LONG-TERM SHOREFACE RESPONSE TO DISEQUILIBRIUM-STRESS: A CONUNDRUM FOR CLIMATE CHANGE

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Abstract

Disequilibrium-stress is proposed as a state in which large-scale episodic changes in environmental conditions occur at rates faster than those at which the shoreface can immediately respond, resulting in a lag in morphodynamic adjustment. Depositional evidence from the southeast Australian coast indicates that disequilibrium stress has persisted for millennia since the onset of the Holocene sea-level stillstand, following the Post-Glacial when sea-level rose more than 100 m.

Measured and inferred trends based on field data obtained in former investigations, along with interactive-inverse simulation experiments, have been used to investigate shoreface response and determine the changes in the geometric shoreface parameters that have occurred since the relative sea-level stillstand (around 6000BP). Mean-trends are examined through a disequilibrium accommodation concept, borrowed from fluvial geomorphology to characterise overfit and underfit inner-continental shelf conditions, arbitrarily inherited from the geographically variable geometry of the continental margin, when flooded by the Post Glacial Marine Transgression.

Simulation results were consistent with the proposal that on inter-millennial time-scales coastal evolution is driven by long-term disequilibrium stress. On overfit shelves, mean-trend behaviours involved a deepening of the lower shoreface and the transfer of sediment landward, from the lower to upper shoreface, accounting for barrier progradation that is common to a number of locations along the NSW coast, occurring throughout much of the late Holocene under relatively stable sea-level conditions. The converse of this response was found to apply for underfit shelves, where simulations showed a displacement of sediment seaward, from the upper to lower shoreface, and the subsequent shoaling of the lower shoreface.

Trends in the rates and direction of disequilibrium have implications for the eventual equilibrium geometry and the time at which equilibrium will be attained, with the overall depth-dependent duration of change since the onset of the Holocene stillstand providing a clear indication of the relaxation time required to attain equilibrium. Under projected sea-level rise, these findings also have a series of corollaries for the response of overfit and underfit shelves, with significant implications for standard methods of predicting coastal response to sea-level rise, based on the assumption that shorefaces typically reside and respond in equilibrium.

Introduction

Evolution of coastal morphology over centuries to millennia (low-order coastal change) is relevant to chronic problems in coastal management (e.g., systematic shoreline erosion). This type of coastal change involves parts of the coast normally ignored in predictions required for long-term management of coastal morphology, in which shoreline evolution linked to the behaviour of the continental shelf and coastal plain is known from geological research to be a significant factor. In this context, the shoreface, defined here as the region extending from the limit of wave run-up on the beachface to the seaward limit of wave-driven sediment transport on the inner-continental shelf, plays an important role in the transfer of sediments to and from the beach, and therefore acts as a filter, source, sink, conduit and/or barrier for sediment transport between the beach and the inner shelf (Thieler *et al*, 1995; Finkl, 2004). As a result, understanding contemporary and long-term shoreface morphodynamics is particularly important for determining or predicting coastal response to predicted sea-level rise, increasing storminess and expanding coastal development (Backstrom *et al*, 2009).

A fundamental underpinning of many coastal models that seek to determine or model long-term morphodynamic behaviour is the concept or assumption of shoreface equilibrium. The basic premise implies that over time, there is a time-averaged or equilibrated profile shape to which shoreface evolution is directed. In a broad sense, equilibrium can be regarded as the balance between the constructive and destructive forces acting on a profile, driven by wave-induced gravity or diffusion processes (Cowell *et al*., 1999). However, when these forces are imbalanced, a disequilibrium exists, and there is a tendency for sediment to be displaced from regions of higher wave energy-dissipation and intense sediment movement, towards adjacent areas of lesser dissipation and less intense sediment movements in an attempt to (re)establish profile equilibrium (Wright, 1995).

Whether or not equilibrium exists is fundamentally dependant on the timescale in question. For example, in dealing with event type responses i.e. storms, the net cross-shore transport of sediments experienced can be cancelled out by successive events; whereas on instantaneous timescales, morphodynamic equilibrium is unlikely to exist, due to the stochastic nature of boundary conditions and the finite morphological response times. However, on timescales of centuries to millennia, and relevant to the prediction and understanding involving long-term morphodynamic response, coastal evolution is hypothesised as partly driven through lower-shoreface disequilibrium-stress (Wright 1995).

This paper reports results of investigations with the aim of verifying shoreface response to disequilibrium-stress on inter-millennial timescales. It is proposed here, that large-scale shoreface change is governed by a departure from equilibrium, with disequilibrium-stress occurring as the result of large-scale episodic changes in environmental conditions (e.g. changes sea-levels), which occur at rates faster than those at which the shoreface can respond. Critical to this premise is the notion of morphodynamic response time, which implies that profile response does not occur uniformly across the shoreface, but rather shows evidence of longer response times with increasing water depth and distance offshore (Cowell and Thom, 1994; Stive and de Vriend, 1995). This idea inherently relates to the concept of geomorphic relaxation (i.e. the time required for the shoreface to attain equilibrium) which is also typically associated with a lag in morphodynamic adjustment (Cowell *et al*., 1999).

Because geomorphic relaxation increases with the morphological timescale, long-term morphodynamic response has been shown to operate at timescales in the order of 10^2 – 10^3 years (Cowell and Thom, 1994; Stive and De Vriend, 1995). This implies that under current conditions of the relative sea-level stillstand and following a period of earlier rapid sea-level change (i.e. the Post-Glacial Marine Transgression), shorefaces would continue to evolve, with many still likely to be in disequilibrium for current stillstand conditions.

Defining shoreface disequilibrium

The concept of shoreface equilibrium dates back to early work conducted by Cornaglia (1889) and Fenneman (1902), and since this time has been furthered by the likes of Johnson (1919), Dietz (1963), Bruun (1962), Moore and Curray (1964), and Dean (1977) among others. Equilibrium in its various forms is fundamentally a product of morphodynamic adjustment, and rests upon principles that a profile of specific grain size, when exposed to constant forcing conditions (e.g. wave climate), will develop a shape that displays no net change in time, although sediment will be in motion (Larson *et al.*, 1999).

The comparison of a shoreface against a theoretical equilibrium provides a means of evaluating shoreface behaviour and time-dependant shoreface change relative to its equilibrium or disequilibrium context. Geometrically, this can be defined in the context of the *shelf regime*, whereby the shoreface is expressed in terms of an evolutionary progression towards an idealised equilibrium state. Classification of the shelf-regime, with respect to the equilibrium assumption, gives rise to three proposed shelf modes: *underfit, overfit* and *graded* (Figure 1). The terminology here is borrowed from those of Dury (1954, 1960), used then in a fluvial context to define misfit (i.e. underfit, overfit and graded) streams.

Applied in a shoreface context, an *underfit* shelf regime can be morphologically defined as being too deep or steep for equilibrium under given conditions of sea-level, coastal-ocean climate and sediment characteristics: defining conditions of positive accommodation (Figure 1b), that is, the lower shoreface is *underfilled* with sediment, providing opportunity for deposition of sediment. On *overfit* shelves, the converse applies, where the lower shoreface is too shallow or flat for equilibrium: i.e. a negative accommodation capacity exists (Figure 1c). Under these conditions, the shoreface is *overfilled*, with a tendency for divergent, across-shelf sediment transport away from the lower shoreface. A *graded* regime applies by definition when a shelf is in equilibrium with the forcing and transport regime for endemic sediments: a neutral accommodation exists (Figure 1a).

Methodology

In principle, questions surrounding shoreface behaviour, large-scale coastal response and disequilibrium-stress could be addressed through direct measurements of cross-shore transport or changes in bed elevations across the shoreface. In practice however, limits to measurement resolution and the extended time-scale at which these processes operate, particularly for the responses of lower shoreface, renders such direct observation impractical. Similarly, modelling of cross-shore transport on the shoreface is notoriously unreliable, thus limiting the feasibility of resolving meaningful residual fluxes (Cowell *et al*, 2001).

The approach therefore employed in this investigation utilised measurements and inferred trends, drawn from extensive field data obtained in previous geological investigations on the NSW coast (e.g. Thom *et al.*, 1978; Field and Roy, 1984; Roy, 1985), and analysed here through inverse simulation experiments. Mean trends are examined for the period of relative sea-level stillstand that followed the end of the Post-Glacial Marine Transgression around 6000 BP. These trends were used to provide estimates for morphodynamic timescales associated with long-term shoreface adjustments, depth-dependent rates of change, and the feasibility of time-averaged cross-shelf transport rates, as inferred from simulated shoreface changes and constrained by the field data.

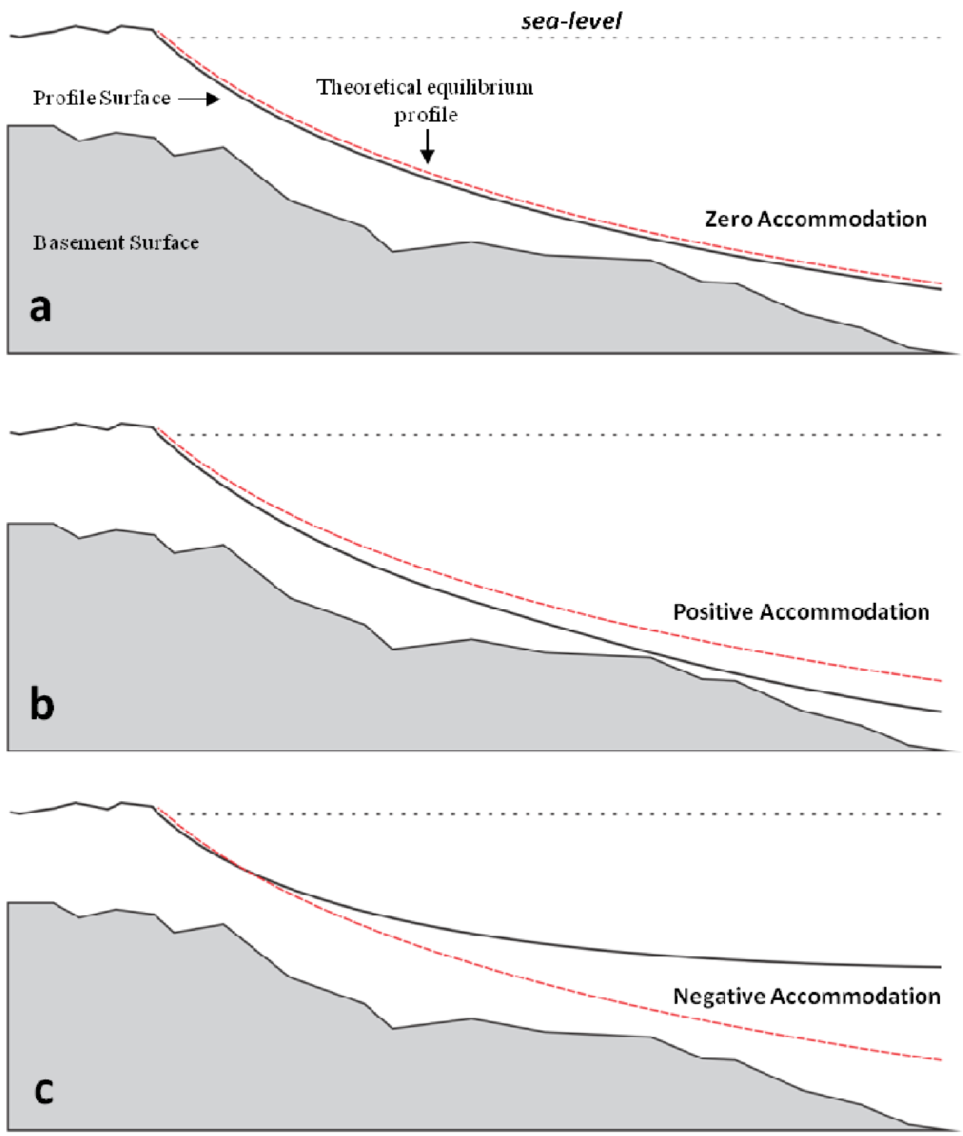


Figure 1 Schematisation of shelf depth with respect to an equilibrium shoreface assumption and accommodation space for the three shelf-regimes (a) graded; (b) underfit; and (c) overfit conditions.

Data and field sites

Over the last 30 years, shoreface and barrier deposits on the southeast Australian coast have been subjected to considerable morphostratigraphic research, with much of this work forming the foundation to understanding barrier evolution over the late Quaternary (Roy and Thom, 1981; Thom *et al.*, 1981; Pye and Bowman, 1984; Thom, 1983; Roy *et al.,* 1994). Data from this research at two locations (Moruya and Bondi, Figure 2) were selected to provide a comparative basis for investigating response of overfit and underfit regimes following the onset of the Holocene sea-level stillstand. The datasets used here were obtained from a combination of bathymetric, sidescan sonar, high-resolution marine-seismic and ground-penetrating radar surveys, for which drilling and vibrocoring results and sedimentological and mineralogical analyses, including the use of radiometric dates, were also available (Thom *et al*, 1978; Roy, 1985).

In the case of overfit shelf regimes two well document examples exist: Moruya and Forster-Tuncurry, located on the southern and northern NSW coasts respectively (Figure 2). Evidence exhibited in a continued progradation of these strandplains throughout much of the mid to late Holocene, is demonstrability of a significant onshore supply of sediment from the lower shoreface and negative accommodation, from which a disequilibrium-stress can be inferred. Due to the intricacies associated with the details surrounding the simulations however, only the Moruya results have been presented in this paper.

Examples of an underfit shelf regime can be found along the South Sydney coast, which is characterised by a relatively steep profile and the presence of headland attached shelf sand bodies (SSBs), the development of which is associated with an offshore sand supply and positive lower shoreface accommodation (Field and Roy, 1984; Roy, 1985). This investigation has focused on the cliffed region at and immediately north of Bondi Beach. Along this region, it has been proposed that offshore deposition and the formation of SSBs are linked to the existence of a former Pleistocene dune field and sand ramp, positioned against the present-day cliffed coast, which following sea-level stillstand was systematically reworked and displaced offshore (Roy, 1984; 1985).

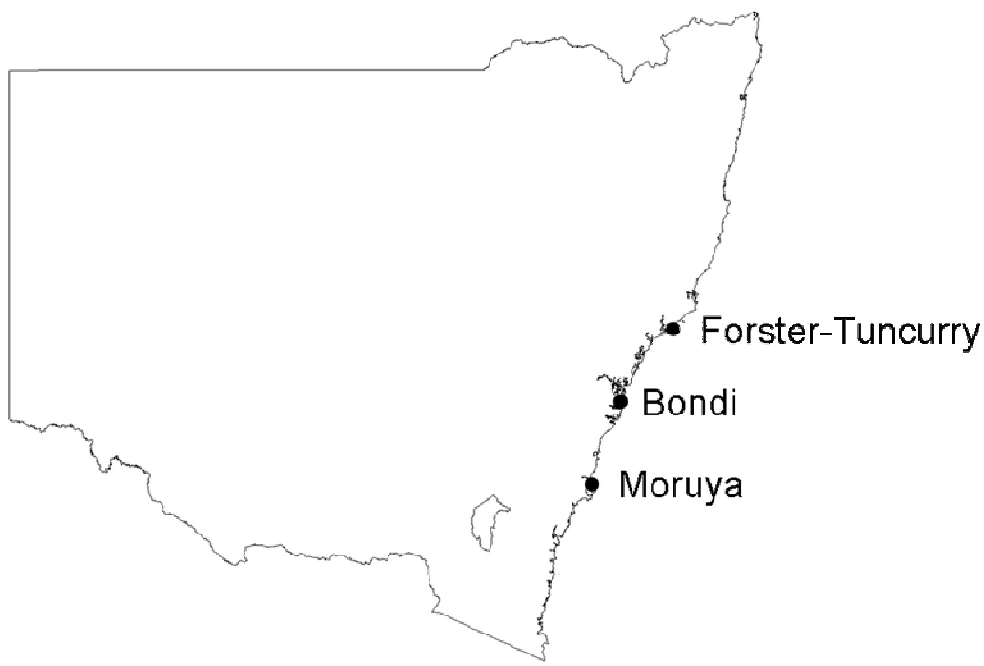


Figure 2 Location of the simulation sites with respect to the NSW coastline.

The Shoreface Translation Model

Simulations in this investigation were undertaken using the Shoreface Translation Model (STM). The STM is an aggregated one-dimensional profile model that adopts a parametric representation of coastal morphology based on principles of mass-continuity and geometric rules for shoreface and barrier morphology (Cowell *et al.*, 1992). In addition, the model also includes provisions for the variable resistance of substrate materials (i.e. rock or sand), sediment grain classes comprising mud and sand, and the capacity to account for the evolution and deposition of backbarrier components (i.e. lakes and lagoons), where present.

Calibration of the STM is provided through use of bulk parameterisation (Cowell *et al.* 1995). The model is designed to simulate the translation of a coastal sand body over any pre-existing substratum, which may also undergo reworking as part of the process. Sediment movements are governed by profile kinematics, that depend upon the geometry of the active shoreface surface, changes in sea-level, shoreface and backbarrier accommodation potential, and any external gains or loss of sediment (Cowell and Roy, 1988; Cowell *et al.*, 1992). For simulations, the model is run in time-stepped intervals, constrained by sediment flows, changes in the parameter values used to define the active profile surface, along with any sea-level variations.

The main advantage of the STM in modelling long-term coastal response is that geomorphic evolution can be constrained using morphostratigraphic measurements rather than through net sediment transport estimates derived from physical processes at the timescale of interest.

Interactive inverse simulation

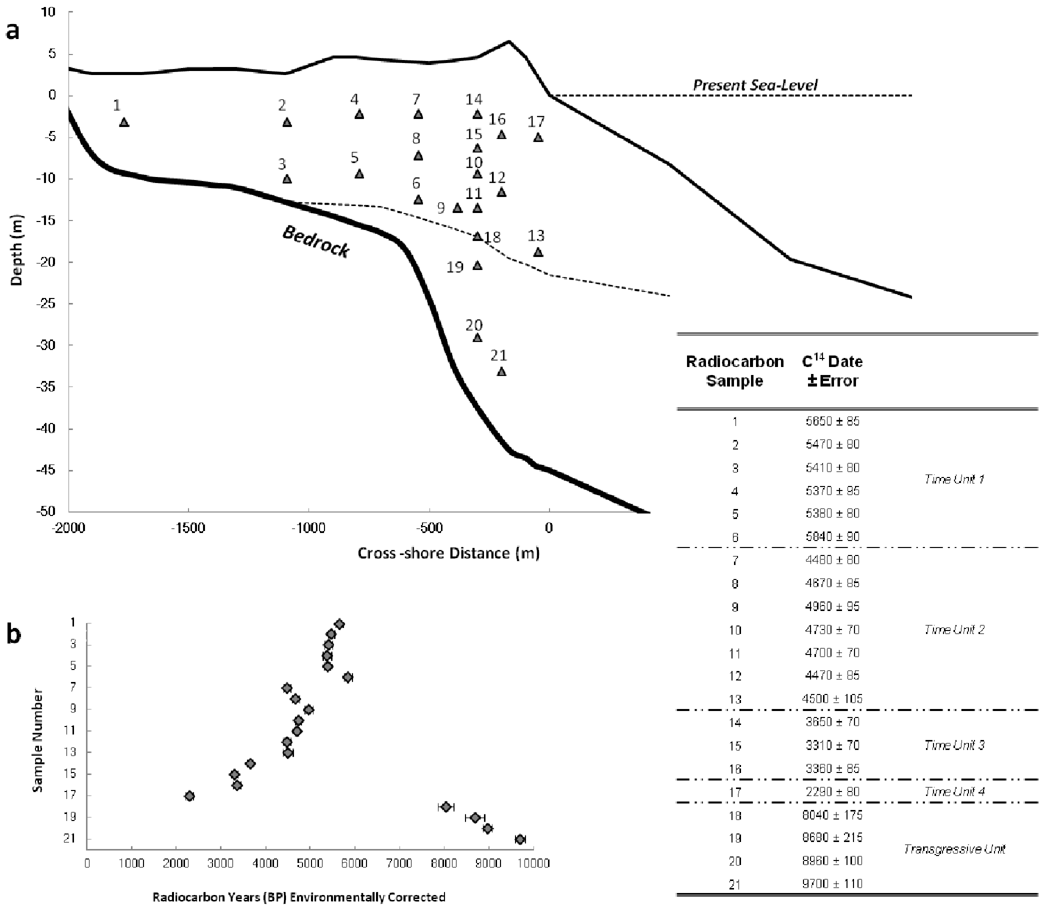
Interactive inversion provides a means of sidestepping many of the limitations associated obtaining direct shoreface measurements. The procedure involves recursively testing hypothetical scenarios optimised using morphostratigraphic data. That is, the inverse simulations are designed to determine the parameter values capable of steering the evolution of deposits towards not only the modern morphology, but also the stratigraphy generated by the morphological response. The procedure thereby allows derivation of initial morphological conditions, optimised for the final stratigraphies and morphologies. The optimised simulations represent the most likely evolution history and morphological response of any particular setting.

The geological and sedimentological evidence used in the inversion methods included the prograded barrier and SSB volumes, plus stratal geometry that provide evidence of sand delivery, derived either from offshore, along the coast, or local deltaic sources. While here there is no counterpart to the depositional volume in the eroded source zones (i.e. the lower shoreface in the overfit case, and the now absent palaeodunes in the underfit case); instead the character of the sediments for instance may provide evidence of a former supply source. For example on overfit shelves, evidence that the lower shoreface may have constituted a sand source can be typically found through the presence of a lag deposit (Cowell *et al*, 2001). Here sediments comprise sand that is coarser than the underlying deposits, the inference being that the finer sand grains have been winnowed out and transported onshore.

Results

Moruya

Stratigraphic reconstruction of the Moruya tract is based upon 35 radiocarbon dates obtained from 8 drill cores across the inshore beach-ridge strandplain presented in Thom *et al.*, (1978). The strandplain itself is comprised of transgressive marine lithofacies consisting of estuarine deposits and shelly sand and gravel, overlain by a regressive marine lithofacies wedge comprising nearshore, beach-ridge and dune sands (Bowman, 1989). A cross-section profile is presented in Figure 3, including 17 of the radiocarbon dates demonstrating the progradation of the strandplain, which has occurred over the past 6000 years. Projection of the strandplain in terms of the proportional barrier width, suggests more than half the barrier was deposited within the first thousand years, with the remaining barrier accumulating since this time (Figure 4).



Radiocarbon Sample	C^{14} Date ± Error	
1	5650 ± 85	
2	5470 ± 80	
3	5410 ± 80	*Time Unit 1*
4	5370 ± 95	
5	5380 ± 80	
6	5840 ± 90	
7	4480 ± 80	
8	4670 ± 85	
9	4960 ± 95	
10	4730 ± 70	*Time Unit 2*
11	4700 ± 70	
12	4470 ± 85	
13	4500 ± 105	
14	3650 ± 70	
15	3310 ± 70	*Time Unit 3*
16	3360 ± 85	
17	2290 ± 80	*Time Unit 4*
18	8040 ± 175	
19	8680 ± 215	*Transgressive Unit*
20	8960 ± 100	
21	9700 ± 110	

Figure 3 Interpreted stratigraphic cross section of the Moruya barrier showing (a) the relative age structure of the strandplain in which the dashed surface separates transgressive from overlying prograded deposits; (b) radiocarbon age distribution ranked by age and sample number shows five distinct time units. Location of the radiocarbon samples and dates are based on environmentally corrected radiometric dating of core samples as presented in Thom et al. (1978).

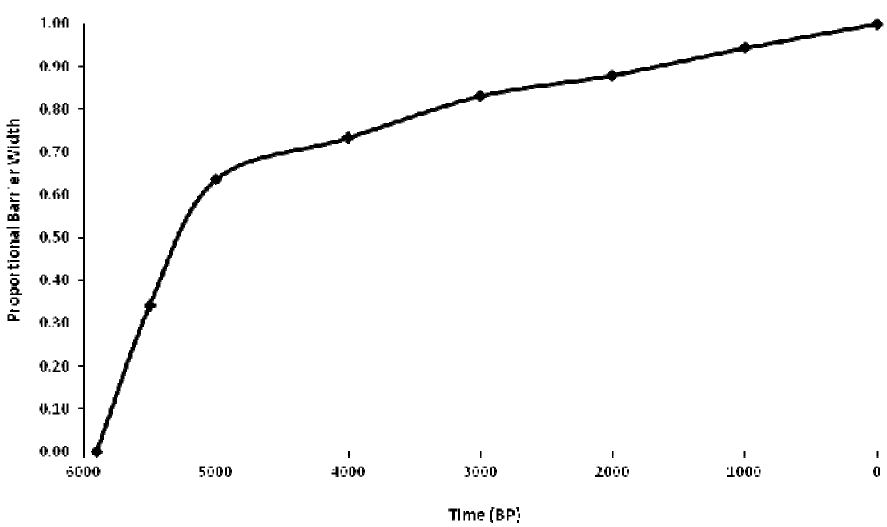


Figure 4 Barrier progradation (proportional barrier width) of the Moruya Barrier through time, as based on the sample locations of the radiocarbon dates taken across the barrier.

Inverse simulations aimed at reproducing this morphology were calibrated with respect to the above. The active surface of the data model was based on the upper regressive unit, which extends into water depths of around 55 m, before grading to mid-shelf muds and marking the toe of the lower shoreface. Offshore the topset of the older transgressive unit, along with bedrock which underlies the barrier inshore was used to define the base of the Holocene substrate. To remain consistent with the aims of the simulations (i.e. exploring the effects of disequilibrium-stress and the subsequent shoreface response following the sea-level stillstand), only the upper (Holocene) surface was set as erodible with the simulation model.

For the model, initial conditions relating to the start-up morphology was based on the heuristic indication of the early isochron geometry established from the radiocarbon dating profile of the strandplain. Simulations utilised multi-step trial and error responses along with time-dependent manipulation of the STM geometric model parameters. The time-series was established starting from 5000 BP and comprising 1000 year time steps. Based on the radiocarbon dating records the opportunity exists to establish an earlier start-up position around 6000 BP (Figure 3). However attempts to model profile evolution from the corresponding position could not be executed due to numerical instability in the STM, when applied to the 6000 BP substrate data model.

Trial and error simulation were run until an optimised starting geometry and subsequent evolutionary response was determined through optimisation against radiometric constraints of the barrier and residual morphostratigraphy corresponding to that of the modern day shoreface. The results of this simulation are shown in Figure 5, and demonstrate that offshore lowering of the shoreface and the subsequent onshore transport are responsible for driving progradation of the Moruya strandplain. Surface lowering averaged across the inner-shelf was around 3.5 m. Results in more detail however showed that lowering is variable across the shoreface, with the greatest volume of sediment supplied from a region around the middle shoreface, where bed lowering reached ~5.5m. Depth dependant responses showed lowering only occurred in water depths greater than 20 m, and peaking in water depth of around 32 m (Figure 5b). Rates of inferred sand supply to the barrier were also shown to decrease through time (Figure 5c), consistent with an exponential decay in rates expected from progressive relaxation of disequilibrium stress.

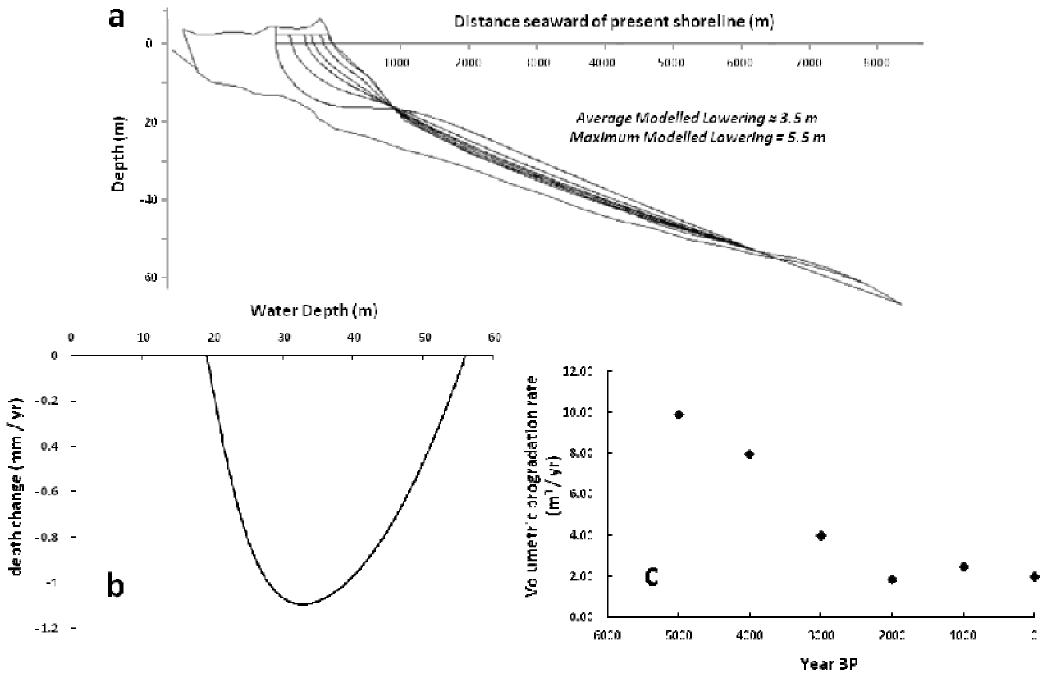
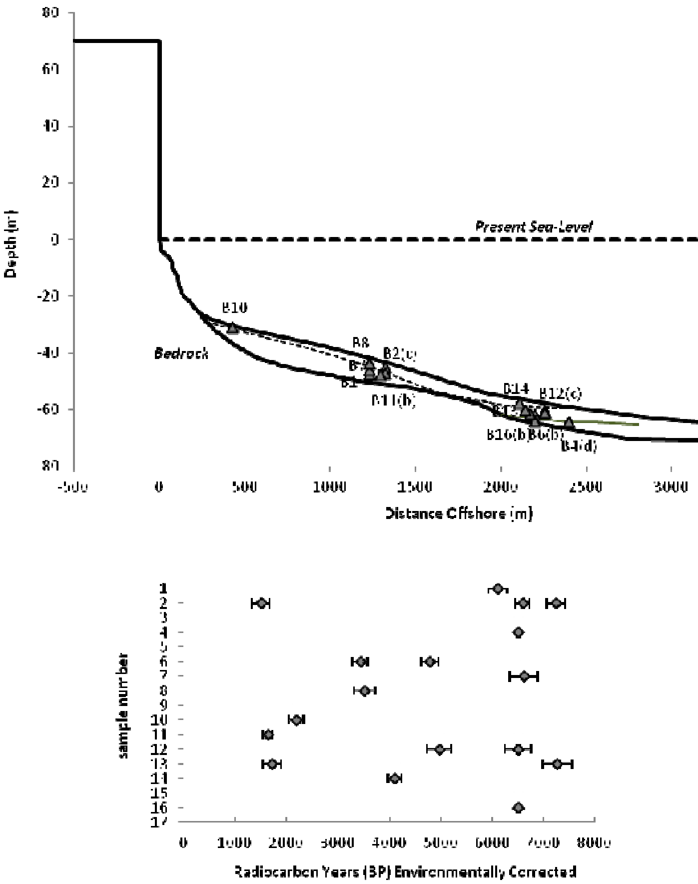


Figure 5 Simulated evolution of the Moruya tract showing (a) the overall profile response including the average and maximum modelled lowering across the shoreface; (b) the depth-dependant rate of lowering over the simulation period; a (c) rate of progradation through time determined from volumetric calculations of the barrier produced in the simulation.

Bondi

Stratigraphic reconstruction of the Bondi tract (Figure 6) was based on 32 radiocarbon samples obtained from 15 Vibrocores and surveys taken across the inner-shelf plain (Roy, 1985). The sedimentology along with the radiometric dating were used to differentiate two primary stratigraphic units: an upper sand body (Unit A) which post-dates the present sea-level stillstand, and a lower sand body (Unit C) which corresponds to the latter stages of the post-glacial marine transgression. The stratigraphy indicates the majority of the lower transgressive unit accumulated at depths between 30 - 50 m, with radiocarbon dating showing sediments of ages between 6000 – 10,000 years. Along the upper unit, the surface morphology, age structure and the geometry are indicative of offshore seaward transport from a landward source (Roy, 1985). Radiocarbon dating throughout this unit also shows the sediment ages mostly less than 7000 years.

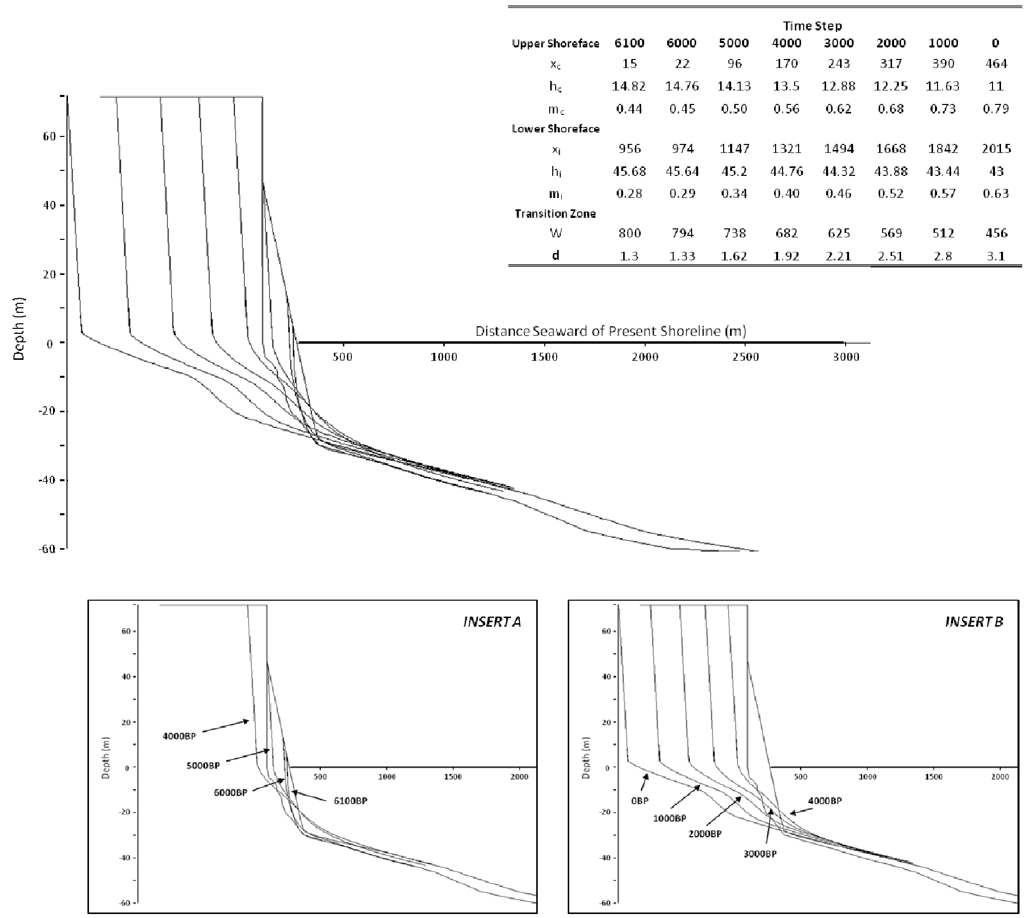
Simulations were calibrated against the morphology of the upper sand body, extending out to a water depth of 43m. This was determined to represent the seaward boundary of the lower shoreface, marked by a profile inflection. Offshore the substrate was defined along the topset of Unit C, whereas inshore where this unit terminates against the bedrock toe of the cliff, the rock surface was used to define the substrate. Within the model only the upper Unit A sand body was set as erodible, with all other units designated as erosion resistant. This ensured the simulations only accounted for the reworking and deposition of the Holocene sediments associated with Unit A.



Radiocarbon Sample Number	C^{14} Date
B1	6100 ± 175
B2(a)	1605 ± 135
	6590 ± 135
	7235 ± 135
B4(d)	6500*
B3(a)	3435 ± 15[illegible]
	4780 ± 135
B7	6620 ± 27[illegible]
B8	3525 ± 205
B10	2100 ± 135
B11(a)	1640 ± 95
B12(c)	4870 ± 235
	6500 ± 20
	6500 ± 23[illegible]
B13	1720 ± 175
B14	2785 ± 23[illegible]
	4110 ± 125
B16(a)	6500*

Figure 6 Interpreted stratigraphic cross section for the Bondi tract showing (a) the stratigraphy and structure of the inner shelf plain; (b) radiocarbon age distribution, although no clear distinction between time-series groups from the samples can be made. Dates are based on the environmentally corrected ages presented in Roy (1985).

Figure 7 displays the history of the Bondi tract, throughout the mid to late Holocene, following the onset of the sea-level stillstand, as determined from the simulations. This simulation indicated that prior to the stabilisation of sea-level, inshore sand onlapping the coastal cliff constituted a relict Pleistocene dune of elevations up to 46m. Simulated details suggest the erosion of the former dune surface was fairly rapid, with most of the sediment volume reworked within the initial 1000 – 2000 years of the sea-level stillstand. The point at which the sand ramp is fully eroded away (i.e. somewhere between 5000 BP and 4000 BP), corresponds to the onset of upper-shoreface translation as a virtual surface extending into the bedrock landward of the cliff. At this point, only the real, exposed portion of the shoreface continues to remain relevant to mass balance related to the sand transfers, with the small remaining volume at the dune base continuing to be reworked downslope, throughout the remainder of the simulation. In line with the deposition of Unit A, the aggradation rates across the shoreface ranged between 0.1 – 0.45 $mmyr^{-1}$ and were also shown to increase in the seaward direction (Figure 8).



	Time Step							
Upper Shoreface	**6100**	**6000**	**5000**	**4000**	**3000**	**2000**	**1000**	**0**
x_c	15	22	96	170	243	317	390	464
h_c	14.82	14.76	14.13	13.5	12.88	12.25	11.63	11
m_c	0.44	0.45	0.50	0.56	0.62	0.68	0.73	0.79
Lower Shoreface								
x_l	956	974	1147	1321	1494	1668	1842	2015
h_l	45.68	45.64	45.2	44.76	44.32	43.88	43.44	43
m_l	0.28	0.29	0.34	0.40	0.46	0.52	0.57	0.63
Transition Zone								
W	800	794	738	682	625	569	512	456
d	1.3	1.33	1.62	1.92	2.21	2.51	2.8	3.1

Figure 7 Simulated evolution of the Bondi tract. Inserts A and B highlight the detailed response separated into two series: 6100 BP – 4000 BP (Insert A) and 4000 BP – 0BP (Insert B).

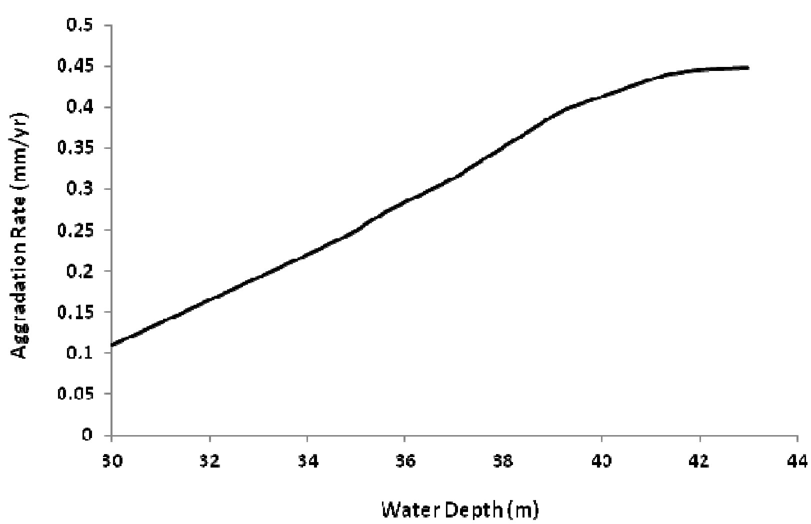


Figure 8 Time-averaged depth-dependant aggradation rate of Unit A seaward of the modelled palaeodune corresponding to water depths of greater than 30m.

Discussion

The simulations experiments on disequilibrium-stress and associated long-term shoreface response demonstrate that the inherited shelf regime plays a fundamental role in determining whether the shoreface functions as long-term source or sink for sand. In the case of the Moruya, the overfit nature of the shelf appears to be the cause of strandplain progradation, in which disequilibrium-stress extending across the shoreface has resulted in a lowering of the offshore bed profile and subsequent onshore transport of sand during the mid to late Holocene.

At Moruya, compartmentalisation provided by the bedrock headlands have been shown previously to protrude far enough offshore to preclude any littoral transport of sediment into the embayment (Roy and Thom, 1981), thereby leaving the lower shoreface as the only viable source of sediment. In order to account for the progradation of the strandplain that has occurred throughout the Holocene, the modelling suggests a lowering of around 3.5 m has occurred across the inner-shelf. Simulated bed changes indicate that on average this lowering occurred at rates between 0.39 and 0.71 $mmyr^{-1}$, a bed lower corresponding to 0.5 and 1.5 grain diameters (per year) respectively. These higher rates occurred earlier, during the period closely following the onset of sea-level standstill, when disequilibrium-stress is expected to have been greatest. The depth-dependant rates of response was found to be greatest around the mid-section of the profile, and corresponded with a lowering up to 1.1 $mmyr^{-1}$, or an adjustment of almost 3 grain diameters. These results are consistent with expectations based on the greater wave-induced bed stresses that are likely to occur over shallower parts of the shoreface, especially considering that Moruya is subjected to a swell dominated wave climate.

Volumetric analysis based on the Moruya simulations suggest following the onset of the sea-level stillstand, about 23,000 m^3 of sand per metre of shoreline has been added to the strandplain, although the rate at which sand appears to have been supplied has decreased over time. This adjustment is indicative of a change or threshold in forcing or in antecedent morphology, which may be the result of the shoreface approaching equilibrium, or due to the effects of bed armouring by the surface lag deposit which has developed on the lower shoreface. However, at present there still remains a mean-trend supply at a rate around 2 m^3yr^{-1}, which implies that a disequilibrium-stress still exists, albeit at reduced magnitude.

The comparative simulations performed on the Bondi Tract provides similar insights into the response of an underfit shelf regime and additionally, in relation to the reworking of a Pleistocene dune, hypothesised to have previously onlapped the coastal cliffs. The optimised simulations leave little doubt as to its former existence, which was found to have extended up to an elevation of around 46m AHD. A volumetric examination determined this dune and the associated sand ramp would have encompassed around 6900 m^3 of sand, which has been subsequently reworked seaward in forming the Unit A SSB. Simulations also showed the rate of deposition associated with the development of Unit A increased seaward across the lower shoreface, and therefore implying an increased disequilibrium-stress further offshore.

These results accord with the systemic conditions of positive accommodation and an underfit shelf-regime, which suggests disequilibrium-stress extends to progressively deeper water depths as the SSB progrades. Moreover, the presence of the hypothesised palaeodune modelled here is consistent with, and also provides a feasible explanation for, the stranded cliff-top dunes found further along the South Sydney coast (Pye and Bowan, 1984). Along the Bondi section of the tract, cliff elevation lay well in excess of the predicted dune heights, accounting for the absence of cliff-top dunes along this section of coast. Further south however, cliff heights are much lower in places such as the Kurnell and Jibbon Peninsulas. Therefore at the onset of the Holocene, these dune heights would have previously overran the present day cliff-line and thereby would account for the now stranded cliff-top dunes that occur in these locations.

Implications for disequilibrium-stress in relation to projected sea-level rise

The persistence of disequilibrium-stress in driving the long-term coastal evolution and in particular, the response of overfit and underfit shelves throughout the Holocene to the present has implications for the expected responses of shorefaces to future sea-level rise, and in turn, the effects on coastal recession. The simulations demonstrated the importance of shelf-regime under stable sea-levels, involving either an onshore sediment supply and barrier progradation on overfit shelves, or on underfit shelves, a tendency for offshore transport and recession. The results indicate that, at the very least, beaches with overfit shorefaces are likely to suffer less recession than those with underfit shorefaces.

Orthodox methods typically applied to determine coastal response to sea-level rise (e.g. the Bruun Rule) are based on the assumption of an invariant profile response, utilising an assumed equilibrium profile. Thus, if the active shoreface morphology is assumed to be in equilibrium then, based on empirical formulae, shallower shelves can be expected to undergo greater recession than their steep shelf counterparts (Bruun, 1962). However, the morphostratigraphic evidence and results of simulations indicates that shorefaces probably still remain out of equilibrium with respect to stillstand conditions, despite roughly 6000 years of relative sea-level stability.

In the case of overfit shelves, as they already appear to be 'too shallow' for current conditions, the possibility exists that onshore sand transport from the inner-shelf may continue despite sea-level rise, at least until a threshold is reached at which overfit disequilibrium stress is ameliorated. However, the effects of increases in sea-level are also likely to reduce the rates of sand supply from the shoreface due to a diminished disequilibrium-stress. This means, as overfit shelves have negative accommodation, sea-level rise will serve to adjust conditions closer to equilibrium, although the degree to which this occurs, would be dependent on both the magnitude of sea-level rise and how far the shoreface initially resides from equilibrium. In contrast, for underfit shelves the opposite considerations apply: that is an increased disequilibrium-stress, due to increased accommodation from sea-level rise, the consequence of which would be to actually increase recession tendencies at the shoreline.

Generally, the above results imply that if long-term equilibrium is unlikely to exist (i.e. there is a long-term disequilibrium-stress) or equilibrium cannot be assumed with confidence, then orthodox methods for predicting coastal response are invalid or, at the very least, need to be treated with extreme caution. Locations subject to these conditions instead require application of more robust models and methods that can incorporate the morphological behaviour associated with shorefaces that still appear to be responding to past sea-level changes, indicative of residual disequilibrium-stress.

Conclusions

Evidence provided through sedimentological and geological data obtained from the southeast Australian coast used to constrain simulations of long-term coastal evolution support the idea that progradation and recession is largely governed by disequilibrium-stress, which has persisted throughout much of the Holocene. Moreover, the continued response at Moruya suggests that this, and possibility other shorefaces, are still yet to fully adjust to the environmental conditions despite 6000 years of relative sea-level stability, and thus also illustrate a significant lag in morphodynamic adjustment associated with long-term coastal response.

Concepts of *shelf-regime* provide a valuable means of evaluating shoreface behaviour relative to disequilibrium-stress. In this context, an overfit regime or shallow shelf regime is defined through negative accommodation and a tendency to transfer sediments onshore from the lower shoreface, resulting in a lowering of the offshore profile and subsequent sediment accumulation on the upper shoreface. In contrast, disequilibrium-stress associated with an underfit regime is indicative of positive accommodation and the propensity for the lower shoreface to act as a sediment sink in sequestering sand from the beach and upper shoreface, resulting in recession at the shoreline and aggradation of sediment on the lower shoreface.

Trends in rates of lower-shoreface change have implications for the eventual equilibrium geometry and the time at which equilibrium will be attained. The overall depth-dependent duration of change since the onset of the sea-level stillstand provides clear indication of the relaxation time required to attain equilibrium, or as a basis for estimating a depth-dependent time lag. Cross-shore sediment fluxes were shown to operate on the order of $10^0 m^3 yr^{-1}$, well below the detectable and predictive limits on annual timescales. Nevertheless, as demonstrated, these small residuals can aggregate through time to account for mean-trend behaviour of long-term coastal evolution.

In general, the simulations indicate the timescales of response associated with disequilibrium-stress involves morphological adjustment, both offshore and onshore, continuing thousands of years after changes in boundary conditions cease. These indications have significant implications for standard methods of predicting coastal response to sea-level rise, which are typically based on the general assumption that shorefaces both reside and respond in equilibrium with forcing conditions.

Alternatively, geological data, and their application through inversion methods, provide a means of downscaling predictions on the interdecadal, climate-change timescale. The across-shelf fluxes of sand inferred from simulations in this study imply that significant recession due to lower shoreface adjustment is entirely feasible on the human-induced climate change timescale, but that estimates need to be evaluated in the context of previous trends indicated in the morphostratigraphy.

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