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Geological control of beach morphodynamic state

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Abstract

The concept of beach morphodynamic states has achieved widespread acceptance in the coastal geological literature since its inception in the mid-1980s and expansion in the 1990s. Much of the pioneering work was undertaken in Australia under a range of environmental conditions in microtidal environments and a close empirical relationship between beach 3-dimensional morphology and the Dean's parameter (H_b/W_sT) was established. Subsequently, the Relative Tidal Range parameter (H_b/TR) was extended to beaches of all tidal ranges.

In this paper, observations are presented from 25 beaches around the north coast of Ireland. These beaches exist on an environmental gradient that encompasses marked tidal and wave energy variability (micro to macrotidal and low to high wave energy). Each beach was visually categorised into one of several established beach states described in the literature, on the basis of field observations. For each beach, the RTR and Dean's parameter were calculated for the immediately antecedent period and used to predict the beach state using published relationships. Observed and predicted beach states were then compared.

Comparison of observed and predicted beach states showed that while beaches with observed dissipative morphology typically matched the expected criteria, most other beach states did not. Lack of agreement between predicted and observed beach states has been reported elsewhere and attributed to failings in the RTR and Dean's parameter. In addition, this study identifies geological factors as important constraints on actual beach state. In the majority of beaches studied, inherited geological factors appear to be more important determinants of beach morphology than contemporary dynamics.

Keywords: beach state models; RTR; Dean's parameter; geological control; sediment supply

1. Introduction

Coastal systems exist largely within an energy-dissipative environment with temporally variable inputs of wave and tidal energy forcing. Many beach studies have adopted the model of a system moving

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towards a state of dynamic equilibrium under steady forcing conditions. Models describing morphological beach form (Dean, 1973; Wright and Short, 1984; Masselink and Short, 1993) have assumed these concepts of equilibrium states and they are now commonplace in many studies of contemporary coastal morphodynamics (Carter, 1988; Woodroffe, 2002). These models relate beach three-dimensional morphology to a small number of environmental parameters. Other studies have also attempted to examine morphological beach state using models based on direct visual observations (Lippmann and Holman, 1990; Short, 1975; Wright and Short, 1983, 1984). This has led to the classification of beaches within dissipative, intermediate and reflective beach modes. Relating beach state observations to forcing factors, Wright et al. (1985) developed a simple predictive model with which to classify beach form. This sequential beach classification scheme was derived from a 6-yr morphodynamic database from a number of Australian beaches and produced an empirical expression describing the relationship between beach state and the dimensionless sediment fall velocity (Dean's number, Ω). Dean's number is a dimensionless parameter first proposed by Gourlay (1968) and then again by Dean (1973), that incorporates both wave and sediment characteristics:

$$\Omega = H_b / W_s T \tag{1}$$

where: H_b = breaker height; W_s = sediment fall velocity and T = wave period. Values of Ω that were less than 1 were associated with *Reflective States*, values between 1 and 6 were *Intermediate States*, while values greater than 6 were typically in a *Dissipative State.*

Recently, however, the use of Dean's number (Ω) for such purposes has been criticised (Anthony, 1998; Levoy et al., 2000; Masselink and Pattiaratchi, 2001) particularly when used in extremely large tidal ranges and low wave energy situations. Under these conditions, the parameters involved in its construction are of relatively low importance in determining beach dynamics compared to factors such as tidal and wind-driven currents. The surf scaling parameter (Guza and Inman, 1975) and the surf similarity parameter (Battjes, 1974; Bauer and Greenwood, 1988) are also commonly employed to differentiate beach states and associated wave conditions within surf zones. They differ from Ω in that they include a measure of beach slope rather than grain size. The surf scaling parameter is given by:

$$\varepsilon = \left(2\pi^2 H_b\right) / \left(gT^2 \tan^2\beta\right) \tag{2}$$

where: H_b is breaking wave height (m), T is wave period and β is local beach slope.

Using (2), surf zone conditions may be categorised into broad classes of reflective ($\varepsilon<2.5$), intermediate ($2.5<\varepsilon<20$) and dissipative ($\varepsilon>20$) conditions.

The surf similarity parameter, ξ, is defined as:

$$\xi = \tan\beta / \left(H_b L_0\right)^{0.5} \tag{3}$$

where: L_0 = deep water wave length (m).

Using (3) wave characterisation (type of wave breaking) is predicted, where surging breakers are defined when $\xi>2$, plunging breakers when $0.4<\xi<2$ and spilling breakers when $\xi<0.4$ (Fredsoe and Deigaard, 1992).

Bauer and Greenwood (1988) concluded that these parameters are useful in discriminating between reflective and dissipative extreme beach states, but do not adequately characterise intermediate situations. Anthony (1998) also noted that for full validation these parameters must be tested against a wide range of natural environments, particularly within lower energy beach systems with a long time response.

Limitations in applying an observational beach state model approach are recognised particularly during 'intermediate' phases as demonstrated by Wright et al. (1987), who found only a 36% agreement between observed and predicted beach states. Ranasinghe et al. (2004) have also expressed concerns about the accuracy of beach state models and the degree of subjectivity involved in their derivation. A general lack of understanding of the forcing variables driving transitional beach state behaviour, lead them to advocate a much more data-rich approach before final derivation of actual beach state classification can be undertaken. Further restrictions on the applicability of these models have been recognised, particularly in their lack of consideration of tidal range effects.

Davis and Hayes (1984) proposed that coastal geomorphology was a function of the *relative* influence of the tides and local wave regime. They noted that absolute values of each of these forcing factors were less important than their relationship. Building on this, Masselink and Short (1993) proposed an additional parameter to take account of tide-induced migration of hydrodynamic processes across the beach profile. This was known as the *Relative Tidal Range*, RTR, where:

$$\mathrm{RTR} = \mathrm{TR}/H_\mathrm{b} \qquad (4)$$

where: H_b is the breaking wave height and TR is the tidal range. This simple parameter was used to quantify tidal effects on beaches; the larger the tidal range the more important tidal effects become *relative* to wave forcing.

Early models (Carter, 1988; Short, 1991) of the morphodynamics of tidal beaches concentrated largely on energy gradations from high to low wave energy. However, these models effectively clustered those beaches with dissimilar tide ranges, sediment grain sizes and beach morphology into a single group (Short, 1991). The work of Masselink and Short (1993) however, proposed a distinctive grouping of beaches on the basis of four constraints; modal breaking wave height, modal breaking wave period, upper beach face sediment characteristics and mean spring tidal range. Further simplification of these was achieved using two dimensionless parameters: the Dimensionless Fall Velocity (or Dean's parameter, Ω) (Eq. (1)) and the Relative Tidal Range (RTR) (Eq. (4)).

The conceptual model of Masselink and Short (1993) is based on both of these parameters (Ω and RTR). The basis of the model is that use of the Ω parameter allows assessment of the likelihood of the beach being dissipative, intermediate or reflective and using the RTR identifies the relative importance of shoaling, surf zone and swash processes in generating local profile morphology (Masselink and Turner, 1999). With increasing Ω and RTR the model suggests a defined beach morphology consisting of wave-dominated beach types, mixed wave-tide beaches and finally tide-dominated beaches. Although the model was generated using examples from 11 sites around the macrotidal beaches of Queensland, Australia, its use has been applied in many other environmental settings around the world. A number of authors have cautioned against the uncritical use of

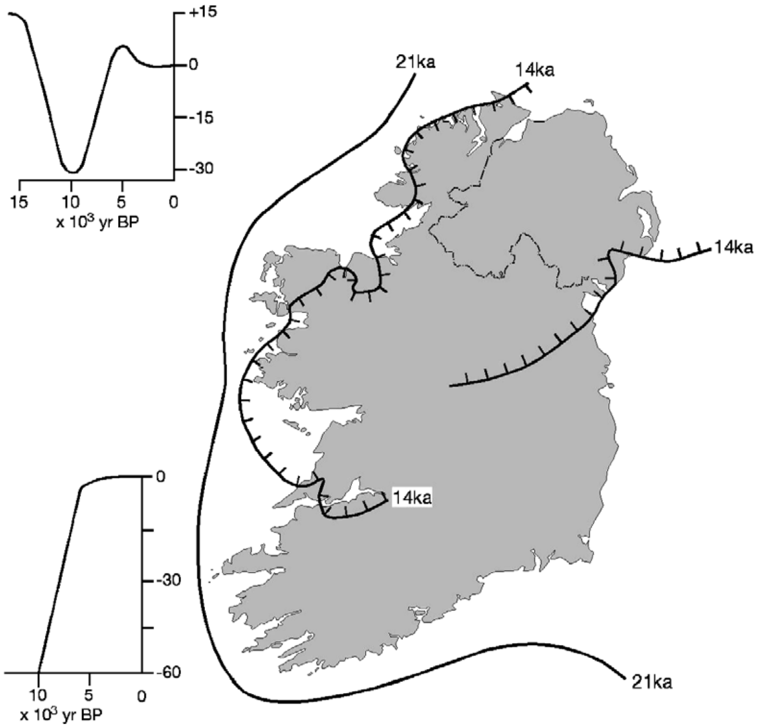

Fig. 1. Main ice limits in Ireland (after McCabe and Clark, 2003) at c. 21 kyr BP and at c. 14 kyr BP and relative sea level curves for the north and south Irish coast (based on Taylor et al., 1986; McCabe and Clark, 2003; Cooper et al., 2002).

these simple models of beach state. Sanderson and Eliot (1999) demonstrated that beach state models are not always practical particularly if complications such as the presence of nearshore reefs exist, and other authors have criticised the use of Dean's number (Ω) in this context (Anthony, 1998; Levoy et al., 2000; Masselink and Pattiaratchi, 2001).

Against this background, this paper aims to test the applicability of the morphodynamic beach model proposed by Masselink and Short (1993) on the dynamically and geologically variable coastline of the north coast of Ireland and Northern Ireland. A range of beaches were selected (Fig. 3) that reflect a variety of tidal, wave, and sediment supply conditions.

2. Environmental setting

Ireland has a 3000-km-long, bedrock-framed coast located between 50 and 55°N (Fig. 1). Coastal plains are absent and coastal sediments usually accumulate as headland-embayment beaches or occasionally as barriers at estuary mouths. The entire island was affected by successive glaciations, although the main Midlandian (= Wisconsinan/Devensian) glaciation and ice limits during deglaciation, are the main constraints on contemporary coastal geomorphology. The main ice limits (Fig. 1) are important factors in coastal geomorphology and dynamics in that they are associated with major sediment sources. Bedrock

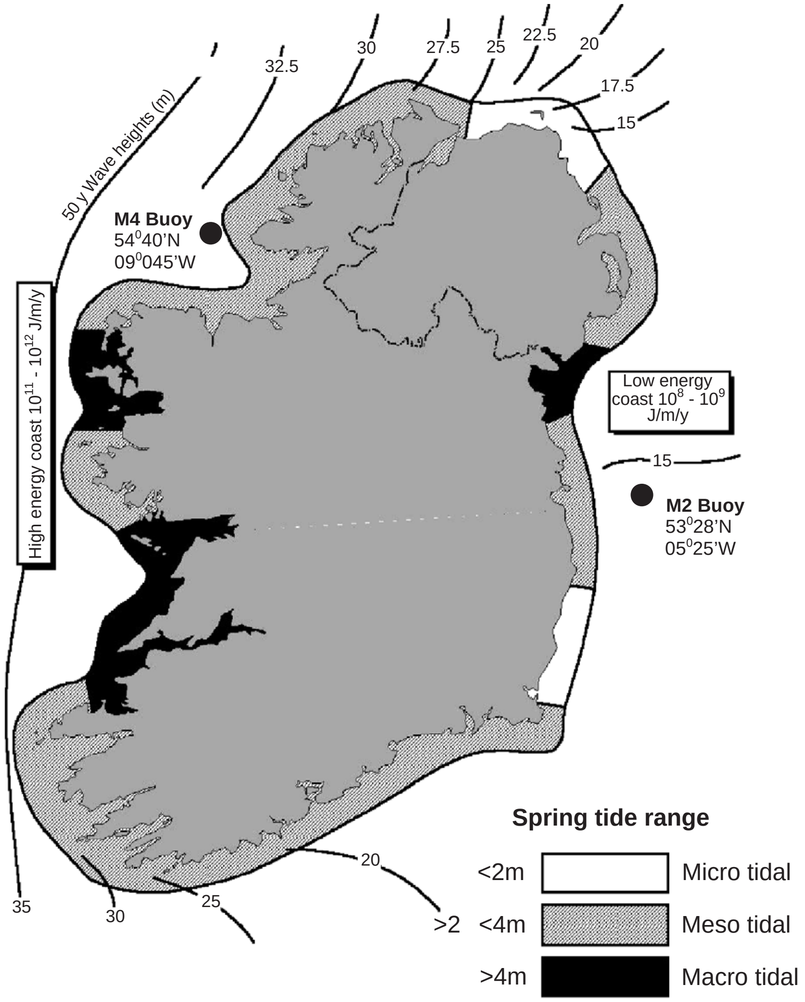

Fig. 2. Tidal range and 1:50 yr wave heights around the Irish coast (source: Carter, 1990).

across the island has been sculpted by glacial processes and glacial sediment was deposited on bedrock veneers. In some areas, a paucity of sediment has left an exposed, sculpted bedrock surface while in others, glacial deposits provide soft, coastal lithologies, vulnerable to erosion at present sea level.

The distribution and variable sediment composition of beaches and barriers in paraglacial settings may be explained in large part by glacial inheritance (Fitzgerald and Rosen, 1987). In Ireland, areas located close to ice limits tend to have sandy barriers, the sand having been deposited initially by outwash and subsequently reworked by marine processes (Cooper, in press). Depositional areas distant from ice margins are instead characterised by coarser sediments (gravel and cobbles) derived largely from reworking by wave action of glacial diamicts. Sediment supply on the Northern Ireland coast occurs predominantly from reworking of shelf sands (themselves of glacial origin) (Cooper et al., 2002), and locally from erosion of bluffs of glacial sediments (Carter, 1991). Coastal sediment supply is thus strongly related to patterns of ice movement, stabilisation and decay during the last glacial cycle.

An additional consequence of the last glaciation is the variable sea level history of Ireland (Fig. 2). In the south, Holocene sea levels have risen steadily through the Holocene from a lowstand at least as low as −60 m (Taylor et al., 1986) whereas the ice-proximal north coast exhibits a relative sea level fall from c. +20 m (McCabe and Clark, 2003) to a Holocene lowstand of −30 m (Cooper et al., 2002). Sea level rise since then has seen a highstand of +2–3 m followed by a fall to present levels (Carter, 1982).

Contemporary rates of sea level change are also variable. Tide gauge observations in the north suggest a near stable or slightly falling sea level over the past 50 yr, while in the south sea level appears to be rising at c. 3.0 mm/yr over the same period (Devoy, 1990).

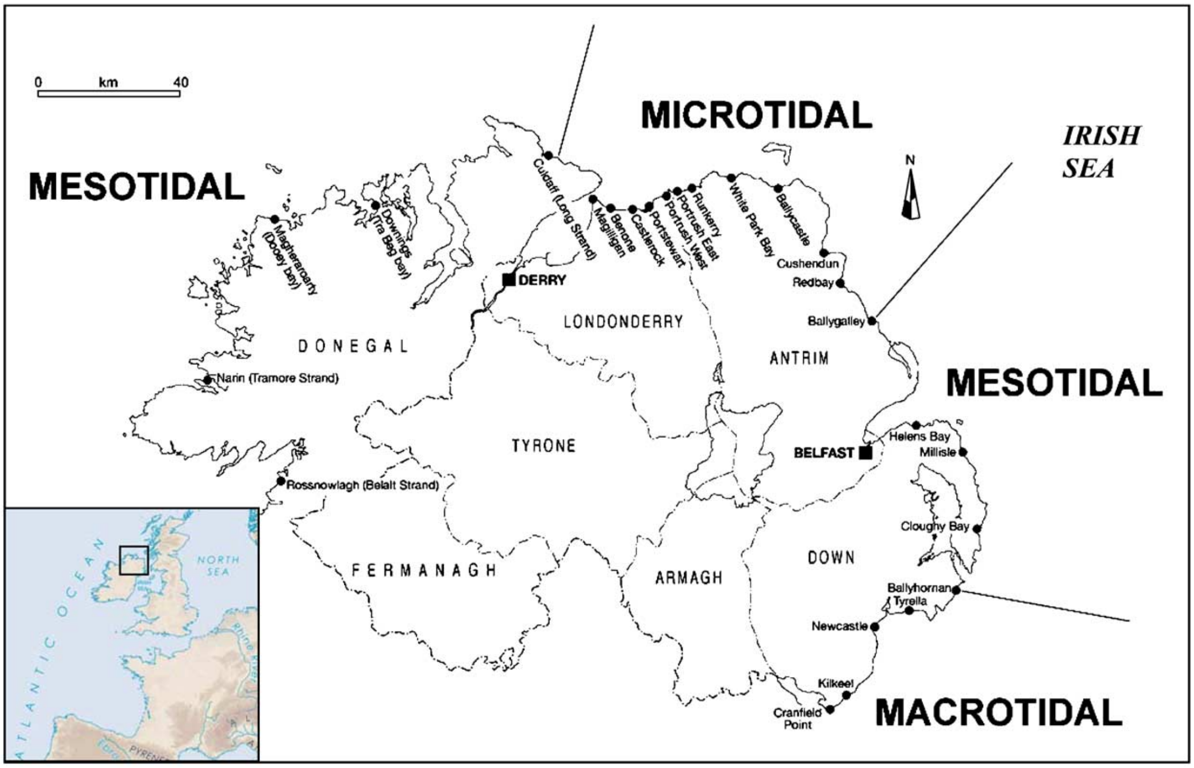

Fig. 3. Location map of the 25 beach sites examined and wave buoy locations.

2.1. Dynamic variables

Around the northern Irish coast there is marked variation in tidal range (Fig. 2). Meso- to macrotidal environments in the northwest give way to microtidal environments around an amphidromic point near Ballycastle. On the northeast coast tidal range increases gradually to macrotidal ranges at Dundrum. The wave regime on the north and northwest is swell-dominated with modally high wave and wind energy. Superimposed on this variability is a strong east–west gradient in wave energy (Fig. 2). The east coast is dominated by locally generated waves produced within the Irish Sea (Orford, 1989). It is thus more prone to energetic short period waves and longshore sediment transport than the west coast where refraction is typically near complete as swell waves approach the shoreline (McKenna, 1990).

These conditions provide gradients of tidal range (macro to micro) in both swell and sea wave environments within which beach morphology can readily be examined in relation to dynamic variables.

3. Methods

To determine the morphology of the beaches used in the study (Fig. 3), shore-normal profiles were established, the number of which was determined by the length of the beach between its enclosing headlands (greater than 500 m—3 or 4 profiles; 500 m or less—2 profiles). Profiles extended from above the high water mark to low water. Most of the field sites were surveyed specifically for this study during autumn 2003, while for some sites (Table 1), profiles measured during previous studies (1999–2001) were used. In all cases a differential GPS (Trimble 4400 series) was used to survey the profiles, providing an accuracy of ±1 cm in the vertical and horizontal dimensions. Textural characteristics of the beaches

Table 1
Beach sites used in the study showing all their major characteristics according to beach slope, mean significant breaking wave height, mean wave period, and mean grain size

	Sites	Mean intertidal slope	Mean spring tidal range	H_0 (mean H_s)	H_b (from mean)	T (mean)	D50 (mm)	RTR (H_{mean})	W_s	Dean (H_{mean})
Mesotidal	Rossnowlagh (Belalt Strand)	0.0139	3.3	2.18	2.49	6.88	0.14	1.33	0.0154	23.38
	Narin (Tramore Strand)	0.0218	3.4	2.18	2.49	6.88	0.18	1.37	0.0175	20.62
	Magheraroarty (Dooey b.)	0.0202	3.4	2.18	2.49	6.88	0.21	1.37	0.0189	19.09
	Downings (Tra Beg b.)	0.0134	3.4	2.18	2.49	6.88	0.14	1.37	0.0154	23.38
	Culdaff	0.0446	2.9	2.18	2.49	6.88	0.23	1.16	0.0198	18.24
Microtidal	Magilligan	0.0375	1.6	2.18	2.49	6.88	0.19	0.64	0.018	20.07
	Benone	0.0194	1.6	2.05	2.4	6.89	0.157	0.64	0.0164	21
	Castlerock	0.0214	1.5	2.26	2.62	7.11	0.166	0.57	0.0168	21.67
	Portstewart	0.0246	1.5	2.26	2.62	7.11	0.157	0.57	0.0164	22.28
	Portrush West	0.0320	1.5	2.34	2.7	7.17	0.186	0.56	0.0178	20.94
	Portrush East	0.0352	1.5	2.34	2.7	7.17	0.197	0.56	0.0183	20.35
	Runkerry	0.0329	1.5	2.18	2.49	6.88	0.28	0.52	0.0218	15.23
	White Park Bay	0.0350	1.2	2.41	2.77	7.22	0.229	0.43	0.0198	19.24
	Ballycastle	0.0823	0.9	2.52	2.89	7.36	0.634	0.31	0.0329	11.85
	Cushendun	0.1037	1.6	1.28	1.38	4.61	0.397	1.16	0.026	11.53
	Redbay	0.0340	1.4	1.36	1.46	4.71	0.169	0.96	0.017	18.31
	Ballygalley	0.0639	1.9	1.52	1.62	4.89	0.218	1.17	0.0193	17.23
Mesotidal	Helens Bay	0.0522	3.3	1.37	1.47	4.7	0.248	2.25	0.0206	15.23
	Millisle	0.0183	3.5	1.38	1.48	4.72	0.141	2.37	0.0155	20.26
	Cloughy Bay	0.0280	3.6	1.55	1.65	4.9	0.17	2.18	0.017	19.79
	Ballyhornan	0.0337	3.8	1.38	1.48	4.72	0.286	2.57	0.0221	14.23
Macrotidal	Tyrella	0.0088	5	1.38	1.48	4.72	0.137	3.38	0.0153	20.55
	Newcastle (Dundrum)	0.0095	5	1.38	1.48	4.72	0.15	3.38	0.016	19.64
	Kilkeel	0.0511	4.0	1.38	1.48	4.72	0.233	2.70	0.0199	15.76
	Cranfield Point	0.0161	4.0	1.53	1.63	4.88	0.214	2.45	0.0191	17.51

were assessed by collecting surface sand samples from the foreshore along a transect running from HWM and LWM. These were then analysed for textural characteristics using a settling tube. Three samples were collected on each profile and two to four profiles were sampled on each beach. Underlying gravel components, if present, were not sampled. The topographic data was used to calculate intertidal beach slopes. Other aspects of beach morphology (presence of cusps, nearshore bars, plan morphology, etc.) were

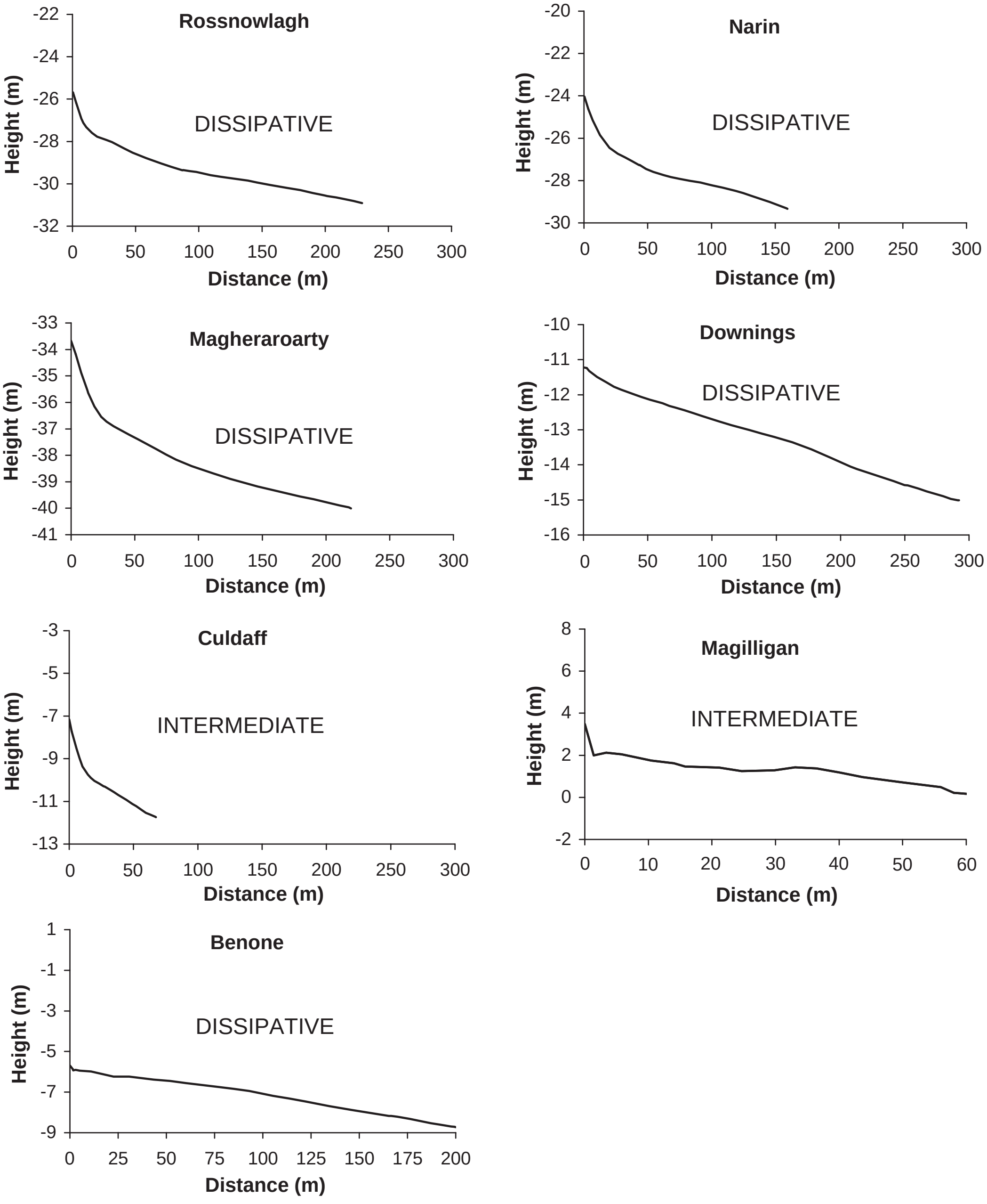

Fig. 4. Profile sections of the study sites located in the mesotidal (2–4 m) northwest coast of Ireland.

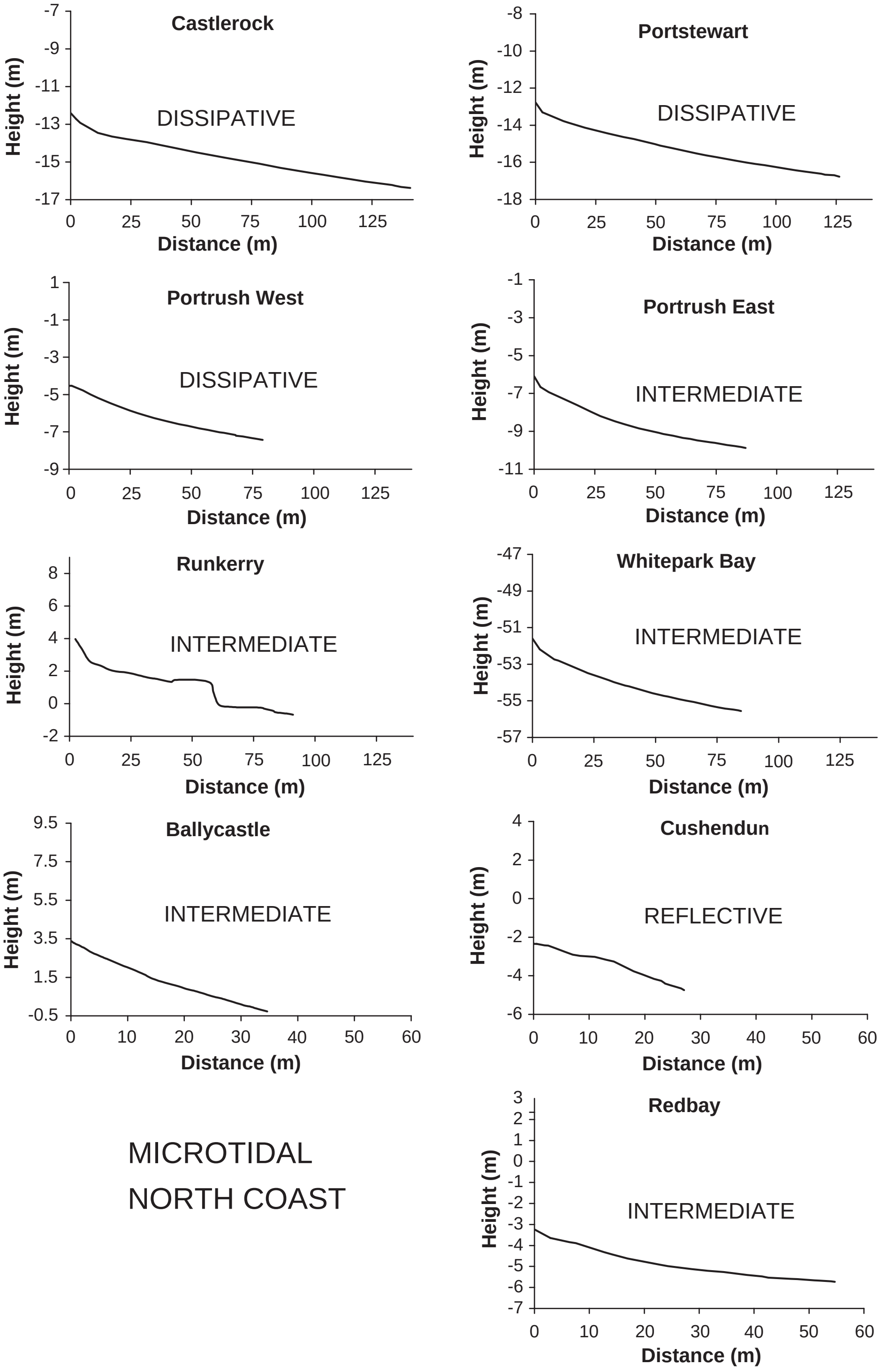

Fig. 5. Profile sections of the sites located in the microtidal (<2 m) north coast of Northern Ireland.

noted in the field. Utilising a combination of observed 3-dimensional morphology and measured beach profiles, each beach was assigned to one of the beach state classes described by Masselink and Short (1993).

Hourly wave data recorded by two offshore buoys (Fig. 1) maintained by the Irish Marine Institute were analysed in order to obtain deep-water modal wave conditions for the month prior to the beach profiling exercise. The M4 Buoy (54°40′ N, 09°04′ W) was used to define Irish Sea wave conditions and the M2 Buoy (53°38′ N, 5°25′ W) described Atlantic wave conditions (Fig. 2). For field sites whose profiles were measured during previous surveys (Rossnowlagh, Narin, Magheraroarty, Downings, Culdaff, and Dundrum), annual averages of wave height and period from the M2 and M4 buoys were used. Breaking wave height (H_b) was computed from the deep-water wave height (H_0) and period (T) for both mean and maximum (90th percentile) waves using the expression (Komar and Gaughan, 1972):

$$H_b = 0.39\, g\, 0.2\left(T H_0^2\right) 0.4 \tag{5}$$

The morphodynamic state of the studied beaches was then predicted according to the model by Masselink and Short (1993) for both modal and maximum wave conditions. For this purpose two parameters were calculated for each beach, the Dean's parameter (Dean, 1973) (Eq. (1)) and the relative tidal range (RTR) (Eq. (4)). Modal conditions are typically used to describe beaches in the literature but the parameters were also calculated using max-

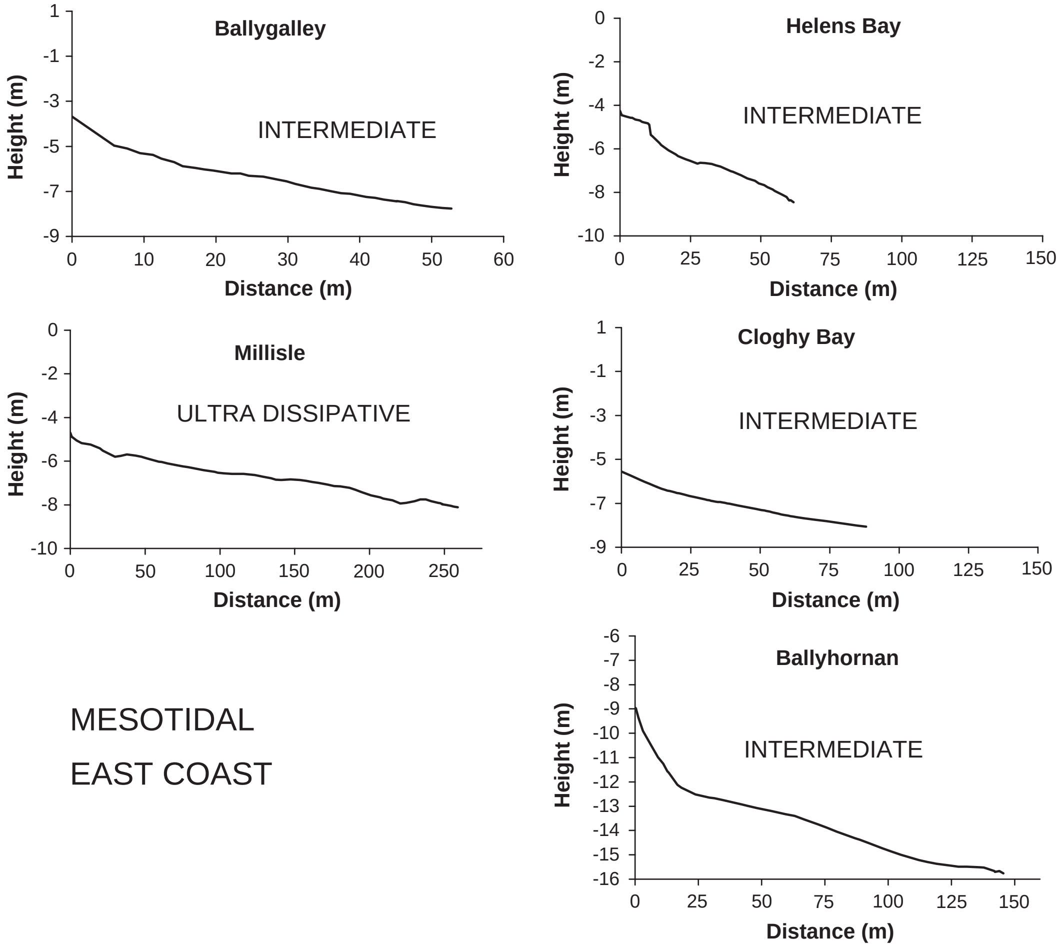

Fig. 6. Profile sections of the sites located in the mesotidal east coast of Northern Ireland.

imum wave conditions for comparative purposes on the premise that modal wave conditions might not be the most morphologically competent part of the wave spectrum.

The observed beach state deduced from field observations and the beach state predicted according to the RTR and Dean's parameter using the model of Masselink and Short (1993) were then compared.

4. Results

4.1. Observed beach state

The measured beach profiles around the northern coast of Ireland show a wide range of morphologies. This is evident in Figs. 4–7 where intertidal profiles of beach sites are portrayed. For convenience description of the beaches is subdivided according to regional tidal ranges into the following regions: NW Ireland (Mesotidal); North Coast (Microtidal); East Coast (Mesotidal); and SE Coast (Macrotidal). Details of the 25 beaches examined together with their sediment, slope, wave, and tidal range characteristics are given in Table 1. Mesotidal beaches in Donegal (NW Ireland, Fig. 4) generally have broad dissipative profiles, with gentle intertidal slopes (e.g. Rossnowlagh). The microtidal North coast (Fig. 5) is largely dominated by intermediate-dissipative beaches in Londonderry (e.g. Portstewart). However, as tidal range decreases towards the east, beaches are in the reflective-intermediate category with relatively steep intertidal slopes along the Northeast coast of Antrim (e.g. Cushendun, Ballygalley). The North coast of Down (Fig. 6) shows largely intermediate beaches (e.g. Helen's Bay) which tend to become more dissipative as tidal range increases towards the South, giving rise to three different beach types: "low tide bar/rip" morphologies (e.g. Ballyhornan), wide ultra-dissipative profiles (Fig. 7) with extremely gentle slopes close to the transition to tidal flats (e.g. Tyrella), and ridge and runnel beaches around Newcastle and Dundrum Bay (Newcastle). The southernmost part of Down is characterised by broad dissipative profiles with morphologies similar to the "low tide terrace" type (e.g. Cranfield). Fig. 8 shows

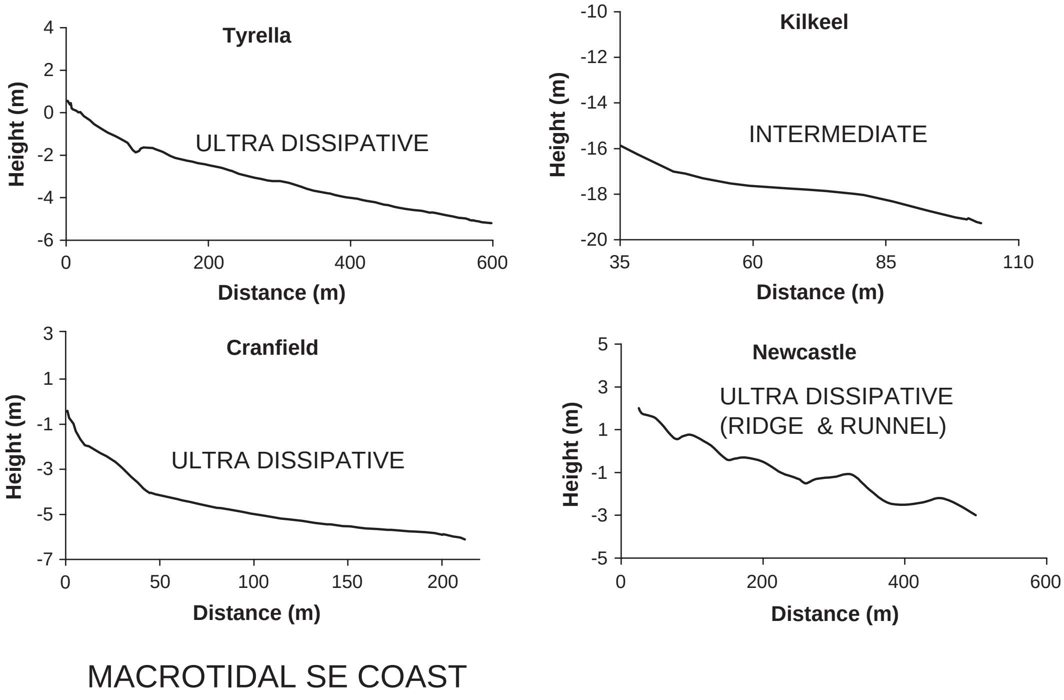

Fig. 7. Profile sections of the sites located in the macrotidal southeast coast of Northern Ireland.

Fig. 8. Selection of sites surveyed and mentioned in the text showing the varied morphologies actually present: (a) Rossnowlagh, Donegal (wide, dissipative); (b) Portstewart, Londonderry (intermediate-dissipative); (c) Cushendun, Antrim (reflective–intermediate); (d) Helens Bay, Down (dissipative); (e) Ballyhornan, Co. Down (Low tide bar rip); (f) Tyrella, Down (wide, ultra-dissipative), and (g) Cranfield, Down (low-tide terrace).

photographs of several of the surveyed beaches to illustrate the large range of morphologies present.

Almost all beaches surveyed were composed of fine sand (mean grain size 0.125–0.250 mm), with only minor variations amongst them. However, there is a regional trend towards coarser grain sizes in beaches in northeast Antrim, with Ballycastle and Cushendun being composed of coarse and medium sand, respectively. As expected, grain size and beach slope exhibited quite a good correlation (Fig. 9-a). This is further improved when profile data from the anomalously coarse Ballycastle beach (Fig. 9-b) are excluded.

4.2. Correlations of environmental and beach parameters

Using results from Table 1, cross-correlations were conducted on local environmental parameters present and calculated beach characteristics. Fig. 10 shows the relationship between (a) Tidal Range and Beach Slope, (b) Beach Slope and Ω, (c) Beach Slope and RTR, (d) Tidal Range and H_b, (e) Ω and RTR, and (f) H_b and RTR. This correlation procedure shows no link between Tidal Range and Beach Slope; Beach Slope and RTR; Tidal Range and H_b or between Ω and RTR. However, the correlation between Beach Slope and Ω is good ($r^2=0.633$) as expected since Ω contains a measure of grain size which is shown (Fig. 9) to be related to slope. The good correlation between H_b and RTR ($r^2=0.608$) is also expected since H_b is a component of RTR.

4.3. Predicted beach state

Using measurements of grain size, breaking wave height, wave period, and tidal range, Dean's parameter and RTR (for both modal and maximum wave conditions) were calculated. These parameters were used to predict the beach state according to the model of Masselink and Short (1993). Fig. 11 shows a plot of RTR versus Dean's parameter for the 25 beaches using modal wave data. All surveyed beaches but one fall into the top right corner, and are therefore predicted to belong to the "barred dissipative" type. Tyrella beach is the only one outside this group and is predicted to belong to the "non-barred dissipative" type. Using maximum wave data, results show an even stronger concentration of beaches on the top right corner, since the increase in H_b increases the values of Dean's parameter and reduces the values of RTR.

5. Discussion and conclusions

Beach state models are often used to predict the morphology of beaches spatially and temporally (e.g. Wright and Short, 1983, 1984; Wright et al., 1985; Lippmann and Holman, 1990, Carter, 1988; Woodroffe, 2002). Our results, however, show in many cases, a marked difference between morphology predicted using this approach and actual morphology, particularly in beaches that are not actually in the dissipative state. Several other authors have identified poor correlation between predicted and observed

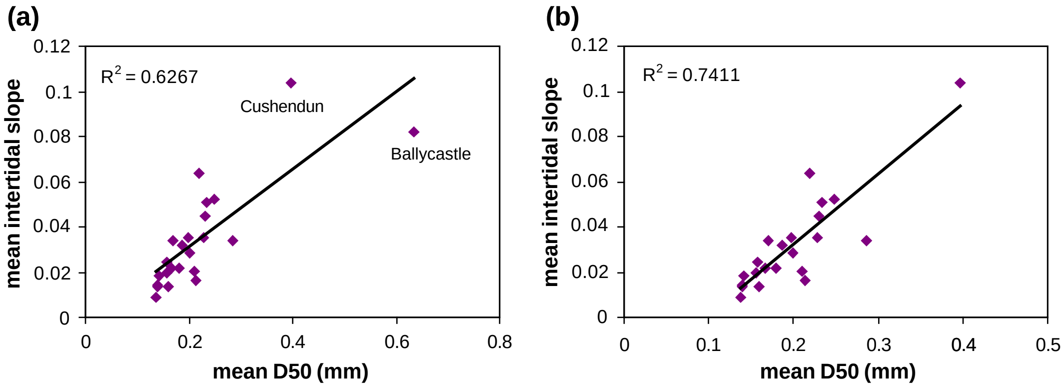

Fig. 9. Relationship of mean grain size and beach slope. Note a good correlation between these variables is displayed for most beaches examined in the study. The anomaly from the point belonging to Ballycastle beach (riverine influence) is removed in graph B improving the correlation.

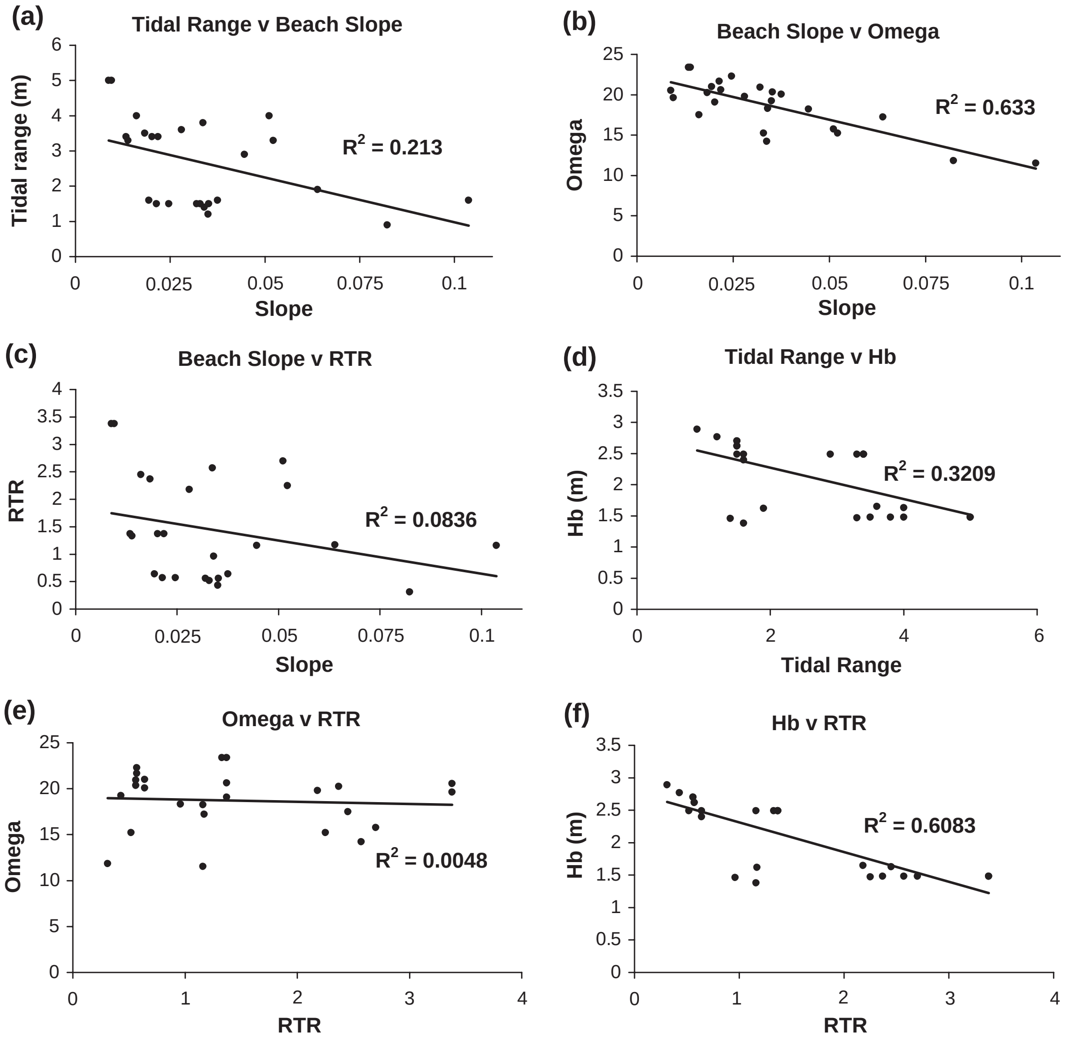

Fig. 10. Plots of environmental factors versus beach parameters. (a) Tidal range vs. beach slope with a poor correlation (r^2=0.213), (b) beach slope vs. Omega showing a good correlation (r^2=0.633), (c) beach slope vs. RTR with poor correlation (0.0836), (d) tidal range vs. H_b with poor correlation (r^2=0.3209), (e) Omega vs. RTR with particularly poor correlation (r^2=0.0048), and (f) H_b vs. RTR showing a good correlation (r^2=0.6083).

beach morphology (e.g. Wright et al., 1987; Sanderson and Eliot, 1999) and have related these to weaknesses in the discriminatory ability of Dean's parameter under certain conditions. While the authors of the beach state models also acknowledge the role of antecedent conditions on beach state evolution, observations on the beaches of Northern Ireland suggest there are several additional factors that are responsible for this deviation. The most important of these relates to geological control.

The geological setting of a beach has two dimensions. The underlying geology establishes the framework within which the beach forms and sets the limits to morphological evolution via the shape and volume of accommodation space (McNinch, 2004). The second important element of geological control lies in the nature and source of beach materials.

The beaches of the north and northwest coasts of Ireland are derived from wave reworking during the Holocene transgression of continental shelf sand

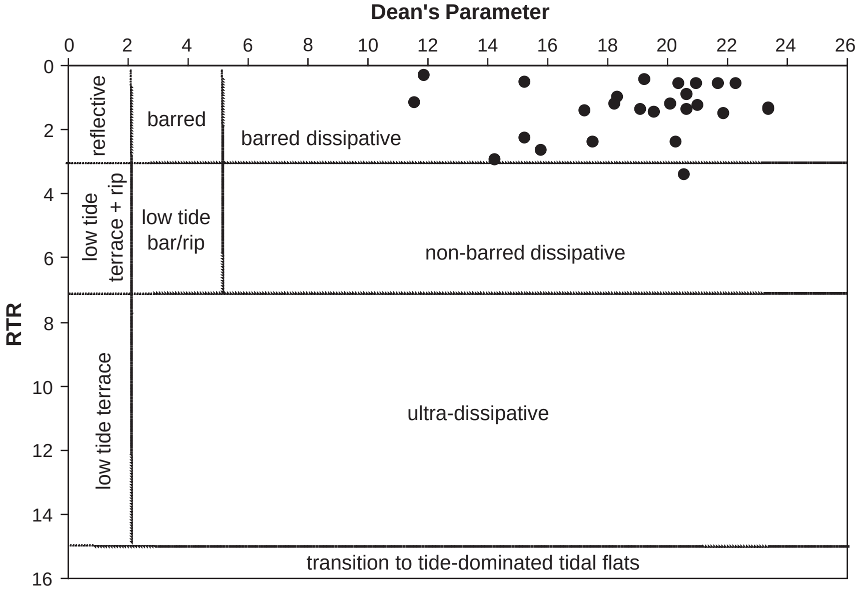

Fig. 11. Plot of RTR (relative tidal range) versus Dean's parameter using modal wave data. All surveyed beaches but one fall into the top right corner, theoretically categorising them as "barred dissipative" types.

(Carter, 1991; Cooper et al., 2002). The resulting beaches have been evolving and have been modified as sea-level has risen during the Holocene. There has therefore been a substantial time period for the contemporary shoreface profile to evolve. This, plus the fact that sediment volumes were substantial and form a veneer of several metres thickness on pre-Holocene sediments (Cooper et al., 2002), means that there is limited geological control on shoreface profile evolution in such sites. The beaches in those areas were all categorised as dissipative, which was in accordance with the beach state predicted by the Masselink and Short (1993) model.

The southeast coast beaches of Dundrum Bay and Tyrella are also derived from offshore sources. These beaches however form a thin, surficial veneer on a relict glacial surface and there is clearly a strong geological control on their morphology. At Newcastle, for example, cobbles are periodically exposed under the sand beach veneer, which is often only centimetres thick (Cooper and Navas, 2004). This underlying surface sets a downward limit for profile modification and thus inhibits profile development (Fig. 12). This situation is markedly different to the north and northwest coasts. In both locations there is abundant sediment (Orford et al., 2003) but in the southeast Irish Sea coast the underlying glacial surface is more gently dipping. It appears to have formed a ravinement surface during the Holocene transgression that now sets a lower limit to beach profile activity. This is likely an important factor in the ridge and runnel topography that exists in Dundrum Bay.

On the east coast, south of Belfast, are a series of beaches (Cloughy, Millisle, Ballyhornan) that are also derived from offshore sources. These beaches, however, are of low volume and overlie relict glacial surfaces or shore platforms (Trenhaile, 2004). Unpublished side-scan sonar data show that there is little remaining offshore sediment supply at present. The morphology of these beaches is constrained both by the low sediment volume (the sediment is worked by waves to the upper limit of the profile) and insufficient sediment to form a full shoreface profile: the lower part of the shoreface is consequently replaced by outcrop of rock or glacial till (Fig. 13). These beaches therefore assume a steeper upper profile than expected and cannot evolve a full beach profile. They have both geological constraint and limited sediment constraints on their morphology.

On the east and northeast coast the beach sediment is essentially derived from landward sources (Carter, 1991; Cooper, in press). Raised fluvio-glacial deltas

Fig. 12. Cobbles exposed under the beach sand veneer at Newcastle beach. This underlying cobble surface creates a downward limit for profile modification, inhibiting further profile development.

(McCabe and Eyles, 1988) on the north Antrim coast are dissected by steep streams that deliver sand and gravel to contemporary beaches (Carter, 1991). These beaches (e.g. Cushendun, Ballycastle, Red Bay) are therefore dependant on the volume of fluvial sediment supply and dispersal and accommodation space in the embayments in which they form. As sea level rose during the Holocene, the same factors would have been at play and the beach would have been confined to the river valley in which it formed. Since they are located in drowned river valleys, limited geological control is expected in their profile but a strong geological control exists in their plan form morphology.

Fig. 13. Beach at Quintin Bay south of Cloughy Bay, showing the lower part of a beach profile made up of exposed rock outcrop/platform giving rise to a sediment limited and geologically constrained profile development of the shoreface. Cliff in background is 7.5 m high.

The extreme south coast of Northern Ireland has a series of beaches (e.g. Cranfield) whose sediment is derived from the erosion of adjacent glacial bluffs composed of sand and gravel. These bluffs provide a ready source for beach development but beaches tend to be confined between a basal ravinement surface (defined by lag boulders) and the active cliff face. The main focus of wave activity is at the base of the bluffs and on the beach. The lag boulders at the lower reaches of the beach set a limit to profile modification under contemporary dynamics. The lack of sediment on the shoreface points to offshore and alongshore dispersal of the beach sediment during transgression.

In all beaches studied excepting those of the north and northwest coasts there is a substantial geological control on beach morphology. The north and northwest beaches do exhibit closer agreement between observed and predicted morphologies than our other sites and it is concluded therefore that geological control does exert a substantial influence on beach morphology. In most of the beaches studied, geological controls appear to limit the influence of contemporary dynamics on beach morphology.

In all cases (but one) the beaches studied had a RTR of<3 which places them in a single morphodynamic category according to Masselink and Short (1993). This commonality of category arises, however, from two contrasting situations. On the north and NW coasts, high tidal range is accompanied by high breaking wave heights, which produces a low RTR value (typically <1). On the east coast, high tidal ranges (5 m) are accompanied by lower breaking wave heights but the tidal range is insufficient to produce the high values of RTR included in Masselink and Short (1993) (typically 1.5–2.0). The coarse divisions of RTR included in Masselink and Short (1993) cannot detect this difference in dynamics. The fact that these beaches do not conform to the predicted mode therefore suggests that this parameter, in cases of relatively high wave energy, is masking important hydrodynamic variability. The mixed energy beaches of Anthony and Orford (2002) show significant variations in wave energy as the tide rises and falls, which can be responsible for morphological variation between beaches.

The results in this paper call into question the ability of RTR to discriminate between beach types. A TR/H_b ratio of 5:1 yields the same RTR as a 1:0.2 ratio and yet the morphodynamic situations in both circumstances would be expected to differ markedly. In the former situation, high wave energy is distributed across a wide and gently sloping intertidal slope. In the latter, small wave energy is dissipated across a narrow intertidal zone that is likely to be steeper. To assign a single RTR value masks this important difference and therefore fails to differentiate beaches.

Finally, the Dean's parameter (Dean, 1973) as a discriminant tool for beach morphology is questionable (Anthony, 1998; Levoy et al., 2000; Masselink and Pattiaratchi, 2001). It is based only upon H_b, T, and grain size. It is known that beach morphology depends on many other variables including those geological controls discussed above (bedrock geology, accommodation space, sediment volume, etc.) and other sedimentary factors (grain shape, packing, composition, porosity, lithification, drainage, biological activity, etc.) as well as dynamic factors (secondary wave motions, tidal currents, edge waves, upwelling/downwelling, gravity, etc.) (Cooper and Pilkey, 2004). In addition, it is not always appropriate or possible to assign single values of grain size, wave height, and period to beaches even at an instant in time: beaches are not affected by monochromatic wave fields. The fact that the model worked under certain circumstances may indicate that these parameters are comparatively unimportant at some sites, but in other localities they may become significant influencers of morphology.

Several other workers (Benavente et al., 2002; Sanderson and Eliot, 1999; Klein and Menezes, 2001; Thieler et al., 2001) have drawn attention to discrepancies between predicted and observed beach states under various conditions. Our findings add to this body of information and urge caution in the application of the beach state approach in predicting beach state from dynamic and grain size data. While the beach states described by Wright and Short (1984) and Masselink and Short (1993) appear to account for a wide range of observed morphologies, it is not always possible to link the morphology with the expected parameters in that model. Several combinations of factors could lead to a similar morphology and further research is required into the field relationships between beach state and associated hydrodynamics to elucidate the controls on beach morphology. Clearly there are further important constraints on beach state than those incorporated within the Wright and Short (1984) and Masselink and Short (1993) models.

The Wright and Short (1984) and Masselink and Short (1993) models rely largely on dynamic factors, which may be appropriate in the steeply shelving inner shelf of Australia where geological control on shoreface evolution is limited. Our observations show a range of inherited geological factors that are at least equally as important in determining contemporary beach morphology.

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