CORRESPONDENCE

# Holocene evolution of the gravel coastline of East Sussex: discussion

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## 1. INTRODUCTION

In a recent issue of the *Proceedings*, Jennings & Smyth (1990) investigated a critical aspect of the Holocene coastal evolution of much of Britain; namely gravel (or shingle) sediment supply and beach morphodynamics through time. Their study area is the coastline of East Sussex, and it should be noted that it is only a component of the larger coastal unit (or 'master cell') between Selsey Bill and Dungeness (Fig. 1) (cf. Steers, 1964). This cell is presently characterized by a net easterly littoral drift. Chalk cliffs with associated minor headlands occur between Brighton and (the most dramatic headland) Beachy Head. While these headlands may be a barrier to littoral drift over short periods ($10^2$ years), there is no evidence for major long-term ($10^3$ years) sediment sinks for gravel except at Dungeness, which is the largest coastal accumulation of gravel in Britain. The source of this gravel is debatable (Greensmith & Gutmanis, 1990), but it is widely considered that easterly longshore transport has made a significant contribution to the gravel volume of Dungeness during the Holocene (e.g.; Eddison, 1983).

Jennings & Smyth identify several important factors in the Holocene coastal evolution of East Sussex, including the fundamental role of Pleistocene-derived gravel in the sediment budget and the much more dissected coastal form which existed earlier in the Holocene. This produced a more compartmented littoral drift system than occurs at present. They also demonstrate that the large gravel cuspate foreland called the Crumbles is a relatively ephemeral feature (see also Jennings & Smyth, 1987), a conclusion supported by earlier historic accounts (e.g.; Redman, 1852). Previous models of the coastal evolution of this area emphasized littoral drift (e.g.; Steers, 1964). Jennings & Smyth provide very different models which include a comparatively recent (800 to 300 B.P.) onshore supply of gravel at the Crumbles combined with morphodynamic changes which first favour shoreline progradation and then favour shoreline recession. These models are questionable in terms of their temporal and spatial scales and in regard to their application of morphodynamic concepts. The author would like to offer an alternative and much simpler explanation which is consistent with the earlier published accounts, Jennings and Smyth's data and our present understanding of beach dynamics: episodic longshore supply of gravel to the Crumbles around Beachy Head from West Sussex. The coastal evolution between Selsey Bill and Dungeness, particularly the area of the Crumbles, over the last 5000 years (here termed the late Holocene) is examined to test the validity of this alternative hypothesis, using major topical areas of argument followed by a general discussion.

## 2. CARTOGRAPHIC ACCURACY

The precision of the cartographic data indicating erosion of the Crumbles from 1610 onwards is questionable (Jennings & Smyth, Fig. 3). It is generally found that, excluding some Tithe maps, pre-first edition Ordance Survey 1:2500 maps are only of qualitative value (Carr, 1980; Nicholls, 1985). Experience in the U.S.A. reinforces this conclusion, pre-1830s data being suspect (e.g.; Leatherman, 1983; Anders & Byrnes, 1991). Therefore, the significant land losses at the Crumbles between 1610 and 1823 shown by Jennings & Smyth should not be interpreted quantitatively, although historical sources (e.g.; Redman, 1852) indicate some erosion has occurred.

## 3. THE AGE OF THE GRAVEL BARRIERS

Jennings & Smyth argue strongly that gravel is relatively new to the East Sussex coast. However, the stratigraphic record which such a gravel system would produce is not well documented. It is important to note that pure gravel beaches do not exist: sand is always present even if the quantities are relatively small. The proportions of gravel and sand may vary with time with consequent changes to the beach characteristics. Such changes can occur rapidly. At Highcliffe, Dorset (Fig. 1) a mixed gravel and sand beach was reworked to an essentially sand system over 30 to 40 years after the removal of the longshore supply of gravel in 1938 (Nicholls, 1985). (This beach has now been nourished artificially with gravel). A similar process may have occurred at the Crumbles comprising episodic gravel supply, followed by reworking. The final product could be a stratigraphic record of sand.

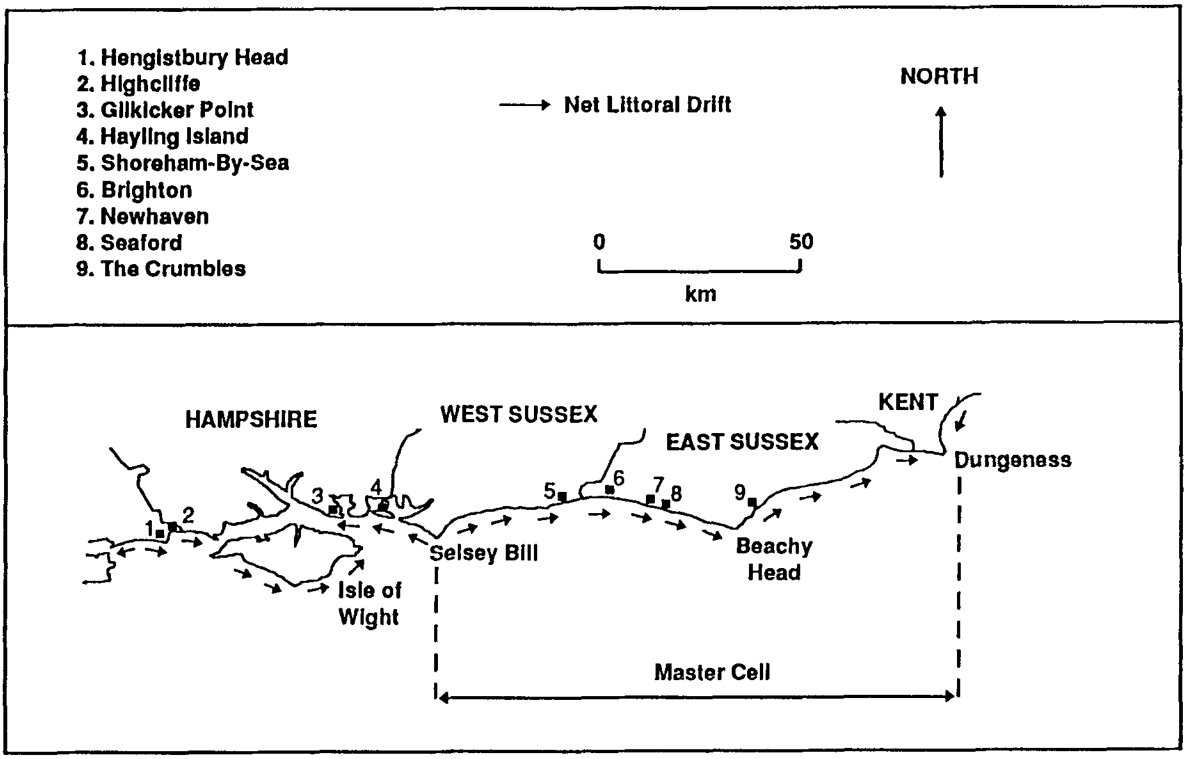


Fig. 1. Location plan showing the net littoral drift and the major coastal cell (or 'master cell') between Selsey Bill and Dungeness.

At Dungeness, Eddison (1983) placed arrival of gravel at about 5000 B.P. followed by a decline in supply as redistribution of existing material became increasingly important. The appearance of gravel has been dated to be no later than 3400 B.P. (Tooley & Switsur, 1988). These observations are consistent with, but not absolute proof of, an easterly littoral drift of gravel from the Crumbles to Dungeness during this time. In summary, gravel or mixed sand and gravel barriers may have been present on the East Sussex coastline for the last 5000 years, although they were probably ephemeral features.

## 4. SEDIMENT SUPPLY—LONGSHORE VERSUS CROSS-SHORE TRANSPORT

Jennings & Smyth consider two possible sources of gravel for the Crumbles: (i) local cliff retreat; and (ii) net onshore movement. They rightly assess the former source as being relatively small (although it will have provided some gravel for easterly littoral drift throughout the late Holocene) and, therefore, propose that onshore movement of gravel must have dominated the sediment budget. (The precise location of this offshore source of gravel is unstated, but a local source off the Crumbles is implied). However, three objections to such a source of gravel can be made:

(i) there is no evidence of an active onshore supply of gravel or any relict offshore deposits at the Crumbles which could have acted as a source of gravel in the period 800 to 300 B.P.

(ii) wave-induced sediment transport at the seabed would have been more effective with the lower sea levels earlier in the Holocene. Thus, the proposed timing of the onshore supply is curious. If storminess drives the process, one would expect onshore transport of gravel in the stormy period identified by Lamb (1977) between 3000 and 2300 B.P. Any such onshore supply would reduce subsequent gravel availability and thus, one would expect any onshore supply of gravel to have declined significantly over the last 5000 years. In summary, it is very unlikely that an offshore source of gravel would appear for the first time at 800 B.P.

(iii) The examples of onshore migration of gravel given by Jennings & Smyth are all gravel barrier beaches which formed in the mid Holocene, demonstrating a critical misunderstanding of process. The original source of gravel may have been offshore in some cases, but once formed, such gravel barriers move onshore in response to sea-level rise by overwashing (Carter & Orford, 1984).

Therefore, a third source of gravel is required. There are large quantities of gravel off the coast of West Sussex with some evidence of active onshore migration (Crickmore, Waters & Price, 1972). As already discussed above, this was probably a more important source of gravel earlier in the Holocene. There is also significant quantities of gravel in Pleistocene raised beach deposits (Hodgson, 1964). Jennings & Smyth discount this source, but Harlow (1979) demonstrated that up to 40,000 $m^3 a^{-1}$ of gravel was available for westerly littoral transport between Selsey Bill and Gilkicker Point over the last few hundred years (Fig. 1). Large coastal accumulations of gravel between Gilkicker Point and Hayling Island suggest that such a source has been operative for much of the late Holocene. The coastline to the east of the drift divide at Selsey Bill is similar, so it is not unreasonable to infer similar quantities of gravel being available. In the long-term this would be expected to be an important source of gravel to East Sussex (Fig. 1). However, a transport mechanism is required.

## 5. EPISODIC LITTORAL DRIFT

Jennings & Smyth note that the chalk cliffs between Brighton and Beachy Head may now be eroding faster than at any time during the Holocene. However, coast protection schemes of seawalls and groynes, such as at Brighton, and harbour moles, such as at Newhaven, have significantly reduced the longshore availability of gravel to the base of the cliffs over the last 150 years. Thus, this could be interpreted as the loss of a protective beach. Jennings & Smyth note that these anthropogenic factors cannot explain the history of the Crumbles as the onset of erosion predates their impact. However, another important factor to consider is the spasmodic nature of longshore transport. Changkuan & Brampton (1988) demonstrated that there is a considerable interannual variability of longshore transport rates around Britain, even under contemporary conditions. If one considers Holocene climatic variability then one would expect even greater variation with time. The magnitude of littoral drift is:

(i) for a given sediment size, a quadratic function of wave height (i.e.; doubling wave height could increase longshore transport by a factor of four);

(ii) very sensitive to the direction of wave approach.

Thus, the periods of storminess described by Lamb (1977) almost certainly caused significant increases in the easterly littoral drift from West Sussex to East Sussex. Of particular interest to this discussion is the increased storminess from 800 to 300 B.P.

In addition to these direct effects, periods of storminess have a less quantifiable, but in this context a potentially equally or more important effect: namely a reduction in the effectiveness of partial barriers to littoral drift such as the chalk headlands of East Sussex. In less stormy periods accumulations of gravel may have developed in areas of potential storage such as Brighton and Seaford because littoral drift was impeded by the chalk headlands. In more stormy periods this stored gravel would be released, amplifying any increase in littoral drift. A return to calmer conditions would allow the temporary sinks to become active again, greatly reducing the availability of gravel. This element of the model must remain rather speculative, but is attractive because it allows the longshore supply of gravel to be almost turned on or off, agreeing with Jennings and Smyth's observations of the abrupt appearance of gravel at the Crumbles about 800 B.P. followed by its disappearance about 300 B.P.

The present volume of the Crumbles is approximately $4 \times 10^7 m^3$ of gravel, assuming an average thickness of 8 m. Assuming formation over a period of 500 years, a littoral drift of 80,000 $m^3 a^{-1}$ is inferred. (This represents a minimum estimate as it is unlikely that the Crumbles was ever a complete sediment trap and some gravel has subsequently been removed to the east by erosion). This is a high sediment transport rate, but similar quantities of longshore gravel transport (63,700 $m^3 a^{-1}$) are estimated for Dungeness under the present wave climate (Muir-Wood, 1970). Given more energetic wave conditions than today, it is not unrealistic that such a quantity of gravel was provided from West Sussex, supplemented by some local erosion of the chalk cliffs.

Evidence for a long-term longshore transport of gravel from West Sussex to East Sussex can also be argued on sediment budget grounds. As already noted, there are no sediment sinks for gravel west of Beachy Head where in excess of 5000 years of littoral drift could be stored. An active easterly littoral drift along this coastline in historic times is indicated by features such as spit development at Shoreham-by-Sea and the problems of shoreline stability at Seaford after the stabilization of the Newhaven Harbour entrance (Steers, 1964).

## 6. SEDIMENTATION AT THE CRUMBLES

The potential for littoral drift is generally a maximum at headlands and often exceeds the available sediment supply (e.g.; Swift, 1976). Downdrift of a headland, which at Beachy Head is in the vicinity of the Crumbles, the littoral drift declines and deposition occurs as the system becomes oversaturated with sediment. A similar situation existed in Christchurch Bay in the period 1848 to 1938 when anthropogenic activity increased the littoral drift rate (Nicholls, 1984). The coast prograded at Highcliffe, a similar location relative to Hengistbury Head as the Crumbles to Beachy Head (Fig. 1). When this supply of sand and gravel was removed (due to groyne construction) the shoreline at Highcliffe became highly erosive. (The reworking of this sediment has already been discussed). Thus, the growth of the Crumbles from 800 to 300 B.P. is consistent with accentuated longshore transport of gravel due to the wave conditions. Since 300 B.P., wave energy and, in turn, the supply of gravel around Beachy Head declined and the sediment budget at the Crumbles went into deficit and shoreline recession commenced.

## 7. BEACH MORPHODYNAMICS

One of the most important insights concerning beach form and its relationship to incident wave conditions in recent years is the recognition of a suite of beach types between reflective and dissipative extremes (Wright, Chappell, Thorn, Bradshaw & Cowell, 1979; Short, 1979; Wright and Short, 1984) and their integrated sedimentary products (Short, 1984). Implicit in these concepts is the modal (or most frequently occurring) beach state. Gravel beaches are steep and thus tend to the reflective extreme. High tide gravel/low tide sand beaches are more complex with an upper reflective element and a lower more dissipative element. The original work showed that changes between beach states took hours to months depending on the direction of the change (accretion or erosion) and the amount of wave energy. Longer term adjustments do occur due to factors such as a changing proportion of sand and gravel: e.g.; a change from dissipative to reflective conditions occurred in south-east Ireland over a period of 10 years due to the closure of an inlet (Orford, Carter, Forbes & Taylor, 1988).

An episodic longshore transport model makes a morphodynamic model unnecessary, but it is still worth considering Jennings & Smyth's ideas. Firstly, the onshore migration of gravel is a poorly understood process. Jennings & Smyth depict the gravel moving onshore as a bar. This is debatable and the process could occur as a thin carpet with little impact on nearshore bathymetry. If one accepts their model of onshore gravel transfer, it is still questionable if the ideas of reflective/dissipative beaches can be applied so systematically over the time period 800 to 300 B.P. It is unlikely that gravel could remain in a dissipative state in the nearshore zone for such a long period. More likely, there would be a relatively rapid transfer of gravel to the shoreline which would produce a reflective gravel beach. Only a major change in the proportion of sand and gravel could cause changes and feedbacks as large as those proposed, although this is not a feature of their model. In short, their morphodynamic model is somewhat speculative. Morphodynamic changes will almost certainly have occurred at the Crumbles, and elsewhere on the East Sussex coastline, but their character requires further research. (The episodic longshore transport model predicts important morphodynamic changes as the proportion of sand and gravel in the beach sediments will have changed with time).

## 8. DISCUSSION

It has been demonstrated that an alternative interpretation of the late Holocene coastal evolution of East Sussex is possible. This simpler model involves episodic longshore transport of gravel to the Crumbles around Beachy Head from West Sussex. This variable longshore transport is driven by the combination of variations in longshore wave energy and the relative trapping efficiency of the chalk headlands which results in large littoral drifts in stormy periods and low littoral drifts in less stormy periods. The model would appear to be consistent with the observations of Jennings and Smyth and negate: (i) the need for significant onshore supply of gravel from an uncertain source during the period 800 to 300 B.P.; and (ii) long-term beach morphodynamic trends for which there is no observational basis.

I would agree with Jennings & Smyth that Pleistocene inheritance is fundamental in determining the Holocene gravel supply to the coastal zone, but I question how that gravel was actually reworked and the time frame over which it took place. Onshore movement plus reworking of land-based deposits provides a large potential source of Pleistocene-derived gravel. The gravel which supplied East Sussex may be largely derived from offshore sources in West Sussex, but longshore transport has been vital in its redistribution. The quantity of onshore movement is probably related to storminess, but other factors such as sea-level and the finite supplies of offshore gravel are also important. Thus, this source of gravel will have declined in importance during the late Holocene and most onshore movement probably predates 800 B.P. This suggests that the reworking of land-based deposits of gravel by coastal erosion has become a relatively more important component of the sediment budget with time. Thus, the accretion of the Crumbles cannot be directly related to onshore movement of gravel. (Onshore movement of gravel may have occurred in East Sussex, to the west of the Crumbles. However, the same arguments regarding timing of this process developed for the West Sussex sources apply).

A fundamental coastal geomorphological concept is the coastal cell and sub-cell (Tanner, 1973; Swift, 1976; Nicholls & Webber, 1987; Carter, 1988). When considering long-term sediment supply it is important to consider the sediment budget of the relevant coastal cell. Jennings & Smyth fail to adopt this approach and consider East Sussex in relative isolation from West Sussex. Sections of the West Sussex and East Sussex coastline may be independent cells over periods of $10^2$ years, but over the timescale of the late Holocene, they only appear to be sub-cells of the larger coastal cell between Selsey Bill and Dungeness (Fig. 1)

The model presented here makes certain predictions which future work can explore. For instance, there would be an inverse relationship between coastal evolution to the east and west of Beachy Head. In calm periods there will be an increase in gravel storage west of Beachy Head and hence greater barrier formation, particularly around Brighton. In stormy periods these stocks of gravel would be depleted by the enhanced littoral drift and reduced effectiveness of the chalk headlands as barriers to littoral drift. At the Crumbles, the reverse is true, with accretion during stormy periods and erosion during calmer periods when the sediment supply fails. This model also predicts that the ultimate sediment sink for coastal gravel in much of West and East Sussex is Dungeness. Such ideas are not new. Over a century ago, Redman (1852) suggested a link between (i) erosion at Brighton and accretion at the Crumbles; and (ii) erosion at the Crumbles and accretion at Dungeness.

This model may not apply throughout the late Holocene. The evolution of the chalk cliffs between Brighton and Beachy Head requires further research, particularly with regard to their trapping efficiency of littoral drift. Possibly they were a more complete or total barrier to littoral drift earlier in the late Holocene, adding more complexity to the coastal evolution of this area.

I would welcome Jennings & Smyth's comments and any clarification they might have of their model of coastal evolution.

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# Holocene evolution of the gravel coastline of East Sussex: reply

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We would like to make the following response to Nicholls' correspondence.

Problems relating to the reliability of cartographic data are well known. However, any doubts concerning the extent of recent historical erosion rates on the Crumbles can be dispelled by the following information, which is additional to that provided in Jennings & Smyth (1990):

1. Between 1736 to 1844 the coastline at the Crumbles retreated by over 1 km (Gilbert, 1963).
2. From the O.S. Map of 1898 (2nd edition), approximately 165 m have been lost since then (L. McMahon, pers. comm.).

It is difficult to respond to Nicholls' discussion on the age of gravel barriers, mainly because much of it appears to be in agreement with our original article. However, the example of Highcliffe, which Nicholls uses twice, is not a relevant modern analogue for the evolution of the Crumbles, because we can demonstrate that the erosion of the Crumbles pre-dates coastal engineering. The situation at Highcliffe has been determined by anthropogenic factors, and the example is on a smaller spatial and temporal scale to that of the Crumbles.

In his section dealing with onshore/offshore movement of gravel, Nicholls uses somewhat inconsistent argument. If the gravel forming the Crumbles originated from offshore, it is not likely to be found now as a relict offshore feature. Sand and gravel can be found in the nearshore zone today along much of the Sussex coastline, and in the form of gravel banks, some of which are moving shorewards. Nicholls fails to recognise the significance of these contemporary features (and others in the southern North Sea), although he mentions them. We agree that sediment supply from offshore is likely to have diminished through the Holocene, as we state clearly in Jennings & Smyth (1990), but offshore sources of gravel do still exist.

Nicholls' concern that we have misunderstood the process of onshore movement of gravel barriers is unfounded. Single ridge gravel barriers can move onshore and further transgress into back barrier areas by overwash, as Nicholls states. This may have applied to the first gravel ridge that formed at the Crumbles, but this 'model' is inappropriate as an explanation for the evolution of the Crumbles because the feature was formed by massive progradation. The examples we gave of gravel barriers moving from offshore demonstrate the efficacy of this source area to provide beach sediment; they were not given as direct analogues for the processes that formed the Crumbles. Most of the gravel ridges of the Crumbles have been destroyed by residential, leisure and commercial development, but no fossil washover features were observed. We believe that this absence of washover features associated with fossil beach ridges is also true for Dungeness, and we would be interested to know whether such features have been recorded there. Overall, Nicholls' treatment of barrier dynamics is simplistic. Gravel barriers exhibit a complex of dynamic responses to variations in sediment supply and to long-term (Holocene) and short-term (periods of increased storminess) relative sea-level movements (Orford, Carter & Jennings, in press).

Nicholls' alternative hypothesis for the formation of the Crumbles by sediment supply via longshore drift relies on a small cliffed section on the eastern side of Selsey Bill providing the sediment. It is unfortunate that Nicholls does not show the location of Pagham Harbour immediately to the east of Selsey Bill on his Fig. 1, as this would indicate the limited extent of these cliffs. According to the Nicholls model, the low raised beaches and periglacial sediments in this area have been responsible for providing most of the late-Holocene gravel found along the Sussex coast, including therefore, the Crumbles (and the supply for our 'proto-Crumbles' (Jennings & Smyth (1990 p. 219))) and Dungeness. He supports this contention by suggesting that the drift system to the west of Selsey Bill is a reliable analogue for the drift system to the east of Selsey Bill (his 'Master Cell'), despite the fact