An Introduction to Coastal Geomorphology

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Preface

The course of geomorphology over the past two decades has tended to emphasize terrestrial landforms - rivers and slopes - and has largely ignored coastal forms. This is quite understandable: geomorphology has gone through a period of renaissance in which the older ideas of landform evolution have been replaced by a more rigorous examination of the processes or mechanisms of landform development. This preoccupation with mechanisms has naturally concentrated on the most familiar and ubiquitous landforms which surround us while the less familiar marine and coastal processes have been, temporarily, forgotten. During this phase, however, other disciplines have proceeded in their study of the coastline: engineers, sedimentologists, geophysicists and ecologists have all made considerable advances in our understanding of coasts. It is now time for geomorphology to assimilate this work and to renew its long-standing interest in coastal landforms.

This book attempts to bring coastal geomorphology into the established framework of process studies. It draws extensively on the work of the numerous other disciplines involved with the coastal environment but reinterprets this from the geomorphological viewpoint. It also examines the temporal framework of coastal development within the Quaternary period in much the same way as terrestrial geomorphologists have begun to consider the sequence of rivers or slope development. The structure of the book reflects this preoccupation with the mechanisms of landform development and maintenance. There are three implicit sections: the first deals with the energy inputs into the coastal 'machine', the second examines the ways in which this energy is transformed into movement - of water and sediments - the basic process of all landforms. The third section looks at the result of such water-sediment movement in a wide range of coastal forms - beaches, dunes, mudflats, marshes, estuaries and cliffs. In this last section a more detailed examination of the processes of sediment transport is given for each coastal environment, aeolian transport on coastal dunes, for example, or suspended sediment over mudflats.

The landforms described in the book are introduced with a detailed description of an actual example. These examples are drawn from many areas of the world, although they perhaps emphasize the author's experience of Mediterranean, west-coast USA and Indian coasts. The spatial distribution of these examples is, however, of secondary importance in a work which intends to accentuate the underlying simplicity and unity of coastal process and form rather than geographical variation.

The book is the result of a lecture course and its associated field classes which I have been giving for the past five years. It owes much to the students who laboured under the preliminary rehearsals and even more to those implicit questions and contradictions which the coastal environment itself continually presents – usually in the middle of a field class. The intention is that the text should be used by undergraduate students either as part of a specifically coastal geomorphology course or perhaps as a supplement to a more general study of landforms. It is not an encyclopaedia of coastal facts but a framework into which such facts can be fitted and it is intended that the reader should read as many of the additional references provided in the bibliography as possible. A short reading list is provided at the end of each chapter which may prove more realistic for this purpose.

Lastly, it has been my intention to emphasize the functional approach which geomorphology has taken recently and it is hoped that the book will steer the reader away from the narrowly academic into more useful, applied, fields. The inclusion of a chapter on applied coastal geomorphology attempts to show the range of applications and the type of methods which the coastal geomorphologist can use. It is only by practical example that geomorphology can reassert its position as a major discipline involved in coastal studies – a position which we once held undisputed.

J.P.
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Plates

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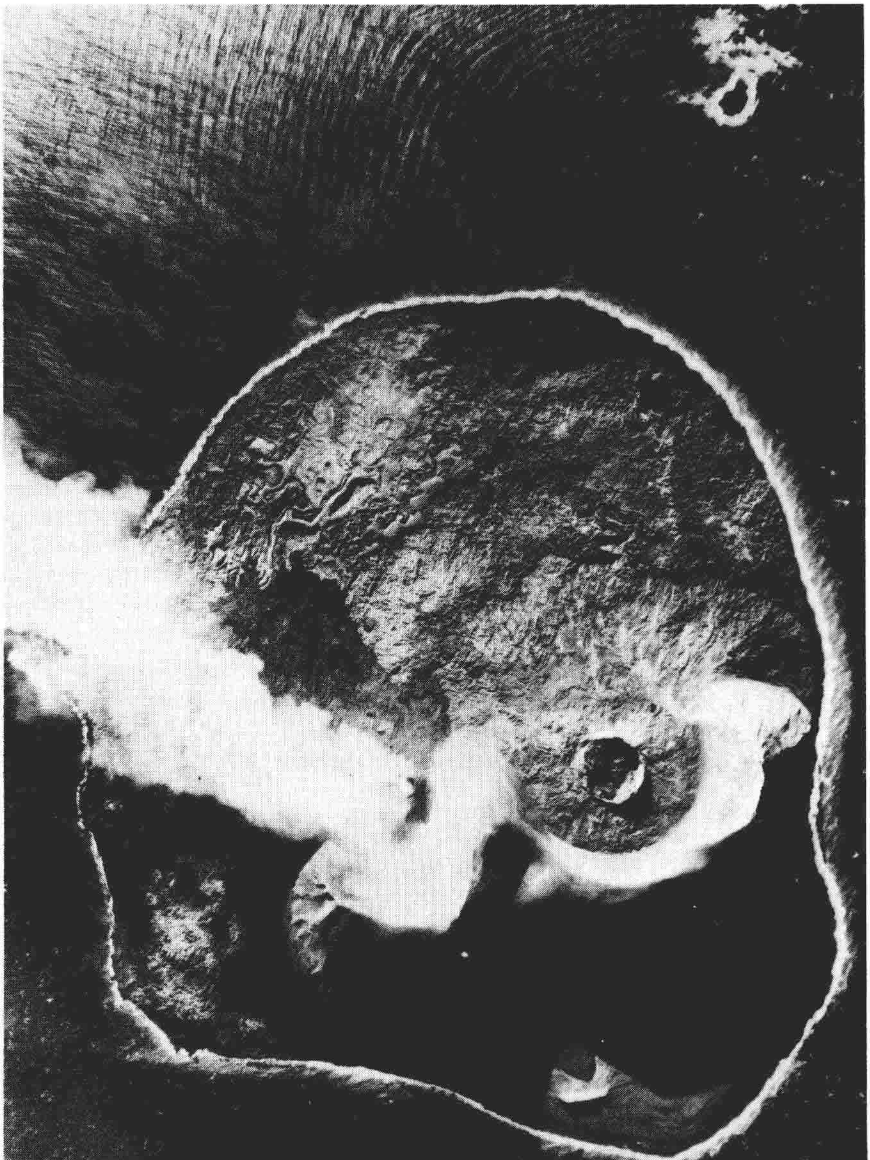


A new coastline: the recently emerged volcanic island of Surtsey, near Iceland, exhibits a coastline which is as yet unrelated to its wave environment. Note the wave refraction (top) indicating considerable longshore transport along this coast, transport that will eventually lead to modifications of the present simple island outline until it eventually reaches an equilibrium with the wave environment. Phote: US Geological Survey.

Contents

1 Coastal geomorphology: an introduction

The study of landforms provides us with an exciting challenge. The proper study of mankind may be man, but the chance to study a subject which is both bigger and older than ourselves sets an intellectual hurdle which requires some flexibility to overcome. If we happened to live for hundreds rather than tens of years then perhaps we would be able to notice landforms developing – rather like a speeded-up film of cloud formations or plant growth. Unfortunately we do not possess such geomorphological insight and consequently we must perform acrobatics with our scientific imagination in order to comprehend the enormous scales involved.

Yet there is one landscape which almost everyone recognizes as undergoing continuous change. The coastline changes; not only over centuries or decades, but in a matter of hours or minutes. This rapid development applies both to the form of the coastline – beach profiles may change quite significantly during a single day – and to the coastal processes – tidal variations being an obvious example. Thus the coastal geomorphologist has the great fortune to be involved in the study of a dynamic landform whose development can be observed directly.

This book is about coastal changes. It does not set out to treat such changes in an historical sense but to analyse the mechanisms which result in change. It also attempts to define the end product of such change – the equilibrium coastal landforms. In order to do this some considerable time must be spent in discussing the forces which drive the coastal processes – waves, tides and currents. This discussion will allow us to examine the processes of coastal landform development – the transport of sediments. Lastly we may apply this knowledge to a consideration of coastal landforms, their development and equilibrium states.

Such a study may provide an exciting intellectual challenge, but it may be questioned whether it should not be of some use at the same time. Yet coastal geomorphology is directly applicable to our lives; the world's coastline – some 440,000 km of it – encompasses only a small area of the total land surface – about 0.03 per cent if the coastal zone is regarded as about 100 m wide – but its importance to man is fundamental. A United Nations estimate suggests that 66 per cent of the world's population lives within a few kilometres of the coast, consequently food production, communications, settlement, even recreation, are concentrated here. However the coastline presents enormous problems for such intensive use; flooding, erosion, pollution and the continued threats posed by rising sea levels – all demand constant action in order to preserve man's investment. Such action depends on knowledge of the mechanisms by which the natural coastal environment functions and is provided by a variety of coastal scientists, geomorphologists among them, whose contribution to such applied knowledge we will examine in a later chapter.

Coastal classifications

Until quite recently, the almost universal approach of the coastal geomorphologist to his subject was to attempt a classification of coastal landforms. It is true that we should be able to recognize and name coastal features and that classification does allow minor discrepancies between components to be put aside in favour of their more significant similarities. Yet classification does tend to describe rather than explain and the task of the coastal geomorphologist must be to understand the relationships between form and process, not merely to describe forms. Thus classifications have tended to retard the development of a truly scientific coastal geomorphology.

Consequently no overall classification will be used in this book; instead, as we have pointed out, our discussion will be concerned with the forces, processes and landforms of the coast. Yet there are classifications which are based upon the controls of the coastal environment and which do provide some insight into the functioning of the coast as a whole. These genetic classifications are dominated by the realization that coastal forms are largely the product of sea-level variations. Several classifications use a division into *submerged* and *emerged* coasts (e.g. Johnson 1919; Valentin 1952). Such classifications suggest that submergence results in fjord or ria coastlines while emergence produces tidal flats or even barrier islands. There is no doubt that the sea-level changes do play a dominant role in coastal development but the complex variations in sea-level even over the past few thousand years makes identification of specifically emergent or submerged coasts extremely difficult. In fact, Johnson's (1919) classification places most of his observed coastal forms into a class labelled 'neutral' in order to avoid any such controversy.

Another basic group of classifications used structural controls to distinguish between various types of coastal landforms. Thus Bloom (1978) distinguished between *bold* and *low* coasts. Bold coasts are developed in resistant rocks and the resultant forms reflect both the inherited sub-aerial topography and the effect of marine erosion in picking out lines of weakness in the rocks. Low coasts are developed on alluvial coastal plains and, rather confusingly, are also associated with recent sea-level variations.

More recently Inman and Nordstrom (1971) have developed a tectonic classification based on plate tectonic theory. They recognize four distinct coastal types: those on actively diverging plates (e.g. Red Sea coasts) those on zones of plate convergence (e.g. the island arc systems of Indonesia and Japan) those on major transform faults (e.g. the coast of southern California) and lastly those coasts developed on stable plate zone (e.g. coasts of India and Australia). This is a useful distinction and is reminiscent of the suggestion by Suess (1904) that coasts could be divided into Atlantic and Pacific types.

A third group of genetic classifications are based on coastal processes. Included here is Shepard's (1963) division into *primary* and *secondary* coasts. Primary coasts are those in essentially the same condition as they were left in at the end of the last sea-level change, that is relatively unaffected by marine processes. The form of these coasts reflects the sub-aerial processes which shaped the land surface before sea-level changes occurred. Secondary coasts have been altered considerably by marine processes such as erosion, accretion and organic deposition.

Also in this group are classifications by Davies (1980) and Tanner (1960). Both these authors classify coasts according to the level of energy inputs that they receive. Davies (1980) distinguishes between *storm wave environments* – primarily those in middle latitudes, and *swell wave environments* – found mainly in low latitudes. Tanner's (1960) classification into *high*, *moderate* and *low-energy* coasts is less geographical than that of Davies but is based on a similar premise.

The form and function of coastal landforms

The inconsistencies involved in applying the generalized classification systems to the enormous range of coastal landforms is obvious enough, and become prohibitive when a study is to be made of an individual landform. In such cases classifications are quite inappropriate and we are forced to consider the problem in its absolute rather than relative sense. One of the major aims of any such investigation will be to gain some understanding of the mechanisms, or processes, at work. It is not sufficient merely to think of such processes as being responsible for the temporal development of a landform – a type of historical chronology. Rather we should think of landforms as machines – or organisms – which continue to work even though no temporal development is taking place. Looked at in this light these various processes are part of the function of the landform. It may be useful to consider what the function of a coastal landform could be.

The wave-energy classification of Tanner (1960) may provide part of the answer to this question. In a later paper (Tanner 1974) he goes on to define the equilibrium coastal landform:

> the equilibrium idea is that an energetic wave system will establish in due time and barring too many complications, a delicately adjusted balance among activity, three-dimensional geometry and sediment transport such that the system will tend to correct short or minor interference.

This statement relates energy inputs, sediment-transport processes and coastal morphology in a functional equilibrium. The coast is a zone of intense energy input; this energy, transported by waves, arrives at the coast and is available for work. The result is that the processes of sediment transport are set in motion – processes that cause morphological change. These changes will continue indefinitely, unless, by chance, a landform is produced in which the energy inputs are dissipated without any net sediment transport. This is the stage of equilibrium, a dynamic equilibrium or steady state which Tanner (1974) referred to as a 'balance between activity, three-dimensional geometry and sediment transport'.

Looked at in this light the function of the steady-state coastal landform is to dissipate wave-energy. Changes in form are necessary only when a change of energy input occurs, in which case the energy will not be dissipated without net sediment transport occurring. Consequently the morphology begins to alter - until a new equilibrium or steady state is established. The time taken for such a re-establishment of steady state is referred to as the *relaxation time* (Chorley 1962).

This delicate balance between form and function is maintained by the processes of sediment transport and driven by the forces of wave, tides and wind - a triple alliance which provides the basis for the structure of this book. Before we progress to an examination of the detail of this interaction however, it may be useful to consider the problem of temporal development or relaxation time, referred to above.

Time and space in coastal geomorphology

One of the more confusing aspects of coastal geomorphology is the extremely wide range of scale covered by the landforms. These include small-scale features such as beach cusps - no more than a few metres across, medium-scale features such as salt-marshes or sand dunes - several kilometres across, and large-scale features - the configuration of the coastline itself for instance - covering tens, even hundreds, of kilometres: a scale which may be called 'capes and bays geomorphology'.

However these variations in the spatial scale are paralleled by changes in the temporal scale, that is, the relaxation time of each landform. Our present day shoreline was formed very recently - in geological terms - during the post-glacial sea-level rise which ended only 6000 years ago (see p. 229). The establishment of a shoreline does not mean that coastal landforms were also produced; of course the shoreline does delimit a series of large-scale capes and bays - but these are not equilibrium coastal landforms, merely the landscape inherited from sub-aerial processes. Once such a shoreline is established however the process of landform development towards a steady state begins. Small-scale features, beach cusps or beach profiles, may reach a steady state with their environmental controls in a matter of hours or days. Salt-marshes take much longer - perhaps between 200 years to 1000 years to complete their relaxation time. Finally the coastal configuration, headlands, bays, estuaries, and so on will take thousands of years to adjust to the environmental changes produced by the new sea-level.

Such an hierarchical development of spatial and temporal scales was recognized for fluvial landscapes by Schumm and Lichty (1965). They suggested that small-scale features such as river channel cross-section will adjust rapidly to environmental conditions so that they are almost continuously in a steady state condition - which they called 'steady-time'. At a larger scale the river long-profile may take years to develop a form which is in equilibrium with its environment. This longer time scale Schumm and Lichty called 'graded-time'. Meanwhile at the largest scale, the drainage basin itself may take thousands of years to adjust to changes caused by, for example, tectonic movements - this is termed 'cyclic time'.

The important point that Schumm and Lichty (1965) make is that none of

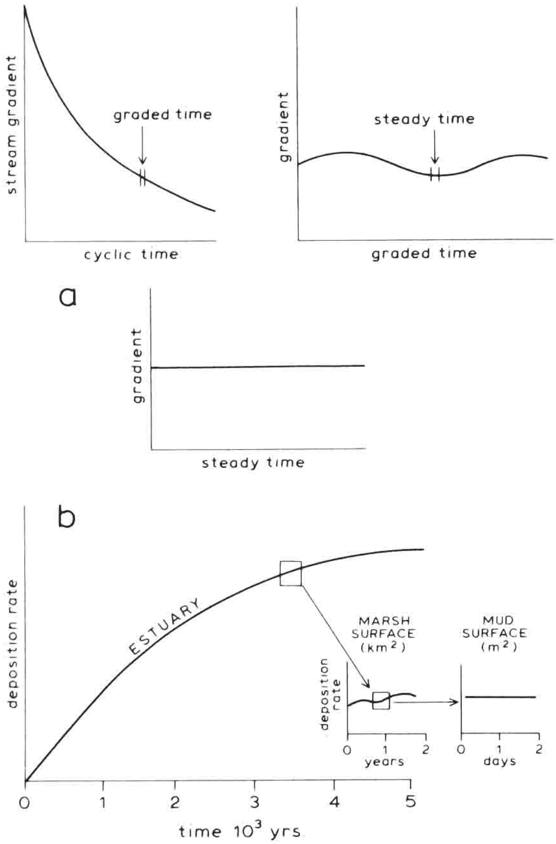


Fig. 1.1: (a) The relationship between time and landform scale for fluvial landscapes (after Schumm and Lichty 1963). **(b)** The concept applied to the coastal estuarine environment. Estuaries react slowly to causal processes such as sea-level changes, whereas at smaller spatial scales their bounding mudflats or salt-marshes reach a steady state between process and form relatively quickly.

these scales are independent of each other. River cross-section may adjust in days to discharge and velocity conditions, but the progressive variation in long-profile slope over a period of hundreds of years means that, even if all other environmental controls were constant, the cross-section would be forced to maintain a continuous readjustment to fit the changing slope and velocity regime. Similarly, the long-term adjustment of drainage basin morphology will cause progressive changes in water and sediment inputs into a single river channel which will force its long-profile to adjust continuously - so that its graded-time of tens of years will nest into the cyclic time of thousands of years (fig. 1.1).

Returning to the coastal landforms, it could be argued that 'steady-time' characterizes the rapid adjustments of the beach profile, while graded-time is applicable to the arcuate shapes developed by the beach plan. The capes and bays of the coastline however are the coastal equivalent of drainage basins and require thousands of years to reach a steady state – the cyclic time of Schumm and Lichty (1965). Similar hierarchies could be assigned to the estuarine environment where the mudflat surface, salt-marsh and estuary itself conform to the steady, graded and cyclic time scales.

Coastal geomorphologists have been slow in applying such terrestrial geomorphic models to their environment. There are exceptions: Dolan (1971), for example, has recognized the relationship that exists between the spatial and temporal scales of a wide range of crescentic and rhythmic coastal landforms. Yet the recognition of such groupings achieves little more than the classificatory approaches to coastal geomorphology discussed previously. The importance of the nesting together of the various scales of landform lies in the insight that this allows into the independent controls of landform development. A beach profile for example may respond to a given wave input during a single day but if the beach profile is monitored over a longer period – 10 years for example – it will be seen to respond to long-term variations which are taking place in the beach plan shape. These longshore changes will alter the angle of wave approach to the beach and thus wave inputs which were a totally independent control of beach profile in the short term become a dependent variable in the longer term.

The coastal geomorphologist must be aware of such scale interactions between the components of his environment before he begins any investigation. One of the major problems he faces in attempting to assess such interactions is the recognition of fossil elements in the landscape. At the largest time-space scale, cyclic time, the development of shoreline configuration may take thousands of years to attain a steady state. Since our present sea-level was established only 6000 years ago this implies that many large-scale features have not yet adjusted to these 'new' conditions. Consequently many of our present-day coastal landforms are responses, not to modern wave or tidal conditions, but to some previous environmental processes. Such fossil forms may have been inherited from a previous high sea-level, in which case they will be a response to marine processes; some may be a response to sub-aerial processes acting during a previous low sea-level. The complexities of such sea-level variation and the resultant fossil landforms will be discussed in detail in chapter 11, but it should be realized at the outset that these landforms present a danger to the geomorphologist wishing to relate process, form and function in a field-based study.

Approaches to coastal geomorphology

The variations that can take place in the independent controls of landforms depending on their temporal and spatial scales suggests that simple genetic classifications can only confuse. There is no single controlling factor but rather a continuum of relationships within the hierarchy that we have discussed above. Classifications have therefore tended to stultify; what is needed is a more flexible and imaginative approach to this challenging environment.

As a result of this stultifying approach many coastal geomorphologists have moved instead to the methods used by coastal engineers. Since the early 1940s there has been an enormous interest in producing predictive, deterministic models of coastal development. Such models have been developed by engineers in response to specific coastal problems and relate process and form using the basic principles of the physical sciences. Coastal geomorphologists have found this approach extremely useful in developing the more theoretical aspects of the subject and we will be discussing these, often elegant, deterministic models throughout the course of this book. Yet one outcome of this approach is that although many of the quantitative models it engenders apply quite happily to controlled experiments in the laboratory they are less successful in predicting the more complex response of the real coast. Fluvial geomorphologists have recognized this in their own work and have for some time adopted a stochastic approach in which a specified amount of uncertainty is introduced into the model.

Stochastic models have not been widely used by coastal geomorphologists, although there are a few important exceptions, but it seems that such an approach would prove of great value. There is in fact a great deal that coastal geomorphology can learn from the concentrated effort put into the fluvial environment over the past two or three decades. We have discussed the application of steady state concepts above, which do allow the links between process and form to be more fully appreciated; we now await the introduction of a more probabilistic approach to the operation of the laws of physics at the coast which form the basis of this book.

Further reading

Good reviews of 'traditional' coastal classification schemes are given in:

KING, C.A.M. 1972: *Beaches and Coasts*. London: Arnold.

and:

BLOOM, A.L. 1978: *Geomorphology*. Englewood Cliffs, AJ: Prentice-Hall.

A more individual approach to coastal classification is that of:

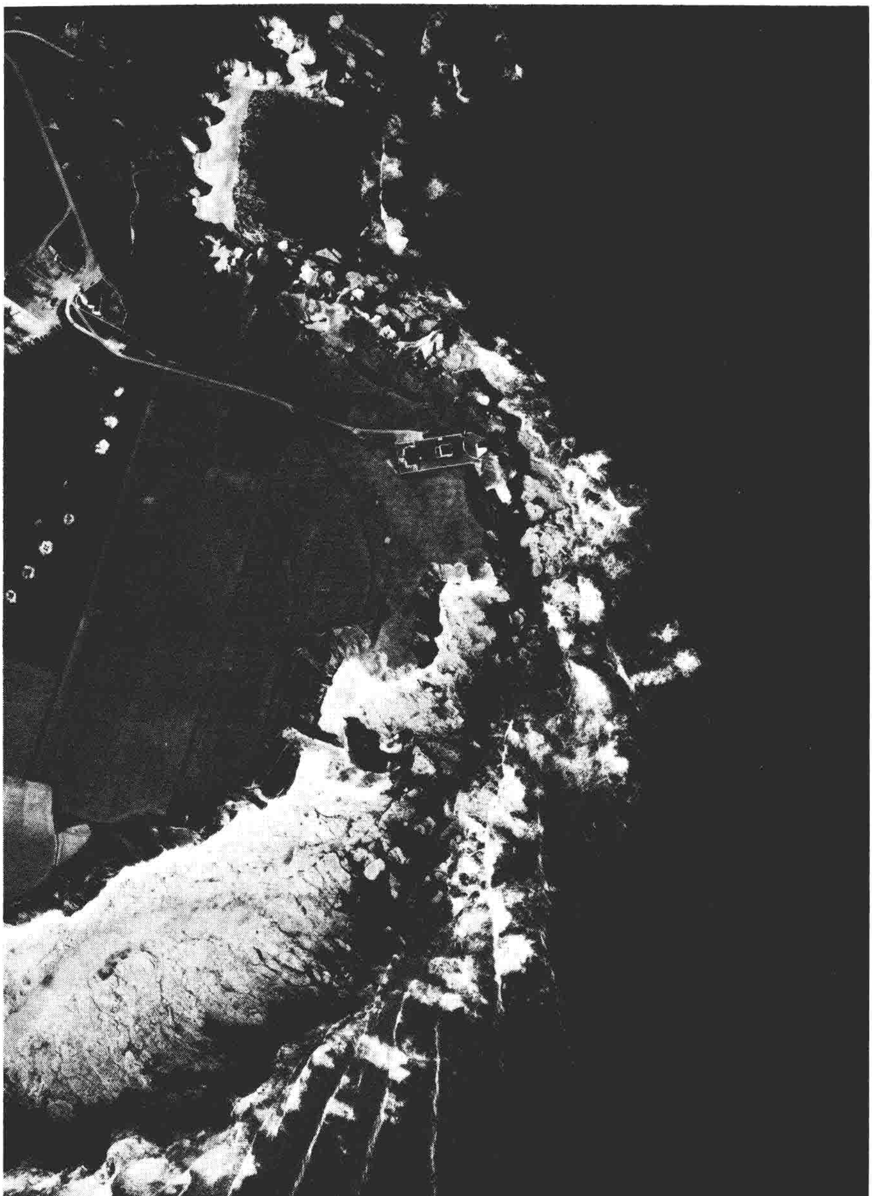
DAVIES, J.L. 1980: *Geographical variation in coastal development*. London: Longman.

The reader interested in applying current geomorphological ideas to the coastal environment will, of course, have a wide choice. The introductory chapter to:

RICHARDS, K.S. 1982: *Rivers*. London: Methuen.

may prove useful in this context. Specific ideas about coastlines and time may be developed from:

THORNES, J.B. and BRUNSDEN, D. 1977: *Geomorphology and time*. London: Methuen.



Wave refraction around a headland: a north easterly wave, period 7 secs, length 60m in deep water enters the shallow water of the coastal zone. Note the decrease in wave length as water depth decreases, the refraction into the 'pocket beach' (top centre) as well as the marked refraction around the headland (bottom). Note too the wide abrasion platform with 55m high chalk cliffs behind. (See p. 201) Photo: Aerofilms.