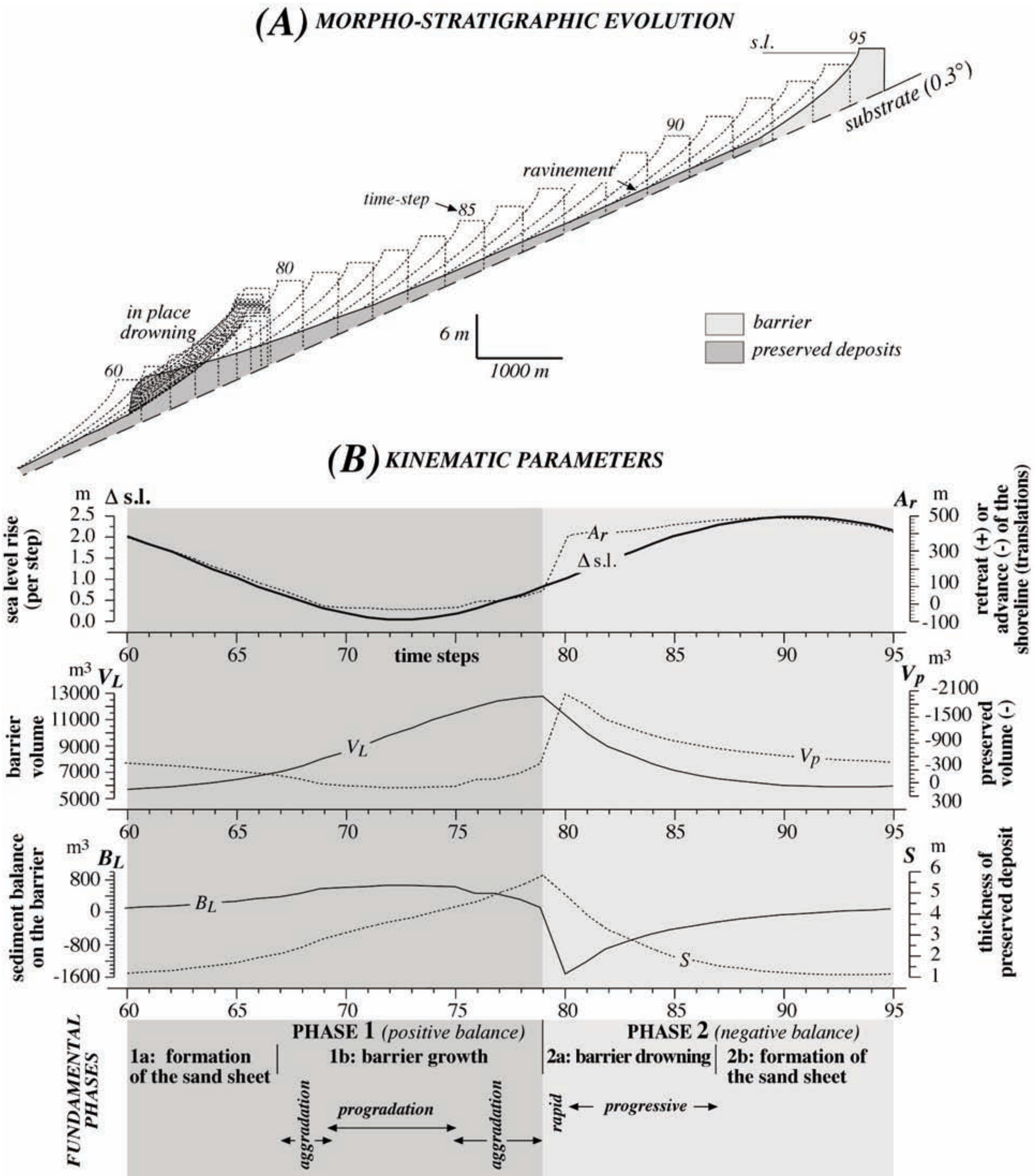


Fig. 6 - Evolution of a depositional roll-over with constant sediment supply (V_s = 500 m^3 per step) and fluctuating rates of sea-level rise: (A) STM simulation; (B) graphs of variations in tracking parameters over time. The evolution involves two main phases of sediment imbalance: positive (Phase 1) and negative (Phase 2), associated to distinctive depositional periods (1a, 1b, 2a, 2b).

(V_s = 500 m^3 per step), produces changes in B_L that depend purely on the variable stratal preservation (V_p): substrate erosion being absent (V_e = 0). The transgression consists of two principal phases (Fig. 6B), of positive balance (Phase 1) and negative balance (Phase 2). They respectively occur when the losses due to stratal preservation are lower (Phase 1) and higher (Phase 2) than the net longshore inputs (V_s). Such losses (DL in Fig. 4) are irrelevant during the barrier-growth period (Phase 1b) and extremely high during barrier drowning (Phase 2a) resulting from the eustatic acceleration. The simulation, among other things, suggests that well supplied transgressions ($V_s >> 0$) are not always accompanied by a positive balance on the barrier, depending on antecedent changes in states.

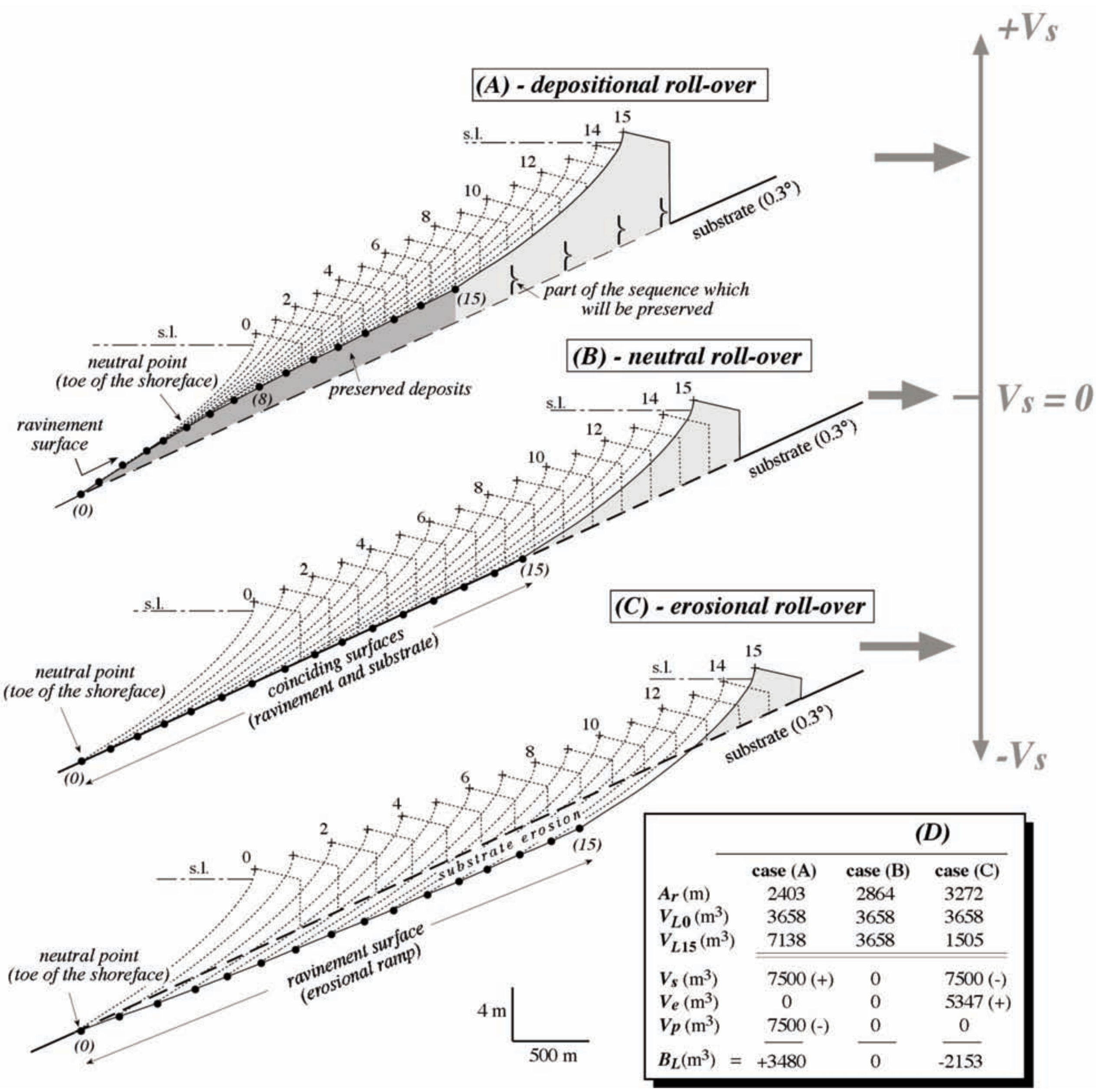
Roll-over types

Roll-over kinematics are favoured by a gently sloping substrate and steeper shoreface gradients (eq. 1), as well as shoreface profiles with mild concavity. Experimentally, three types of roll-over may be reproduced (Fig. 7), whose occurrence depends on the sediment supply ($\pm V_s$): (a) depositional ($V_s > 0$); (b) neutral ($V_s = 0$, closed or balanced system); and (c) erosive ($V_s < 0$). The first of these preserves tabular deposits, the second is a discrete transitional type that does not produce any stratigraphic effects due to the absence of erosion and stratal preservation, and the third causes erosion of the substrate, activating an intrabasinal sediment source.

These three roll-over types are associated with respectively higher rates for the horizontal component of translation, *Ar* (Fig. 7D). They are distinguishable by the position assumed by the ravinement surface (the succession of neutral points, Fig. 7): respectively coinciding or above or below the original substrate profile (Cowell et al., 1999). With reduction in the external sediment supply, V_s, for the respective roll-over types, increased rates in the horizontal component of translation push the barrier further landward onto more restricted space with respect to accommodation. For example in the case C, with high horizontal translations, this space is insufficient and the shoreface accommodation necessarily involves substrate erosion (see Fig. 2).

Similarly, the trajectory of the neutral point progressively lowers from above to beneath the pre-existing topography, for cases where $V_s > 0$ and $V_s < 0$ respectively (Fig. 7). Reduced thickness of the preserved deposits accompanies lowering of the neutral-point trajectory to the transitional type, with increased substrate erosion as the trajectory lowers further due to larger sediment deficits.

In the natural geological records, however, it is difficult to



	case (A)	case (B)	case (C)
A_r (m)	2403	2864	3272
V_{L0} (m^3)	3658	3658	3658
V_{L15} (m^3)	7138	3658	1505
V_s (m^3)	7500 (+)	0	7500 (-)
V_e (m^3)	0	0	5347 (+)
V_p (m^3)	7500 (-)	0	0
B_L(m^3) =	+3480	0	-2153

Fig. 7 - Comparative translation rates for the three types of roll-over under different conditions of sediment supply (V_s): (A) depositional roll-over with positive net supply (V_s = 7500 m^3 for the total period); (B) neutral roll-over (V_s = 0); (C) erosive roll-over (V_s = -7500 m^3 for the total period). In (D), tabulated values for tracking parameter values: *Ar* = total littoral retreat; V_{L0-15} = volume of the littoral body at step 0 and 15; V_e and V_p = total sediment volume gained from substrate erosion (V_e) or lost from stratal preservation (V_p); BL is the sedimentary balance on the littoral between steps 0 and 15.

stratigraphic evidence →	***barrier kinematics***
(1) ravinement surface without transgressive deposit	(1') precise identification is impossible: neutral roll-over, erosive roll-over, under-supplied (V_S <0) hybrid and encroachment acting on pelitic substrates (not able to regenerate the barrier when eroded)
(2) preserved coastal lithosomes (deposit DL: fig. 4A), with back-barrier facies (lagoonal, washover, tidal delta, landwards mobile dunes), bordered above by ravinement surface and below by the unconformity surface	(2') depositional roll-over (over-supplied transgressions: V_S >0)
(3) retrogradational shoreface deposits (Fig. 3B and C) above the ravinement surface	(3') hybrid or encroachment, discernible using Fig. 5, or by deducing the paleo-bathimetry of the neutral point. A neutral point which is close to the shoreline may indicate encroachment, but if closer to the surf base, it approaches roll-over dynamics
(4) DL deposits of type (2) bordered from above by the ravinement surface and overlain by DS deposits of type (3) as in Fig. 4B	(4') Very well supplied hybrid or encroachment (V_S >>0), discernible as above (3') with a focus on the DS deposit

Tab. 1 - Stratigraphic evidence expected in outcrop for the three modes of barrier migration.

distinguish the workings of neutral roll-over from erosive roll-over (Tab. 1), unless morphological lowering of the substrate by erosion is evident. Even then, *in situ* superficial reworking of the substrate by storms and bedform migration can be expected to further blur field evidence regarding erosion, unless significant truncation of substrata or thickness of lag deposits is evident (Cowell et al., 1995; 2001).

Kinematic inertia of barriers

The migration of the coastal system gives the appearance that the entire mass moves intact whereas, in reality, barrier kinematics involves a continuous reworking of sediments in the landward direction through the cut and fill process, generally resulting in a continually varying geometric form of the littoral sand body. Experimentally, the migration velocity depends on the rate of sea level rise, the shelf gradient (α), the sediment input ($\pm V_s$), and the morphological profile of the barrier itself (*M*). Every variation in these factors results in acceleration or deceleration of the barrier, the effects of which continue for a long time until the barrier eventually assumes a constant velocity. That is, the migration of coastal systems in STM simulations is subject to a state-dependent *morphokinematic inertia*. Instructive model experiments for the comprehension of this state are reported in Tortora and Cowell (2005), and Wolinsky and Murray (2009).

Causes of the kinematic inertia are here discussed with reference to two simulations (Fig. 8). Both depict roll-over, initially in neutral mode (step 0) but then forced to evolve under constant conditions for *SLR*, V_s, α, and shoreface $h(x)$: one simulation involves depositional roll-over with V_s = 500 m^3 per step (Fig. 8A and A1), and the other erosive roll-over with V_s = -500 m^3 (Fig. 8B and B1). The tracking parameters, defined in Fig. 1, change continually as the barrier gradually adjusts to the imposed conditions (Fig. 8A and B) until steady-state kinematics are attained, when the barriers finally assume constant form through time (Fig. 8A1 and B1).

The gradual adjustment occurs through 25 to 35 m of sea-level rise respectively for the depositional (Fig. 8A) and erosive (Fig. 8B) cases. This period would correspond roughly to 2800 and 4100 years at the average rate of sea-level rise during the Holocene transgression (118 years per time step). A quasi-equilibrium in kinematics (90% of full adjustment) is reached in the simulations after 1900 and 2350 years respectively for depositional and erosive roll-over. Changes in the migration rate, plotted as the tracking parameter A_r (Fig. 8A and B), indicate that the imposed conditions (SLR, V_s, α, $h(x)$) disrupt the initially static barrier (step 0), at first producing a rapid acceleration (step 0-1) that is stronger in the depositional than erosive roll-over. This is followed, under constant conditions, by kinematic adjustments in which the migration rates of each roll-over scenario converge towards a common value. The convergence involves progressive acceleration for depositional roll-over (Fig. 8A) and deceleration for erosive roll-over (Fig. 8B), with these kinematic differences averaged through time to give a lower overall migration distance for the former. Once the kinematic inertia is finally overcome, the two types of roll-over assume the same velocity and uniform motion (A_r stabilises).

All the tracking parameters vary progressively through time in concert with A_r. All the parameters therefore reach an asymptotic threshold beyond which the two transgressions evolve in a state of kinematic equilibrium. Before the threshold, the geometry of the barrier changes progressively, acquiring a stable form (equilibrium) at the same time that the tracking parameters reach the threshold. Therefore the period of kinematic inertia involves a sequence of self adjustments in the barrier mass, reflected in changes to the tracking parameters, that finally lead to a new state of kinematic equilibrium while the imposed conditions remain constant.

For depositional roll-over (Fig. 8A1), kinematic equilibrium ensues when the lateral sediment input to the barrier (longshore drift) is fully compensated by the mass abandoned on the shelf ($V_p = V_s$). A similar compensation in erosive roll-over (Fig. 8B1) is finally established between the lateral sediment output and the volume derived from substrate erosion ($V_e = V_s$). Kinematic equilibrium therefore occurs when geometric readjustments in the barrier allow an internal sediment balance to be achieved: i.e., $B_L = 0$ (eq. 2). Under these conditions the plane of translation has a

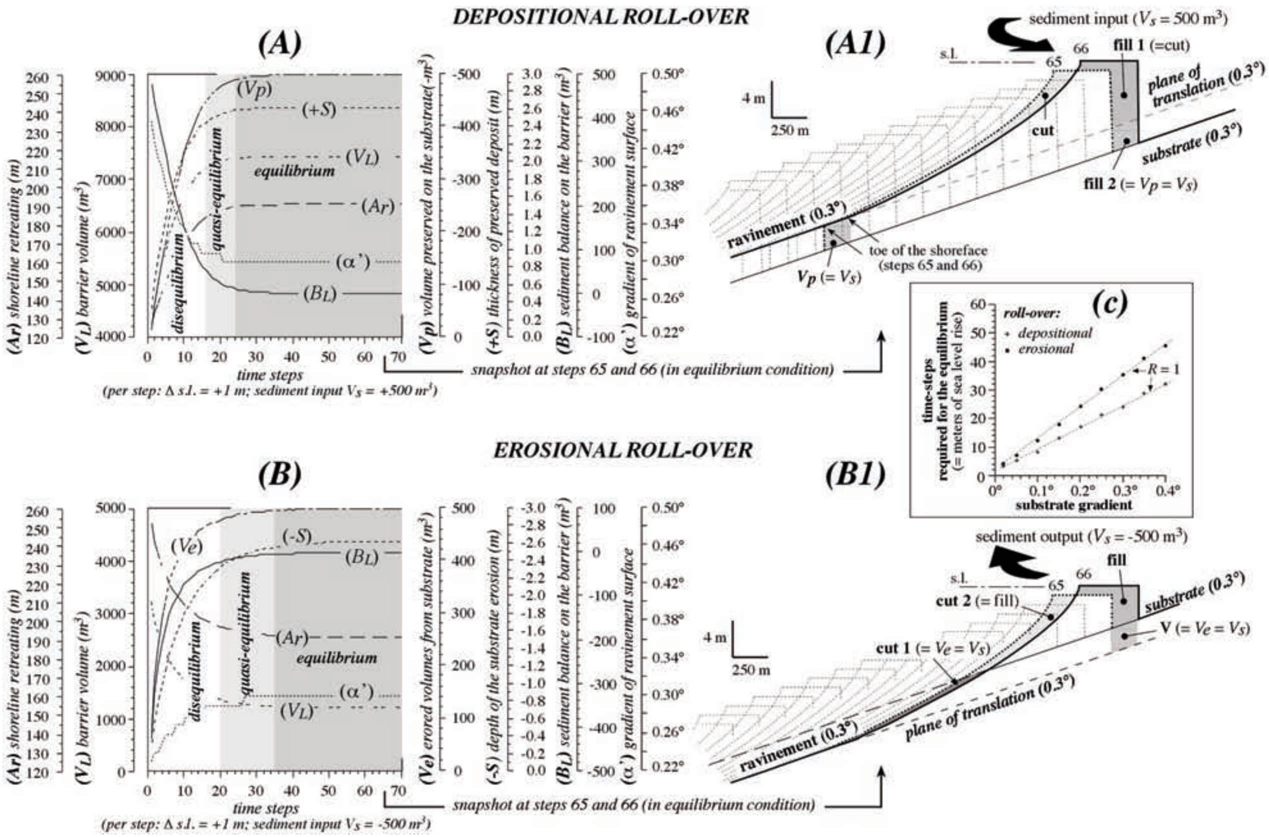


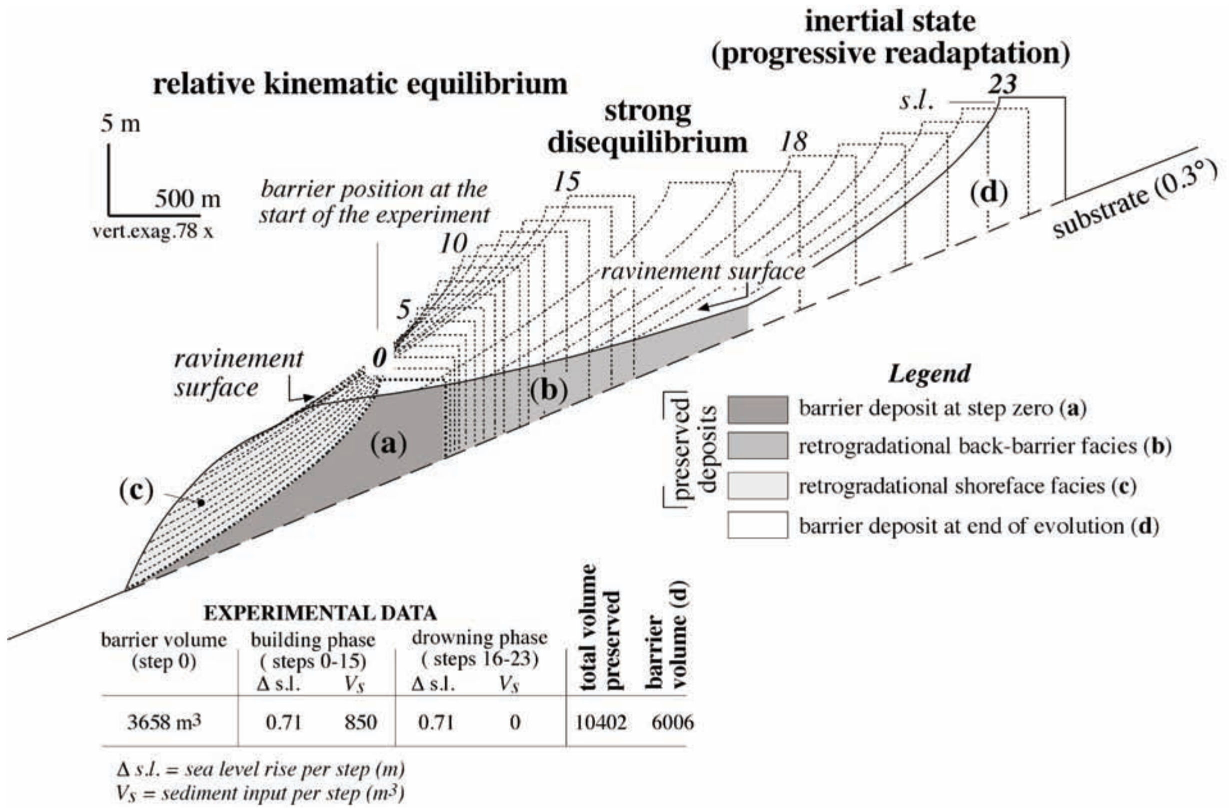
Fig. 8 - Comparative evolution of two littoral complexes perturbed from common initial conditions (step 0-1) by positive and negative sediment supply (V_s = ±500 m3) and SLR held at constant rates throughout the simulations: (A) tracking parameters for V_s = +500 m3; (A1) barrier geometry kinematic equilibrium attained after SLR = 24 m; (B) tracking parameters for V_s = -500 m3; (B1) barrier geometry kinematic equilibrium attained after SLR = 35 m; (C) plot of time to equilibrium against slope of the shelf.

constant gradient (α'), so as to ensure constant motion, that is identical to that of the substrate ($\alpha' = \alpha$). It is in this respect that the neutral roll-over (Fig. 7B), by definition, remains in a perpetual state of kinematic equilibrium: $V_s = V_e = V_p = 0$, and thus $B_L = 0$ (eq. 2).

In the depositional-and-erosive rollover simulations, the *kinematic relaxation time* (i.e., the time taken to reach kinematic equilibrium) - under constant conditions when repeating the two experiments on different substrate slopes - was found to be inversely related to the gradient of the substrate (Fig. 8C). For example, on gradients of α = 0.02°, the relaxation time is reduced to just 350 years for each type of roll-over (corresponding to 3 m of SLR), compared to the 2800-4100 years for the two examples in Fig. 8 that involve a 15 times steeper slope (α = 0.3°). Wolinsky and Murray (2009) demonstrate that the relaxation time-scale depends on the effective height of the barrier profile (height difference between shoreface toe and backbarrier-substrate intersection). So, with a decrease of the substrate gradient, this effective height becomes smaller giving a shorter relaxation time.

More generally, kinematic inertia is an inevitable delay in adaptation of the coastal system to new conditions. Orford et al. (1995; 2002) identify active kinematic inertia of barriers in a modern gravel-dominated coast. They concluded that the inertia increases with sediment volume within the barrier structure. We found, to the contrary, that strength of the kinematic inertia at any instant (time step) depends on how poorly adapted the barrier shape is with respect to the prevailing conditions (independent of the barrier volume): i.e., how much the barrier shape differs from the equilibrium morphology relevant to the prevailing conditions (see Wolinsky and Murray, 2009). Therefore, it can be inferred that kinematic inertia acts within any transgression as a strong inheritance factor that prolongs the effects of antecedent perturbations through time: generally on time scales of 10^3 years.

The simulation in Fig. 9 highlights the possible implications of kinematic inertia for meta-stability of coastal systems. The example refers to a case of a barrier that undergoes "in-place drowning" (Sanders and Kumar, 1975; Carter et al., 1986), reproduced under conditions of constant SLR with initially high sediment input (steps 0-15, V_s = 850 m3 per step), followed by a period of balanced or zero net input (16-23, V_s = 0). The evolution may be divided into three phases. The first one, depositional, amplifies the topographic relief between the barrier top and the coastal plain (see step 15), while in the second (steps 15-16) and third phase the drowning phenomenon starts and evolves, respectively. During the three phases the transgression is, successively, in a state of near kinematic-equilibrium, in strong disequilibrium, and then weakening disequilibrium. The second phase represents the instantaneous response of the system to the perturbation that occurs between steps 15 and 16 (V_s



barrier volume (step 0)	building phase (steps 0-15)		drowning phase (steps 16-23)		total volume preserved	barrier volume (d)
	Δ s.l.	V_S	Δ s.l.	V_S		
3658 m^3	0.71	850	0.71	0	10402	6006

Fig. 9 - Consequence of kinematic inertia illustrated by "in-place drowning" of the coastal barrier during constant increments of sea-level rise, with a positive sediment budget in the first phase (V_S = 850 m^3, 0-15 steps) that switches to a balanced sediment budget in the second phase (V_S = 0, up to step 23). Note the kinematic inertia of the coastal system following the large translation at time-step 15-16 that marks the barrier overstep event.

reduces from 850 to 0 m^3), with the third phase involving the attempt by the system to reach kinematic equilibrium under the new conditions. Variations in barrier geometry during the third phase depend entirely on the kinematic inertia, since all factors controlling the kinematics remain constant. If these factors subsequently remain constant, the system relaxes toward kinematic equilibrium at step 75 (not shown in figure), when the barrier starts to migrate as a neutral roll-over, specific to conditions in this case.

CONCLUSIONS

Transgressions are controlled by (1) relative sea level rise, (2) sediment input, (3) substrate gradient, and (4) shoreface morphology. These factors in combination determine the trajectory of the barrier migration, which is the real plane of translation recorded by the shoreface-ravinement surface. The three modes of coastal migration, known as roll-over, hybrid and encroachment (Cowell et al., 1995), depend on the geometric relation between this plane and the shoreface. They are distinguished by the position of zones of erosion and redeposition along the coastal profile, by the sediment transfer mechanisms connecting these zones, and by the stratigraphic architecture produced. The three modes, despite having different sedimentary processes, regenerate the littoral system progressively further landwards.

The ravinement surface is traced by the lower extremity in the erosive segment of shoreface (the neutral point). In roll-over the neutral point is at the toe of the shoreface, while in the other two modes it is in a more coastal position, being closest to shore in encroachment. The erosive and depositional potential of the shoreface are dependent on the position of the neutral point, respectively maximised during roll-over migrations (the entire shoreface is erosive) and encroachment (all or almost all is depositional). The shoreface-ravinement surface is a faithful record of the trajectory traced by the neutral point during the course of the transgression. This surface defines the trajectory in all three modes of transgression and in principle is preserved in the rock record, making it a much more useful tracking point than the shoreline trajectory analysed in other studies (Helland-Hansen and Martinsen, 1996; Cattaneo and Steel, 2003; Wolinsky and Murray, 2009). The three modes have defined boundary conditions which depend on the gradient (α') of the plane of translation (i.e. ravinement surface), as well as on the steepness (β) and concavity (m) of the shoreface. Specific numeric fields (of α', β, m) result in the generation of the three modes of coastal migration.

Considering that the plane of translation (barrier trajectory) over the long term assumes a gradient quite similar to that of the continental shelf, the roll-over mode of transgression is generally favoured by gently sloped shelves and more steeply sloping shorefaces, and by either slightly concave or convex shoreface profiles. For profiles typical of the Italian coast, like that adopted in the simulations (β=0.6°; m=0.68), roll-over occurs on continental shelves, or portions of them, with gradients of α < 0.4°. It can also occur on steeper shelf-gradients if shorefaces are sufficiently steep and concave.

Roll-over transgressions cause erosion along the entire shoreface and redeposition behind the barrier (through overwash and flood tidal delta processes). Due to the continual landwards reworking of material, these transgressions tend to conserve the barrier volume and therefore represent efficient systems of sediment mass transfers along the shelf profile. Three types of roll-over are possible, which occur as a function of the sediment supply to the coastal cell (V_S). Neutral roll-over ($V_S = 0$: closed or balanced system) does not alter the underlying shelf, while depositional roll-over ($V_S > 0$) and erosive roll-over ($V_S < 0$) alter it respectively through stratal preservation and erosion. The three types are distinguishable by the position of the ravinement surface: coinciding with (neutral), above (depositional) and below (erosive) the original substrate topography. Allochthonous and autochthonous transgressive sedimentation (Swift et al., 1971) is generally associated with the depositional and erosive roll-over types, respectively.

The barrier migration involves phases of acceleration and deceleration, prolonged through kinematic inertia, typically by more than 1000 years even during the prevalence of constant conditions. Our experiments suggest the following points could also be valid in nature: (1) kinematic inertia can exercise strong influence on the transgression; (2) the strength of this inertia at any time depends on the kinematic disequilibrium between the barrier geometry and prevailing conditions (SLR, V_S, α, $h(x)$); (3) the inertia is an inherited factor by which antecedent conditions prolong their influence through time; (4) the kinematic inertia involves a sequence of geometric self-adjustments of barrier shape that, through mass balance of sediments, ultimately leads to a state of kinematic equilibrium; (5) this state is difficult to reach in nature, requiring constant conditions for long periods of time (typically on the order of 10^3 years), unlikely to occur during real transgressions; (6) a state of quasi-equilibrium may be attained occasionally in nature and is more likely in transgressions over gentlest sloping substrates; (7) cases of rapid evolution can occur when conditions of strong kinematic disequilibrium arise (Fig. 9 from step 16). This final point conceivably applies to modern coasts, especially where dunes have been artificially stabilised under conditions of rising sea level, such as along the coast of the Netherlands: *Dolan's dilemma* (Dolan, 1972).

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REFERENCES

Belknap D.F., Kraft J.G. 1985. Influence of antecedent geology on stratigraphic preservation potential and evolution of Delaware's barrier systems. In: Oertel G.F., Leatherman S.P. (Eds.), Barrier islands. Marine Geology: 63, 235-262.

Boyd R., Penland S. 1984. Shoreface translation and the Holocene stratigraphy record: examples from Nova Scotia, the Mississippi delta, and Eastern Australia. Marine Geology: 60, 391-412.

Bruun P. 1962. Sea level rise as a cause of shore erosion. Journal of Waterways Harbour Division, American Society of Civil Engineers, Proceedings: 88, 117-130.

Carter R.M., Carter L., Johnson D.P. 1986. Submerged shorelines in the SW Pacific: evidence for an episodic post-glacial trasgression. Sedimentology: 33, 629-649.

Cattaneo A., Steel R.J. 2003. Transgressive deposits: a review of their variability. Earth-Science Reviews: 62, 187-228.

Chiocci F.L., D'Angelo S., Romagnoli C. (eds) 2004. Atlante dei terrazzi deposizionali sommersi lungo le coste italiane. Memorie descrittive della Carta Geologica d'Italia, Istituto Poligrafico e Zecca dello Stato: 58, 198 pp.

Chiocci F.L., La Monica G.B. 1996. Analisi sismostratigrafica della piattaforma continentale. In: Improta, S. (Ed.), Il Mare del Lazio. Università degli Studi di Roma "La Sapienza", Regione Lazio Assessorato Opere e Reti di Servizi e Mobilità: 2-37.

Chiocci F.L., Orlando L., Tortora P. 1991. Small-scale seismic stratigraphy and paleogeographycal evolution of the continental shelf facing the S.E. Elba island (northern Tyrrhenian sea, Italy). Journal Sedimentary Petrology: 61/4, 506-526.

CNR-MURST 1997. Atlante delle spiagge Italiane: dinamismo, tendenza evolutiva, opere umane. Fogli 111, 127, 135, 142, 149, 158, 170, 171. Selca, Firenze.

Cowell P.J., Kench P.S. 2001. The morphological response of atoll islands to sea-level rise; Part 1: Modifications to the shoreline translation model. Journal of Coastal Research: 34, 633-644.

Cowell P.J., Roy P.S. 1988. Shoreface Transgression Model: Programming Guide (Outline, Assumptions and Methodology). Unpub Report, Coastal Studies Unit, Marine Studies Centre, University of Sydney, pp. 23.

Cowell P.J., Thom B.G. 1994. Morphodynamics of coastal evolution. In: Carter R.W.G., Woodroffe,C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, 33-86.

Cowell P.J., Roy P.S., Cleveringa J., De Boer P.L. 1999. Simulating coastal systems tracts using the shoreface translation model. Society of Economic Paleontologists and Mineralogists, Special Publication: 41, 165-175.

Cowell P.J., Roy P.S., Jones R.A. 1992. Shoreface Translation Model: computer simulation of coastal-sand-body response to sea level rise. Mathematics and Computers in Simulation: 33, 603-608.

Cowell P.J., Roy P.S., Jones R.A. 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology: 126, 45-61.

Cowell P.J., Stive M.J.F., Niedoroda A.W., De Vriend D.J., Swift D.J.P., Kaminsky G.M., Capobianco M. 2003a. The Coastal-Tract (Part 1): A conceptual approach to aggregated modelling of low-order coastal change. Journal of Coastal Research: 19, 812-827.

Cowell P.J., Stive M.J.F., Niedoroda A.W., Swift D.J.P., De Vriend D.J., Buijsman M.C., Nicholls R.J., Roy P.S., Kaminsky G.M., Cleveringa J., Reed C.W., De Boer P.L. 2003b. The Coastal-Tract (Part 2): Applications of aggregated modeling to low-order coastal change. Journal of Coastal Research: 19, 828-848.

Cowell P.J., Stive M.J.F., Roy P.S., Kaminsky G.M., Buijsman M.C., Thom B.G., Wright L.D. 2001. Shoreface Sand Supply to Beaches. Proceedings 27th International Coastal Engineering Conference: 2495-2508.

Dean R.G. 1991. Equilibrium beach profile: characteristics and applications. Journal of Coastal Research: 7, 53-84.

Dean R.G., Maurmeyer E.M. 1983. Model of beach profile responses. In: Komar P.D., Moore J. (Eds.), Handbook of Coastal Processes and Erosion. Boca Raton, CRC Press: 151-165.

Fleming K, Johnston P., Zwartz D., Yokoyama Y., Lambeck K., Chappell J. 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. Earth and Planetary Science Letters: 163, 327-342.

Dillenburg S.R., Roy P.S., Cowell P.J., Tonazelli L. 2000. Influence of antecedent topography on coastal evolution as tested by the Shoreface Translation Barrier Model (STM). Journal of Coastal Research: 16, 71-81.

Dolan R. 1972. Barrier dune system along the Outer Banks of North Carolina: a reappraisal. Science: 176, 286-288.

Helland-Hansen W., Martinsen O.J. 1996. Shoreline trajectories and sequences: description of variable depositional-dip scenarios. Journal of Sedimentary Research: 66, 670- 688.

Kench P.S., Cowell P.J. 2001. The morphological response of atoll islands to sea-level rise. Part 2: Application of the modified shoreline translation model (STM). Journal of Coastal Research: 34, 645-656.

Leatherman S.P. 1983. Barrier dynamics and landward migration with Holocene sea-level rise. Nature: 301, 415-418.

Milne G.A., Antony J.L., Bassett S.E. (2005). Modelling Holocene relative sea-level observations from the Caribbean and South America. Quaternary Science Reviews: 24, 1183-1202.

Niedoroda A.W., Reed C.W., Swift D.J.P. 1995. Modelling shore-normal large-scale coastal evolution. Marine Geology: 126, 181-199.

Orford J.D., Carter R.W.G., McKenna J., Jennings S.C., 1995. The relationship between the rate of mesoscale sea-level rise and the retreat rate of swash-aligned gravel-dominated coastal barriers. Marine Geology: 124, 177-186.

Orford J.D, Forbes D.L., Jennings S.C. 2002. Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. Geomorphology: 48, 51-85.

Pilkey O.H., Young R.S., Riggs S.R., Smith A.W., Wu H., Pilkey W.D. 1993. The concept of shoreface profile equilibrium: A critical review. Journal of Coastal Research: 9, 255-278.

Roy P.S., Cowell P.J., Ferland M.A., Thom B.G. 1994. Wave dominated coasts. In: Carter R.W.G., Woodroffe C.D. (Eds.), Coastal evolution: late Quaternary shoreline morphodynamics. Cambridge University Press, Cambridge: 121-186.

Sanders J.E., Kumar N. 1975. Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barriers, shelf off of Fire Island, New York. Geological Society of America Bulletin: 86, 65-76.

Schwartz M.L. 1967. The Bruun theory of sea-level rise as a cause of shore erosion. Journal of Geology: 75, 76-92.

Stolper D., List J.H., Thieler E.R. 2005. Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behaviour model (GEOMBEST). Marine Geology: 218, 17-36.

Storms J.E.A., Weltje G.J., Van Dijke J.J., Geel C.R., Kroonenberg S.B. 2002. Process-response modelling of wave-dominated coastal systems: simulating evolution and stratigraphy on geological timescales. Journal of Sedimentary Research: 72, 226–239.

Short A.D. 1979. Three dimensional beach stage model. Journal Geology: 87, 553-571.

Swift D.J.P., Phillips S., Thorne J.A. 1991. Sedimentation on continental margin, IV: lithofacies and depositional systems. In: Swift D.J.P, Oertel G.F., Tillman R.W., Thorne J.A. (Eds), Shelf sand and sandstone bodies, geometry, facies and sequence stratigraphy. International Association of Sedimentologists, Special Publication, Blackwell Scientific Publications: 14, 89-152.

Swift D.J.P., Stanley D.J., Curray J.R. 1971. Relict sediments on continental shelves: a reconsideration. Journal Geology: 79, 322-346.

Tarantola A. 1987. Inverse problem theory: methods for data fitting and model parameter estimations. Elsevier, Amsterdam, 613pp.

Tortora P. 1989. La sedimentazione olocenica nella piattaforma continentale interna tra il promontorio di M. Argentario e la foce del Fiume Mignone (Tirreno centrale). Giornale di Geologia: 51/1, 93-117.

Tortora P. 1996a. Depositional and erosional coastal processes during the last postglacial sea-level rise: an example from the central Tyrrhenian continental shelf (Italy). Journal of Sedimentary Research: 66, 391-405.

Tortora P. 1996b. Utilizzazione di carte granulometriche vettoriali nelle indagini sulla provenienza e dispersione del sedimento: un esempio dal fondale ad est del promontorio di Monte Argentario (piattaforma toscana). Bollettino Società Geologica Italiana: 115, 219-240.

Tortora P., Bellotti P., Valeri P. 2001. Late-Pleistocene and Holocene deposition along the coasts and continental shelves of the Italian peninsula. In: Martini I.P., Vai G.B (Eds.), Anatomy of an orogen: the Apennines and adjacent Mediterranean basins, Kluwer Academic Publishers, Great Britain: 25, 455-478.

Tortora P. and Cowell P.J. 2005. Principi geometrici nei sistemi costieri trasgressivi. Parte 1a: processi di migrazione del litorale. Geologica Romana: 38, 61-75.

Tortora P, Cowell P.J, Adlam K. 2009. Transgressive coastal systems (2nd part): geometric principles of stratal preservation on gently sloping continental shelves. Journal of Mediterranean Earth Sciences: 1, 15-32.

Wolinsky M.A., Murray A.B. 2009. A unifying framework for shoreline migration: 2. Application to wave-dominated coasts. Journal of Geophysical Research: 114 (in press).