Vol. 18: 147–156, 2001

CLIMATE RESEARCH
Clim Res

Published October 18

A review of relative sea level rise caused by mining-induced subsidence in the coastal zone: some implications for increased coastal recession

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ABSTRACT: This paper addresses how mining activity under coastal zones impacts on the surface and whether any consequent changes to beach and offshore morphology affect the shoreline dynamics on the beach. The extent of mining activity under coasts is reviewed, with a focus on the interaction of changes in land level, induced by coal extraction at depth under coasts, with sediment and wave processes. The hypothesis is proposed that surface changes, such as a change in substrate gradient, influence the response of beaches to shoreline dynamics. The literature relating to the main parameters governing beach response on macro-tidal coastlines is reviewed, then evidence from reported literature is collated as an example of changes in morphology in a case study on a macro-tidal coastline in NE England. Results from this case study suggest that land subsidence due to mining activities can have a local impact on coastal areas exceeding that of projected sea level rise due to climate changes. Permanent changes in beach gradient cause an altered response to wave dynamics, and a consequent change in the classification of these beaches compared to control beaches, where no subsidence has taken place.

KEY WORDS: Relative sea level rise · Land subsidence · Breaking wave height · Beach classification

1. INTRODUCTION

The 2 most recent, major publications in the field of sea level rise and the coast are those of Bird (1993), and Milliman & Haq (1996). Milliman & Haq's comprehensive collection of edited papers on sea level rise and coastal subsidence includes studies from around the world covering many of the natural and anthropogenic causes of sea level rise. These focus mainly on the extraction of water, oil and gas in coastal areas, e.g. the impact of land subsidence in coastal lowlands (Jelgersma 1996). The present paper extends the subject by considering the extraction of coal from depth beneath macro-tidal coasts, in particular the hard-cliffed coasts of northern England, and the impact on the overlying strata in relation to changes in the surface.

2. REVIEW OF GEOLOGICAL PARAMETERS CONTRIBUTING TO MINING-INDUCED SUBSIDENCE

Table 1 shows the scale of vertical movement (and subsequent relative sea level rise) due to subsidence following the extraction of coal, other minerals, and water from coastal or estuarine areas. In many cases the total amount of subsidence, especially that due to extraction of coal, potash and salt, is of the same order as or exceeds the predicted global, eustatic rise in sea level for this century of between 30 and 110 cm (Haq & Milliman 1996). The following section reviews the literature relating to factors which influence amount and form of surface subsidence following the extraction of coal at depth beneath the coast, the consequent collapse of mined tunnels and the transmission of strains from these collapsed voids. Two factors in particular are examined: firstly processes related to the mining methods employed in the extraction of coal and sec-

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Table 1. Summary of anthropogenically induced subsistence (adapted from Lambeck & Johnston 1995, Table 1)

Region	Vertical movement (mm)	Principal cause	Sources of data
Newcastle, New South Wales, Australia	52–168	Coal extraction	Kapp (1977)
River Trent, England	25	Coal extraction	Shadbolt (1972)
Lynmouth Beach, England	3000	Coal extraction	Anon (1985)
Dawdon Beach, NE England	4000–5000	Coal extraction	Humphries & Ligdas (1997)
Saskatchewan, Canada	100 (yr^{-1})	Potash extraction	Bawden & Mottahed (1986)
Alsace, France	160	Potash extraction	McClain (1963), Potts (1964)
Esparza mine, Spain	670	Potash extraction	Oyanguren (1972)
Windsor, Ontario, Canada		Solution mining of rock salt	Terzhagi (1969)
Cheshire, England	1000–1500	Solution mining of rock salt	Calvert (1915)
Twente, Netherlands	345	Solution mining of rock salt	Bekendam & van Vliet (1995)
Hengelo area, Netherlands	10000	Solution mining of rock salt	Bekenden & van Vliet (1995)
Boulby Cliff, Yorkshire, England		Aluminium working	Steers (1953)
Wilmington, Long Beach, CA, USA	>9000	Oil extraction	Mayuga & Allen (1969)
Ameland, Wadden Sea, Netherlands	180	Gas extraction	Eysink et al. (1996)
Coastal Louisiana, USA	8 (yr^{-1})	Oil and gas extraction	Davis (1985)
Houston, TX, USA	>2000	Groundwater	NRC (1991), Holla (1986)
Port-Adelaide Estuary, South Australia	2.8 (yr^{-1})	Groundwater	Belpeiro (1993)
Ravenna, Italy	1300	Water and gas extraction	Gambolati et al. (1991), Bird (1993)

ondly the influence of the overlying rock type on the transmission of strains to the surface.

2.1. Mining methods

Surface damage from the extraction of deep-mined coal has been extensively investigated in the UK mainly in relation to damage to property (SEH 1975). In offshore areas attention has focused on the engineering requirements of a minimum overburden of rock to maximise safety for mining operations. Concerns centre on protecting the tunnelled voids from the ingress of water from the seabed (Whittaker & Breeds 1977). Little attention has been paid to the nearshore coastal zone (except for a passing reference to changes in the sediment transport patterns related to undermined areas in NE England; Tooley 1989). While many of the cases of subsidence arising from abstraction of water are situated near or on the coastline due to the needs of industry or development, local geology determines the location of coal and other mineral reserves. Whittaker & Reddish (1989) give a major review of the technical aspects of coal mining subsidence. The authors credit Wardell (1950, 1953-54, 1954) and Orchard (1956-57) for their work in laying the foundations for the collation of field observations that ultimately resulted in the UK Coal Mining Industry's Subsidence Engineers' Handbook (SEH 1966, 1975). This publication has been the basis for the prediction of land surface subsidence in the UK for the past 30 yr.

Coal mine subsidence is caused by the collapse of a mined-out or tunnelled void. Subsidence depends on the number, type and lateral extent of the voids (NRC 1991). Subsidence due to coal mining at depth depends partly on the method of extraction. With older methods such as room and pillar mining, the pillars, columns of coal, are left to support the roof. More modern methods include longwall mining, where sections are completely extracted and the roof allowed to collapse behind the advancing wall. The older methods led to less subsidence in the short term due to more roof support, but the subsidence could occur for up to 100 yr after extraction. This was due to the unpredictable rate of collapse of the pillars. With longwall mining, the subsidence is controlled, it can be estimated to within 10% (Whittaker & Reddish 1989), and the duration of residual subsidence is likely to be up to 12 mo after mining operations halt. Whittaker & Reddish (1989) conclude that longwall operations appear to have a virtually instantaneous response; residual subsidence is 5 to 10% of the maximum and is likely to be less.

Maximum subsidence occurs over the centre of the extracted panel of coal. The overlying strata are also affected some distance outside the immediate extraction area, up to the limit line. The latter is determined by the angle of draw, which is approximately 35° in the UK (Whittaker & Reddish 1989). When surface rock is subject to subsidence, the subsidence trough overlying an extracted panel of coal produces regions of extension and compression because of relative displacement towards the centre of the trough (Whittaker & Breeds 1977). The tensile strain (negative values) and compressive strain (positive values) are measured in mm per m of displacement. Donnelly & Reddish (1994) suggested that geomorphological steps, even in the absence of fault outcrops, are most likely to occur within a certain proportion of the subsidence trough subject to tensile strains. The step is more likely to occur at prominent joints or at a well-defined discontinuity.

If these coal reserves extend under the seabed, then their extraction is tightly controlled. The Production Department Instrument, PI/1968/8 (Whittaker & Reddish 1989), which forms the basis of the safe design of undersea coal mining operations, governs the extraction of coal seams under the sea in the UK. It is designed to protect mines and workers rather than consider the impact on beach or marine processes. One of the major constraints is to set a maximum amount of coal thickness to be extracted under a particular thickness of cover between extraction and the seabed. For example, a maximum of 1.7 m may be extracted by the longwall method of operation for a cover thickness of 105 m. The maximum strain value of 10 mm m^{-1} should also not be exceeded (Whittaker et al. 1985).

2.2. Influence of rock type on surface subsidence

Studies of the natural subsidence from solution under calcareous beds in South Wales (Thomas 1952) found general surface depressions and swallow holes, the linear development of swallow holes being associated with major fault lines. Similarly, for mining, geological factors such as lithological type and also mining techniques influence the subsidence and strain characteristics that occur in the overlying strata. ICE (1977) also highlighted the importance of geological structure in ground control aspects of subsidence. The nature of the overlying strata, faulting systems, fractures and breaks are mentioned as special factors. The presence of thick strong competent beds in the overburden has been shown to steepen the subsidence profile and increase surface strain values.

Shadbolt (1972) described the general influence of near-surface rocks on subsidence. The pre-existence of natural jointing, fissuring or faulting offers potential lines of weakness, which can cause the concentration of mining subsidence strains. Valley bulging encourages the opening of fissures and joints in limestone (Shadbolt et al. 1973). Whittaker & Breeds (1977) studied the influence of surface geology on mining subsidence in Triassic sandstones and Permian limestone (noted for brittle joint controlled character), and coal measures rocks (mudstones, siltstones, sandstones and coal seams) which demonstrated greater plasticity on a massive scale. Kapp (1985), in his paper on mine subsidence in the Newcastle district of New South Wales, found that the massive, strong conglomerates overlying the extracted seams had a significant effect on the value of maximum subsidence. Limestone cliffs backing coastlines such as those in North East England (Humphries & Ligdas 1997) are under the same natural strains, causing their joints and fissures to open. Magnesian limestone exhibits brittle properties and possesses a well-developed regional trend (King et al. 1974). ICE (1977) recognised one lithology in particular, Magnesian limestone, as exhibiting significant fracturing and intense differential displacements. They suggest that this lithology has the potential to cause serious damage at the surface. In the UK, the coastline from Co. Durham to the River Tyne has the only coastal exposure of Magnesian limestone and is also extensively undermined, so there is potential for extensive coastal subsidence.

Another surface impact of deep extraction is the effect on surface water and streams. Peng et al. (1996) modelled the effects of stream ponding associated with longwall mining. They found that impacts included change in the angle of stream flow and a change in gradient of stream flow associated with the formation of troughs caused by subsidence. Other impacts on the water table are caused by rebound after the mines have closed, when water is no longer pumped from the mine shafts. Smith & Colls (1996) found that fieldwork and inspection of abandoned mine plans demonstrated renewed subsidence associated with groundwater rebound in the Leicestershire, UK, coalfield. Damage is more apparent where there are differential ground movements (Donnelly & Reddish (1994), such as that caused by a fault step at depth. Donnelly & Reddish (1994) give an example from the Donetz coalfield in the Ukraine of subsidence of 3 to 4 m at the surface where coal mining at a depth of 500 m and the presence of a fault step has worked its way to the surface through thick superficial glacial cover.

2.3. Dynamics of shoreline processes and its impact on subsided coasts

One of the difficulties in predicting the impact of the extraction of coal at depth from beneath coastlines is that changes to the surface are masked by the mobile nature of beach sediment. Subsidence may affect a large area and cause a general lowering of the cliffs and beaches or act differentially, causing local variations in beach gradient. The aim of the following review of the parameters affecting the ways in which beaches are classified is to assess how the impact of physical changes on subsided beaches changes beach classification.

Beach classification classically depends on the morphodynamics of the beach system. Morphodynamics has been defined as 'the mutual adjustment of topography and fluid dynamics involving sediment transport' (Wright et al. 1977). The questions to be asked when considering morphodynamics and how it affects subsided coasts are to what extent subsidence may affect the responses of beaches to breaking wave energy and to what extent modifications to substrate gradient may affect on- or offshore sediment transport. Pilkey et al. (1993) questioned the assumption that underlying geology does not play a role in profile shape.

Many shoreline change models such as the 'Australian School' of coastal geomorphology (Wright & Short 1983, 1984) provide a framework for studying beach and nearshore changes. Wright & Short (1983, 1984) summarised earlier models into 6 beach states ranging from dissipative at one extreme to reflective at the other, with 4 intermediate states. Studies of beach changes are often conveniently studied using the 2-dimensional, shore-normal variations in morphology using beach profiles.

Recent developments in the classification of beaches have been reviewed in Carter (1988), Pilkey et al. (1993), Short (1996) and Anthony (1998). All macrotidal beaches exhibit predominantly high-tide reflective conditions and mid- to low-foreshore dissipative conditions. Anthony's (1998) review of the use of sediment-wave parameters to identify thresholds between various beach morphodynamic states argues that the problems of temporal wave height variability, large tide ranges and sediment variability mean that beach morphodynamic systems cannot be meaningfully characterised by sediment wave parameters. He concluded that beach slope is a better index of characterisation of spatial and temporal changes in the reflective to dissipative beach morphodynamic continuum. If beach slope is to be used to characterise coasts, we need to consider how a mining-induced permanent change in beach topography will impact beach stage models.

2.4. Models of beach response to a relative rise in sea level

The substrate gradient used in the classification of beaches is assumed to be constant. In the case of beaches affected by subsidence, the premise is that there may be an increased gradient in the substrate and a consequent increase in water depth at the cliffline or shoreline. Many papers on the response of beaches and cliff recession in response to a sea level rise discuss the use of a modified form of the Bruun Rule (Hands 1979, Everts 1991, Bray & Hooke 1997). The basic Bruun Rule (Bruun 1962) is given by the equation:

$$\text{Shoreline erosion } (R) = \text{profile width } (x) \times \text{sea-level rise } (S') / \text{profile depth } (z)$$

In addition to the horizontal rate of recession, Zenkovich (1976) related the lowering of subaquous bedrocks, dz/dt, to the rate of horizontal erosion of a sub-aerial cliff, dx/dt, by the equation:

$$dz/dt = dx/dt \times \tan\beta$$

where β is the angle of the beach slope as measured from the horizontal.

Wave parameters such as wave height (H) and wave length (L) are important in initiating sediment transport. H/L is a measure of wave steepness, which affects sediment transport on- and off-shore and tends to build beaches or level them. This in turn affects the shape and hence the slope of the beach. Doornkamp & King (1971), King (1972) and Hardisty (1990a) in their empirical studies related the beach gradient to values for H/L. All the models show an increasing beach gradient with a decreasing wave steepness; thus the beach gradient varies indirectly with wave steepness (H/L). Therefore conditions favouring steep waves (large values of H/L) give rise to low gradient beaches. More recently, Hsu (1998) undertook a theoretical analysis to determine the most important parameter governing beach profile changes. He considered that beach gradient, $\tan\beta$, the height of the breaking wave at the shoreline, H_b, the grain size, D, and the wave period, T, were the important parameters. The relationship is denoted by Sunamura's (1992) formula:

$$\tan\beta = 0.12\,(H_b/gD_{50}T^2)^{-0.25}$$

where g is the acceleration due to gravity (9.81 m s^{-2}) and D_{50} is the median grain size. Hardisty (1990b) explained the form of equilibrium beach morphology in terms of the velocity fields shoreward of the breaking point. Dynamic equilibrium is only achieved when shoreward sediment transport is balanced by seaward transport of the returning flow. He concluded that if the gradient increases the breaker type will change. Shoreward sediment transport in the breaker zone decreases with increasing beach gradient.

2.5. Breaking waves and the dissipation of energy

The dynamic pressure (as opposed to static pressure, which relates to the depth of water) depends on the wave type. This in turn depends on the wave dimensions and the bottom slope (Kirkoz 1982).The pressure rises dramatically when the leading face of the wave is vertical, i.e. when both trough and crest hit the cliff at the same time as the water level rises (wave height held constant); the wave type changes through spilling, plunging and eventually reflecting waves (greatest erosion) (Kirkoz 1982). Wave energy interacts with beaches and nearshore zones and is either reflected or dissipated across it. One important measure of the energy reflected by sloping beaches is the reflection coefficient K_R, which is defined as the ratio of the reflected wave height to the incident wave height (Horikawa 1988). Battjes (1974) obtained an empirical formula for the reflection coefficient of a sloping bottom:

$$K_R = 0.1\xi^2$$

where ξ is the surf similarity parameter. ξ is defined as

$$\xi = \tan\beta\sqrt{H/L}$$

For breaking waves this is also known as the Iribarren number. Okazaki & Sunamura's (1991) laboratory study plotted H_0/L_0 against $\tan\beta$ and demonstrated the demarcation between breaker types. For the same wave conditions, i.e. the same steepness values of H_0/L_0 or the breaking equivalent H_b/L_0, beaches with a shallow gradient (0.038) and values of H_0/L_0 of say 0.030 give spilling waves. A beach with a steeper gradient of 0.1 creates plunging breakers. This was supported by Hsu (1998) in his experimental work, which showed that the steeper beach profiles had values of ξ which showed a transition from spilling to plunging waves.

Anderson et al. (1999), starting from an expression for an exponential decay water-depth dependence of the sea bed erosion rate based on Sunamura's (1992) work, calculated the energy needed to drive cliff erosion by integrating an expression for the wave energy dissipation rate over the shelf. The energy E_{cliff} available for driving cliff retreat (see Fig. 2) is E_o, the original energy in the wave field climate, reduced by the spatial integral along its path

$$E_{\text{cliff}} = E_o - \Delta E$$

where

$$\Delta E = \int_0^\infty \left(\frac{dE}{dx}\right) dx$$

For a simple case of a planar shelf with a uniform slope of θ, $h = x\sin\theta$, and the integral then becomes

$$\Delta E = \left(\frac{dE}{dt}\right)_0 4h/V\sin\theta$$

where V is the component of the wave speed normal to the coast. The horizontal length scale is

$$x^* = 4h/\sin\theta$$

where x^* corresponds to the length of shelf over which most of the energy is dissipated. The expression shows that regions with extensive shallow shelves (low values of θ) should dissipate most of the energy, leaving less to drive cliff erosion. The corollary is that increased values of θ will shorten the shelf, allowing less energy dissipation. Fig. 1a–c shows the dissipation in energy as waves approach the cliffs.

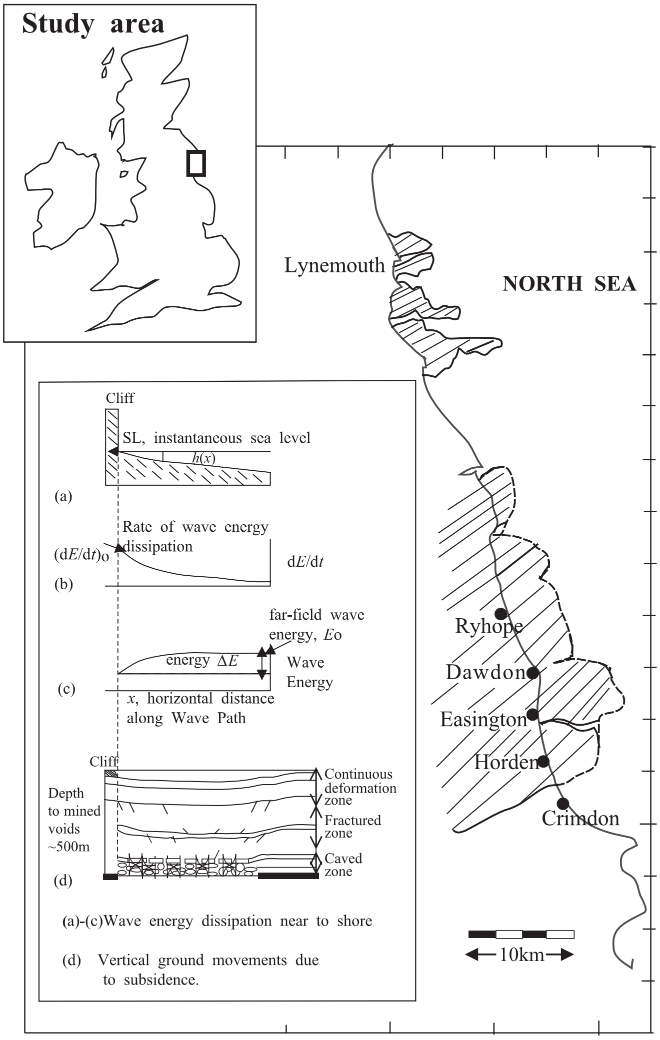

Fig. 1. Location map of areas of the Northumberland and Durham coast under which coal has been extracted at depth (compiled from Taylor et al. 1971, Smith & Francis 1967, Smith 1994). Hatched area: concealed coalfield from which coal has been extracted. Insets (a–c) based on Fig. 4 in Anderson et al. (1999) and (d) based on Fig. 2 in Mohammed et al. (1998). The rate of dissipation of wave energy decays exponentially with water depth (h). The water depth profile dictates the dissipation rate and the erosion rate. The energy remaining in the wave declines rapidly near the shore to leave $E_o - \Delta E = E_{\text{cliff}}$ at the cliff edge; E_o is the fraction of energy remaining to drive cliff retreat

2.6. North East England case study

The North East England coastline has been subjected to more extraction of coal at multiple levels than any other site and also the largest lateral extent of extraction under a coastline. It is a good model for testing relative sea level (RSL) change due to anthropogenic causes because of the minimum influence by other causes of RSL rise on this coast. 'The present configuration of the coastline of the southern North Sea basin was more or less established by 7.5 to 7.8 ka B.P. and isostatic recovery in northern England has outstripped eustatic sea level rise' (Devoy 1987). The present pattern of land uplift and subsidence in North West Europe, which is based on tidal data, shows this same region lying between the –1 mm yr^{-1} isobase (North Yorkshire) and the 0 mm yr^{-1} isobase (Northumberland coast) (Devoy 1987, Fig. 4.9). This is in line with the 10 to 15 cm rise over the last century reported by Gornitz et al. (1982), Barnett (1984) and Titus (1987), so any changes in RSL on this coastline can be attributed to the general global rise in sea level plus the local anthropogenic changes. It should be possible to test the hypothesis that subsided coasts show different response to wave processes by a detailed examination of wave processes and cliff recession from the published work on this particular coastline.

One of the earliest studies to highlight anomalous beach response was an empirical study of the factors affecting beach gradient on UK shore platforms by Trenhaile (1973). He found, for most of the UK beaches studied, a positive correlation with tidal range and a negative correlation with tidal fetch. However his results from the Magnesian limestone platforms of North East England found that some beaches (beneath which coal was being extracted) had structural problems, and he had to disregard all but the data from Hartlepool. Tooley (1989) reported that coastal dumping of mine waste in Northumberland may have been responsible for a change in sea currents leading to sand no longer being replaced on the beach at Newbiggin. The loss of sand was blamed on mining subsidence in the bay and in areas of offshore rocks that protected the bay by absorbing wave energy. Tooley stated that wherever there was significant mining settlement on the foreshore along the North East coast the result would be coastal erosion and coastal protection problems. An engineering report on coastal recession for Sunderland Council (UK) (Anon 1990) found problems in ground control along the coast south of Sunderland and suggested that an estimated subsidence of 200 mm under the cliffs was the cause. The anomalous behaviour of these beaches was also noted by Humphries' (1996) study of the beach classification on this coastline from Ryhope to Hartlepool. Humphries (1996), using geomorphological parameters based on the Australian School of beach classification (Wright & Short 1983, 1984), found steeper gradients (4 to 9°) and smaller beach widths on beaches from Ryhope to Horden (Fig. 1) compared with a larger beach widths and shallower gradients (2 to 3°) at Crimdon and Hartlepool.

Three of the parameters that may possibly change if an area of coast has been undermined by the extraction of minerals are the depth of water at the cliffline, the position of breaking waves and the beach gradient. The occurrence of different types of waves arriving at the foot of a cliff depends on the relative magnitude of the breaking depth of incoming waves, h_b, and the water depth in front of the cliff, h (Sunamura 1992). Sunamura's (1992) model for the evolution of rocky cliffs through a prolonged stable sea level has been applied to 5 initial landforms, Coasts I to V, ranging from a uniformly sloping coast with a low gradient with waves breaking offshore through to the other extreme where water depth at the cliff is greater than the wave height so that waves are always reflected from the cliff face.

In a scenario of mining-induced subsidence this could be adapted so that a Coast II landform, where $h = 0$, develops into a Coast IV landform, where $h = h_b$, with time (Fig. 1). Fig. 2 is an adaptation of Sunamura's model of rocky coast evolution in which it is assumed that different types of beaches can be assigned to a subsidence-induced change in coast (Coast IV) compared to an unaltered type (Coast II). The assumption is based on the morphology of the beaches described in Humphries' (1996) study. The cliffed coastline of North East England, from Ryhope to Crimdon, can be classed as a Type A coastline according to the Sunamura classification (1992, p. 181) with Crimdon being Coast II and Ryhope being Coast IV. These beaches form part of the same coastal sub-cell (Motyka & Bevan 1986), but classifying the beaches according to Sunamura's classification puts beaches within this same cell in different categories.

The beaches at Ryhope and Crimdon are exposed to the same wave and wind conditions and should show similar profile responses and form. As the beach classifications demonstrate their difference in form and response, the most notable difference is that the more northerly beaches have been undermined by the extraction of coal at depth, while Crimdon and Hartlepool are unaffected by mining extraction at depth beneath the coast (Fig. 1).

3. DISCUSSION

Using Sunamura's (1992) equation (p. 7) on a shoreline where wave characteristics are the same, if the breaking wave height H_b remains numerically the same (but breaks nearer the cliffs) and the beach slope ($\tan \beta$) increases, the mean diameter of the sediment would have to increase for the beach to remain in equilibrium. This may limit profile changes caused by onshore or offshore transport of sediment in response to changing wave conditions. Disentangling the effects of rising sea level and the role of sand budget can be difficult. The eastern coast of the USA experiences

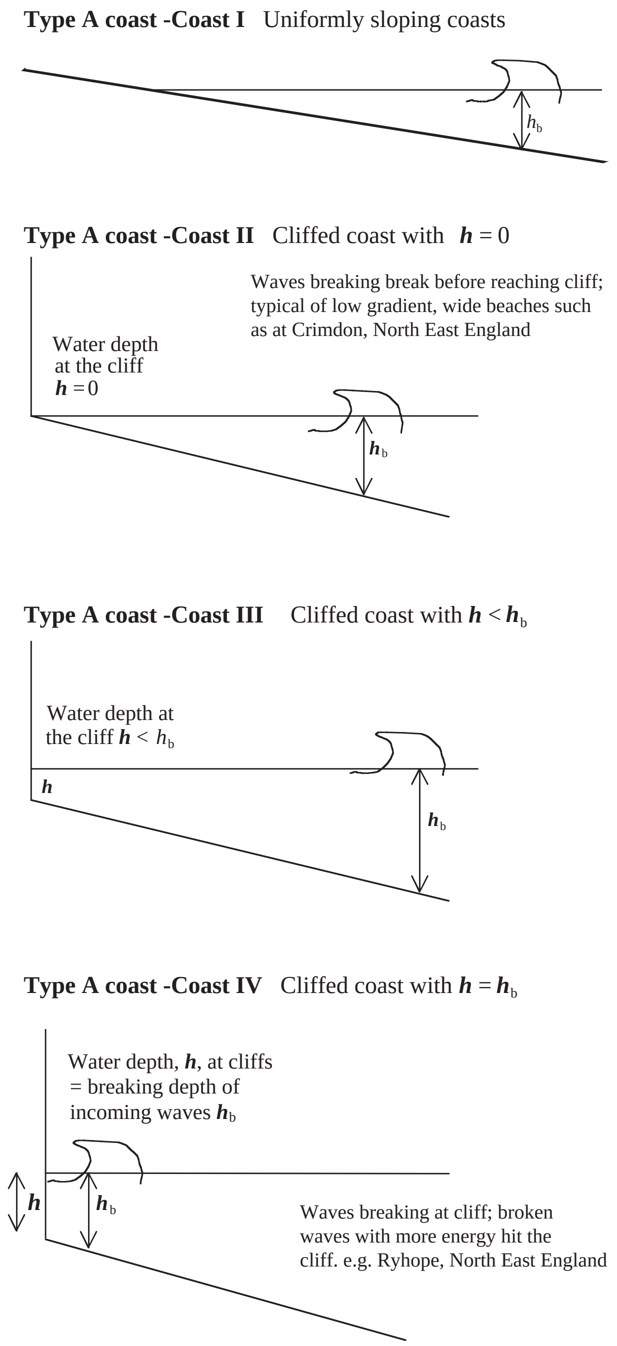

Fig. 2. Four of the 5 initial landforms adapted from Sunamura's model (1992, Fig. 725) for rocky coast evolution (Coast V is a cliffed coast with $h > h_b$)

mostly a slow marine transgression but locally where there is an imbalance in sediment supply this counterbalances or reinforces the effect of rising sea level (Roy et al. 1994). Similarly an artificially increased input into the sediment budget by the tipping of millions of tonnes of colliery spoil onto the beaches of North East England has until the closure of the mines masked the impact of RSL rise (Humphries & Scott 1991, Humphries & Ligdas 1997). Pringle (1985), in a study of cliff erosion and volume of beach material, found that there was a 4 times increase in sediment transport where 'ords', a locally occurring geomorphological feature, lowered the beach level in front of the cliffs. There is a parallel here with local variations in beach height caused by subsidence on the Co. Durham beaches. The difference in beach widths may partly be explained by reduced sediment supply in the longshore drift direction (southwards on the North East England coastline) because of beach defences to the north of the Co. Durham beaches, especially at Ryhope. However, this does not explain the increased gradients on beaches supplied with an abundance of sediment from mining activities; millions of tonnes of shale and other mine waste was tipped onto these beaches until 1993 (Humphries & Ligdas 1997).

The collapse of voids at depth may increase the strains produced in some rock types, e.g. massive sandstones and Magnesian limestone. The instability of cliffs may increase because of mining-induced strains opening up joints. Local rates of cliff erosion may be decreased by cliff resistance forces (F_R) and increased by wave assailing forces (F_w). The balance of these 2 forces determines cliff recession (Sunamura 1992). Fig. 3 is presented as a summary of the above arguments and as a conceptual model of the interaction of factors affecting cliff recession on a subsided coast.

4. CONCLUSION

Where there is an abundance of sediment, beach profiles will respond to changing conditions by producing shallow gradients under high values of wave steepness (H/L), which is related to large tidal fetch values. However, on the North East England coastline, where some beaches have been undermined, anomalous behaviour in response to the same conditions on nearby beaches which have not been undermined suggests that the substrate gradient has increased. These beaches exhibit an increased beach profile gradient and a smaller beach width. The conditions allow a different type of wave to break (a change from spilling to plunging breakers) very close to the cliff. Less energy has therefore been dissipated across the steeper, shortened profile and more is available to increase the rate of cliff erosion.

The review suggests that profile changes are a good indicator of changes in beach morphodynamics, but the range of classification of beaches is limited on subsided coasts to reflective beaches with higher beach

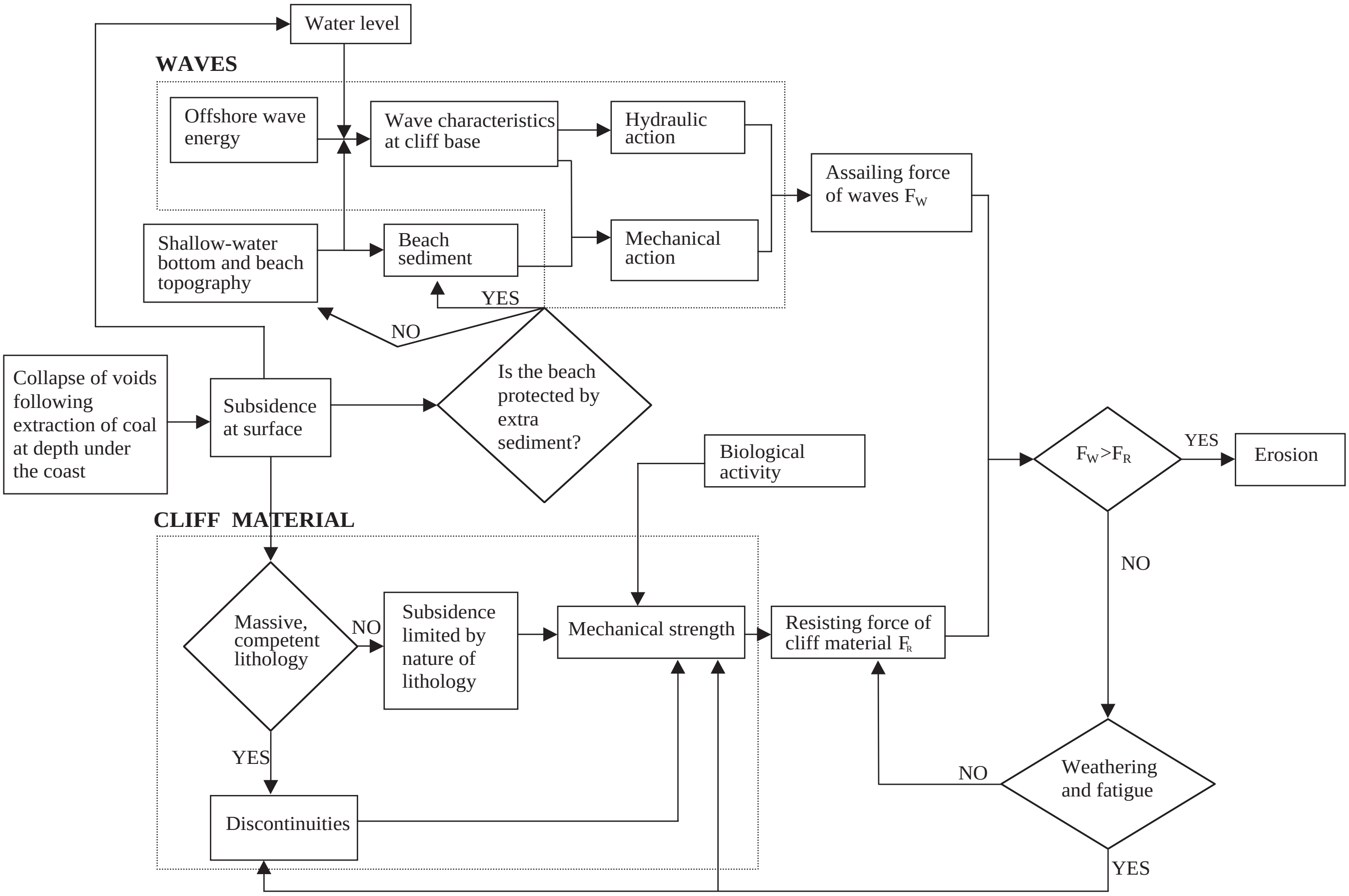

Fig. 3. Effect of mining-induced subsidence on the factors affecting cliff base erosion by waves (after Sunamura 1992, Fig. 52)

gradients. The changed morphology of beaches which have been undermined by the extraction of coal at depth is most likely a result of a change in the substrate gradient. Such an increase in gradient would allow a different kind of breaker to form, and the waves will break nearer to the cliffs with less energy being dissipated. The consequence of this is an increase in the local rate of erosion. As shoreward movement of sediment decreases with increased beach gradient, a permanent increase in beach gradient may result in a net loss of sediment offshore.

Coastal management where beaches have been undermined will require long-term monitoring of beach width and gradient and observation of breaker type to confirm a permanent change to the substrate gradient.

Acknowledgements. The author would like to thank Dr Mike Elliott and Prof. Jack Hardisty (Hull University) and Sandra Alker (Urban Mines Ltd) for their helpful comments on earlier drafts of this paper.

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Submitted: October 15, 1999; Accepted: May 4, 2001

Proofs received from author(s): July 17, 2001