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Coastal Classification: Systematic Approaches to Consider in the Development of a Comprehensive Scheme

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ABSTRACT

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Many different kinds of classification have been applied to coasts in attempts to characterize dominant features in terms of physical or biological properties, modes of evolution, or geographic occurrence. Some of the earlier general classifications were broad in scope but lacked specificity while other specialized systems were narrowly focused, providing uneven coverage of taxonomic units for coastlines of the world. Due to more comprehensive study of coasts and the increasing availability of information, especially digital formats in GIS frameworks, integrated and systematic approaches to coastal classification are favored. The complex demands of today require sophisticated solutions to overlapping and interrelated problems in the littoral, as facilitated by organization of biophysical parameters into a coherent whole or universal scheme. The developmental approach to a new comprehensive classification system is thus proposed for the coastal fringe, a swath zone 5 to 10 km wide across the shoreline, which incorporates all important parameters necessary to categorize geomorphic units that can be mapped at meaningful scales. Consideration of coastal geomorphological properties are the theme of this approximation toward a modern taxonomic system where morphostructures are the unifying links that facilitate transition from one hierarchical level to another. The proposed approach employs differentiating criteria for hard rock (automorphic) and soft rock (allomorphic) coasts which are divided by chronometric parameters related to the antiquity of littoral landforms. Other levels of primary differentia include geodynamic-climatomorphogenic process zones, relief types (morphoregions), morphogenetic relief features, and relief elements and genetically homogeneous surfaces. Morphotypes are lower level taxons that provide examples of ingressional, egressional, and complex process-forms. The proposal for a unified system requires testing in the field and mapping at myriametric scales to update subsequent approximations.

ADDITIONAL INDEX WORDS: Coastal classification, coastal landforms, beach, coral reef, shore, coastal zone, rocky coast, shore platform, coastal evolution, sand dune.

INTRODUCTION

Since modern scientific investigations of the land-sea boundary began in the early 1800's, the classification and nomenclature of coasts has been somewhat problematic. Although there have been many attempts to solve the problem, no mutually satisfactory or complete solution has yet been found. This situation obtains because philosophies of coastal classification are guided by existing knowledge and pragmatic circumstances that seek to service an identifiable audience. The coastal zone is multipurpose and therefore its study is germane to several academic disciplines. No single classification can equally serve all who seek to study coastal features for their own special purposes. To a large degree, a classification system reflects the level of perception of research and understanding of natural bodies (morphological features) in terms of process and form. KUBIENA (1948) succinctly emphasized this relationship to the soil science community when he stated "Show me your [classification] system and I will tell you how far you have come in the perception

of your research." Although this comment was made over a half-century ago to researchers in another discipline, the observation is relevant to the coastal sciences today. To a certain extent, coastal researchers are still attempting to understand processual relationships between form, function, time, and space in one of the most dynamic environments on earth. It is thus not surprising that terminologies, classifications, and morphodynamic models are approximations of the moment. The present situation was, to a large degree, forecast by R. J. Russell in his remark, "Much of the literature on sea coasts is concerned with classification of shoreline types, but to me this is both unfortunate and premature. Taxonomy should follow, rather than precede, the acquisition of more precise and factual information than we now possess . . . I think we know altogether too little about coasts to line up examples and shove them into appropriate pigeonholes" (RUSSELL, 1967, p. 84). Although still true in certain respects, coastal geomorphology has certainly advanced a long way down the road of understanding, especially in the areas of morphodynamics and modeling.

The preceding comments relate conceptually to the big pic-

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ture, past and present, but there are also perceptual inequities that are associated with definitions of 'coast' as an object of study, related to areal and temporal extents, but perhaps most problematic is the complex compounding of time-(in)dependent forms one upon another at all scales. It might be suggested, therefore, that coastal classifications are somewhat enigmatic because most coasts are compound representations of overlapping terrestrial, coastal, and marine processes that produce multifaceted, polygenetic features and forms on an inherited geologic framework. Coasts are also difficult to define because they represent spatially and temporally transient manifestations that are loci of unique assemblages of erosional and depositional processes (e.g. RUSSELL, 1958, 1967; SHEPARD and WANLESS, 1971; BLOOM, 1978). As SHERMAN and BAUER (1993) and SCHWARZER *et al.* (2003) emphasize, coastline evolution occurs over different time scales ranging from storm events to millennia and because of the time-transgressing nature of coasts, different methods are used to study, describe, and classify sedimentological and morphological variations and changes. Thus, small- and large-scale coastal behavior (e.g. COWELL *et al.*, 2004a, b) and morphological modeling and description depend largely on investigations from short events to long-term processes. An additional complicating factor is the interaction of effects of coastal processes that operate on different time scales (e.g. HANSON *et al.*, 2004). There is thus a complicated mix of temporal and spatial scales of observation that requires a degree of cognizance prior to rationalization of coastal morphologies at different scales.

Coastline length also militates against comprehensive systems that must incorporate great diversity over long distances where similar kinds of coast (kind, sequence and arrangement of morphological features) transcend national borders, suggesting that such efforts must be international in scope. One way to perhaps appreciate the magnitude (scale) of the problem is to consider length of coastline for ocean margins (not including coastline lengths of islands, archipelagos, embayments, *etc.*): Arctic Ocean (126,347 km), Baltic Sea (11,939 km), Indian Ocean (75,873 km), Mediterranean Sea (52,977 km), North Atlantic Ocean (216,320 km), North Pacific Ocean (216,832 km), South Atlantic Ocean (16,931 km), South China Sea (63,024 km), Southern Ocean (17,968 km), and the South Pacific Ocean (56,827 km), for a total of 855,038 km. The length of coastline for the top ten countries and territories comes to 531,864 km accounting for 63% of the world's total viz Canada (243,791; 29%), Indonesia (54,716; 6.5%), Greenland (44,087; 5.2%), Russia (37,653; 4.5%), Philippines (36,289; 4.3%), Japan (29,751; 3.5%), Australia (25,760; 3%), Norway (21,925; 2.6%), United States (19,924; 2.4%), and Antarctica (17,968; 2.1%) (*World Factbook*).

Because coastal forms successively overprint younger morphologies and because there is a multiplicity of morphologies associated with ascending and descending coastlines (associated with temporal fluctuations of sea level), no classification of coasts is widely accepted but some general morphological and tectono-morphological schemes are favored viz. SHEPARD (1973), INMAN and NORDSTROM (1971). There is a multiplicity of special purpose classification schemes for intrinsic

properties of discrete landform systems such as dunes (e.g. COOPER, 1958; OLSEN, 1959; SHORT and HESP, 1982; NORDSTROM, 1990), spits and bars (EVANS, 1942); coral reefs (e.g. DARWIN, 1839, 1842; FAIRBRIDGE, 1950a, 1967; MAXWELL, 1968; GUILCHER, 1988), beaches (e.g. WRIGHT and SHORT, 1984; MASSELINK and TURNER, 1999; SHORT, 1975, 1978, 1979, 1982, 1993, 1999), rocky cliffs and platforms (e.g. TRENHAILE, 1987; SUNAMURA, 1992), or coastal landscapes such as oceanic islands (e.g. NUNN, 1994), coastal scenery (e.g. ARBER, 1911), or even coastal forms related to levels of wave energy (e.g. TANNER, 1960b) *etc.* but comprehensive approaches that organize individual landforms into a universal hierarchy are yet to be devised. In addition, numerous systems have been developed for the ecological regionalization of coasts (e.g. BAILEY *et al.*, 1994; BAILEY, 1998; DETHIER, 1992; GREENE *et al.*, 1999; HAYDEN *et al.*, 1984; UDVARDY, 1975; WIELAND, 1993) and in the last decade there has been a proliferation of classification systems that qualifies the need for habitat classification (e.g. MUMBY and HARBORNE, 1999; ROFF and TAYLOR, 2000). This need has, in fact, led conservation scientists and resource managers to develop dozens of classification systems that target various types of coastal systems, as described by MADDEN (2003). Whatever the system features, whether ecological regionalizing (ecoregions, bioregions), classification of biota and habitats, coastal-marine systems, biogeography, or land systems, organization of physical (geomorphological) systems provides a framework or underpinning for other types of classifications. The plethora of coastal classification systems heralds the desire to formulate a universal scheme for geological (geomorphological) zones (and features) that in turn can be used as underpinnings to biologically-based systems via terrestrial forms and bottom types (sublittoral and submarine morphologies). Although physically based coastal forms are the subject of this paper, they are discussed in relation to other approaches as all efforts combine into a larger coherent whole where the sum is greater than any of its parts.

Purpose

This paper attempts to define a universal, catholic approach to coastal classification, but the proposal is seen as an open-ended approximation that can be modified. The original purpose of the proposed classification system was to provide organization to a laundry list of coastal landforms that are likely to be encountered in amphibious landings anywhere in the world, as part of a U.S. Navy research project. Some sites were clearly unsuitable as landing zones and they needed to be identified just as clearly as sites that are suitable. The development of a coastal geomorphic site selection system (FINKL *et al.*, 1997; YUHR *et al.*, 1997), after an on-and-off gestation period of several years, now seems to have grown beyond what was initially perceived as a relatively specialized but simple coastal classification system. The purpose is presently seen as an attempt to consider the development of a multipurpose, comprehensive, and unified classification system for coastal landforms. Strictly speaking, this proposal is not a 'new' classification *per se* but an approach to an amal-

gamation or re-organization that employs useful parts of prior efforts.

Philosophical Background to Classification

Because the nature of the problem requires careful consideration, it is appropriate to inquire into the objectives of coastal classifications and to examine some principles involved in their construction (see discussions by TANNER, 1960a; COOPER and McLAUGHLIN, 1998; FAIRBRIDGE, 2004). Although these objectives and principles are often implicit, there has been some direct discussion and philosophical summations of classificatory underpinnings of specialized schemes that organize coastal morphologies (e.g. GUILCHER, 1958, 1988; KING, 1966; DAVIES, 1964, 1973; BIRD, 1976; FITZGERALD and HETEREN, 1999). Inevitably and ultimately, however, the problem of classification in general entails the problem of terminology and nomenclature (e.g. FINKL, 1981). Scientific names denote a group or class of objects of concern into classes or categories to which names can be given. Thus, the first purpose of classification is to provide groupings with appropriate names that can substitute for a description of the objects that are classified. Only by use of specific names or categories can researchers communicate effectively. To be successful, therefore, a system of nomenclature and classification must have general agreement of those who have need of the system. According to MILL (2002, reprinted from 1843 edition), who discussed the logical bases and principles of the overall classification process, natural phenomena are classified in order to:

- (1) Organize knowledge (thereby contributing to economy of thought)
- (2) Bring out and understand relationships among individuals and classes of the population being classified.
- (3) Remember properties of the objects classified.
- (4) Learn new relationships and principles in the population that is being classified.
- (5) Establish groups or subdivisions (classes) of the objects under study in a manner useful for practical, applied purposes in:
 - a. Predicting their behavior.
 - b. Identifying their best uses.
 - c. Estimating their productivity.
 - d. Providing objects or units for research and for extending and extrapolating research results or our observations.

In general and rudimentary classifications, the system is arranged or structured so that it does some or all, of the above five functions. Classification for a specific, applied, practical purpose is referred to as a *technical grouping*. However, in scientific activities knowledge is organized without reference to a specific, applied objective, so that the classification system is set up in such a way that each group has as many unique, natural properties as possible and its name and properties relate to it but separate it from all others. Such systems are commonly called *scientific or natural classifications*. Stated another way, the purpose of a natural classification is to bring out relationships of salient properties of

the population being classified, without reference to any single specified and applied objective. In a natural classification, all attributes of a population are considered and those which have the greatest number of covariant or associated characteristics are selected to define and separate (MILL, 2002, reprinted from 1843 edition).

It is often posited that precision in classification leads to precision in thought and is therefore of great value as a mental discipline. A classification embodies in shorthand form knowledge about a subject; the construction of a classification is thus an attempt to organize knowledge. In short, its second objective is the schematic representation of ideas or concepts. Coastal features, being objects of common experience and observation, were subject to early classification efforts. With increasing sophistication of coastal research, greater knowledge about materials, processes and forms (coastal configuration, landform evolution, morphodynamics), the classifications became broader in scope, more focused, and better organized.

Approaches to Coastal Classification

There have been various attempts to classify coastal landforms (including shores and shoreline features) but none were entirely successful (BIRD, 1976), for reasons already indicated. Although many different schemes have been proposed, no completely satisfactory classification of coasts has yet been devised. This situation perhaps partly results from widespread beliefs in the superiority of genetic approaches over descriptive classifications, as reported by KING (1966). Part of the difficulty also stems from the fact that a genetic classification can only be applied satisfactorily when the processes of landform development are known. Other attempts to use particular types or associations of landforms as indicators of particular modes of origin frequently cause interpretive errors that are exposed by subsequent research.

Previous investigations propose that several salient factors should be taken into account when devising a coastal classification (cf KING, 1966; DAVIES, 1964, 1973; BIRD, 1976; FAIRBRIDGE, 1989): (1) the shape or form (morphology) of the land surface (above and below sea level), (2) the movement of sea level relative to the land and *vice versa* (e.g. change in relative sea level, RSL), (3) modifying effects of marine processes, (4) climatic influences on process and form, and (5) age and durability of coastal materials. Some of these factors have been used in various proposed classifications. An additional factor that must be considered is the scale of observation (e.g. SHERMAN and BAUER, 1993), a parameter that is often implied but not explicitly indicated. A range of spatial scales determine the kinds of features, materials, or processes that can be seen in the field, on maps, and from photographs or satellite images. For the sake of the following discussion, the range of scales in common usage include: global (worldwide coverage), continental, regional, and local (detailed). The general categories of phenomena that are studied in coastal classification can be grouped in terms of (1) processes, (2) materials, (3) forms, (4) age or stage of development, and (5) environments (e.g. ecological regions, land systems, morphodynamic zones). Most systems focus on one or

two of these categories and are thus specialized rather than comprehensive.

PROCESS-RELATED COASTAL CLASSIFICATIONS

Due to the complexity of coasts, numerous attempts to organize coastal features or processes have been put forward but no single system of classification has been comprehensive in scope or coverage. The following summation groups the main kinds of coastal classification that have been attempted so far. Most of these preliminary systems were genetic in approach, global in scope, but often of limited perspective. The following brief review, for convenience, groups some of the better known schemes into the following categories of classification: (1) geotectonic systems (geodynamic processes), (2) sea-level change (eustatic processes), (3) marine modification and terrestrial inheritance, and (4) coastal erosion (shoreline retreat) and deposition (shoreline advance). It is noted that most coastal classification systems overlap in certain ways and are not mutually exclusionary. They also tended to adopt the dogma of the times and thus to some extent they are records of conventional wisdom at select points in history.

Coastal Geotectonic Provinces

Early attempts at classification of coasts were general but not necessarily comprehensive systems that were intended for application over broad areas from regional to global scales. One of the earlier attempts was made by SUESS (1888), almost incidentally, when he proposed in his book *The Face of the Earth*, the now well-known *geotectonic classification* of "Atlantic" and "Pacific" coasts. Resulting from different tectonic styles, these two broad types of coast were seen to have distinctive characteristics that are still recognized today in the framework of plate tectonics and continental drift. In **Atlantic type (transverse) coasts**, the general trend of tectonic structures strike the coastal margin at right angles. Most plate-imbedded, or trailing edge coasts, which correspond to Suess's Atlantic-type coasts, have hilly, plateau, or low hinterlands, and wide continental shelves. The structural lineations of these coasts are discordant with the shore. In general, Atlantic-type coasts tend to be indented, partly resulting from lines of structural weakness and exposure of rocks of variable resistance to wave erosion, as seen in the example of a rocky coast near Halifax, Nova Scotia (Figure 1).

In the **Pacific (longitudinal) type coasts**, structural lines (geologic grain) parallel the coast. Pacific-type coasts tend to be fairly straight and regular in planform, with few indentations where rivers have broken through resistant strata to expose weaker inland materials. There may be a flight of raised terraces on the steep, tectonically unstable mobile hinterland, which is an abundant source of coastal sediment. Although the structural dichotomy is much generalized, it can be applied in a broad sense to the hinterland of most coasts. They are high, straight coasts with narrow continental shelves, as seen for example along the Pacific Coast of Mexico near Manzanillo (Figure 2).

A different dichotomy (an alternative to classification of coasts into Atlantic and Pacific types), although this design-

ation is useful and deployed in other schemes (e.g. INMAN and NORDSTROM, 1971), was proposed by COTTON (1918, 1925) where there were two major divisions between coasts of *stable regions* and those of *mobile regions* (Table 1). Submerging and emergent coasts occupied a lower second level in the scheme. Cotton's classification considers aspects of structural (tectonic) stability of the land surface and related changes in relative sea level. Many of Cotton's examples are taken from New Zealand which is affected by earth movements along parts of its coast. KING (1966) suggests that Cotton's classification could be considered partly as a sub-division of the all-embracing *compound group* of JOHNSON (1919). Thus, it is suggested that the last major change in base level (i.e. the grand base level in a geomorphological sense, mean sea level) is the most important in defining the types of coasts which may be combined with other features, such as faulting or flexure, to give different categories of coast. BIRD (1969) indicates that Cotton's system is most useful as a clarification of Johnson's scheme, the analysis of submergence and emergence enabling certain types of compound coast to be separated.

Building on Suess's lead more than a century earlier, FAIRBRIDGE (1992) discussed the regional aspects of Holocene coastal paleogeography of the United States and suggested that there are two basic categories of environmental setting that are of overriding importance: primarily, the *geotectonic province* and secondarily, the *climatic province*. He broadly defined seven main geotectonic provinces as: (1) active (convergent) plate margins and back-arc basins (**Subduction Coasts**), (2) taphrogenic (mainly strike-slip) plate margins (**Taphrogenic Coasts**), (3) passive plate margins (beyond glacial forebulge) associated with thick geosynclinal sedimentary sequences (**Sedimentary Coasts**), (4) passive plate margins (with former glacial forebulge), also with thick sedimentary sequences, (5) active plate margins and back-arc basins (within former glacial loading and forebulge areas), (6) semi-stable platforms, dominated today by wind and meteorological tides and by geostrophic current dynamics, and (7) oceanic fracture-zone volcanic complexes and seamount-related atolls.

Superimposed on these seven structurally dependent foundations are the latitudinally related regional-scale *climatic provinces* that often appear to play a dominant role on a short-term basis. FAIRBRIDGE (1992) designated the climatic provinces, with some generalization, as follows: (1) high Arctic, (2) Sub-Arctic, (3) west-coast westerly, (4) east-coast westerly, (5) subtropical and trade wind. By linking geotectonic and climatic provinces, Fairbridge provided a useful means for describing broad coastal characteristics that are now comprehended in an updated reformulation (FAIRBRIDGE, 2004) that is much more complete and globally comprehensive.

Classifications Based on Changes in Relative Sea Level

Rather than being based on tectonics or structure, other earlier classifications of coasts emphasized relative movements of land (geodynamic processes) and sea (eustatic processes), giving the main coastal groups as those dependent on relative submergence or emergence. One of the first re-



Figure 1. Rocky (automorphic) coast near Halifax, Nova Scotia, Canada. The sedimentary strata dipping seaward show little modification by marine processes, except for the formation of structurally controlled platforms that have formed along unconformities. Note the presence of re-entrants where weaker beds have eroded away allowing ingress of the sea. [Classification (Hectometric scale): Automorphic rocky intertidal coast]

searchers to recognize the influence of submergence on the coastal outline was DANA (1849), who reported that the deeply embayed coast of Tahiti was the result of a rise in sea level which drowned coastal valleys to form deep inlets. The part played by marine modification was not explicitly formalized by DAVIS (1898) in his classification due to his emphasis on the *cyclicity of marine erosion*. In that system, sequential stages of coastal types were deduced as having resulted from a cyclic progression of landform evolution. DAVIS (1898) and GULLIVER (1889) both used the distinction between submergence and emergence as the basis of their coastal classifications, although SUESS (1888) and RICHTHOFEN (1886) had also considered submergence and emergence criteria in coastal description. DALY's (1926, 1934, 1938) work on the glacial control of sea level, in relation to the formation of coral atolls and other features, drew attention to oscillations of sea level resulting from glacial-interglacial cycles.

Perhaps one of the better known early coastal classifications is the one proposed by JOHNSON (1919), a scheme that is often appreciated as a classification of coasts, rather than of individual coastal types. Enlarging the previous dichotomy

of coastal types put forward by other workers, Johnson retained two major groups, coastlines of submergence and emergence, but added neutral and compound coasts (Table 2). Neutral coasts included those which were not mainly due to submergence and emergence such as delta shorelines, alluvial and outwash plains, and fault shorelines. Compound shorelines showed features of two or more of the other three main categories. Johnson's main coastal types are subdivided to give the classification outlined in Table 2. This classification has the advantage of being based on genetic interpretations but, when strictly applied, many coasts fit into the compound category. Recent research shows that very few coastal areas have not been affected by sea-level change as a result of glacial control (*e.g.* VALENTIN, 1952; BLOOM, 1978, 1983; FAIRBRIDGE, 1950b, 1992). Relative sea-level change is also related to tectonic movements and other crustal instabilities such as isostatic rebound, diastrophism, and orogenic movement. KING (1966) points out that perhaps the least satisfactory group in Johnson's classification is the last category of compound coasts. In the emergent category, Johnson recognizes only the emergence of a very flat gradient seafloor



Figure 2. Rocky shore near Manzonillo in the Department of Colima on the Pacific coast of Mexico. The foothills of the Sierra del Cuale meet some sections of the coast where there is no coastal plain. These rocky shores contain small marine benches but are mostly steep-to. Pocket beaches occur between rocky promontories. [Classification (Landscape, mesomorphostructural scale): Automorphic rocky coast with cliffs, platforms, sea stacks, and skerries (with pocket beaches at hectometric scale) on a Pacific Type (Cordilleran Subtype) coast]

which would give rise to a straight coastline in planview, on which barrier beaches and islands develop as a result of the gentle gradient of the coastal zone.

SHEPARD (1937, 1948, 1973) abandons the high-level classificatory submergent-emergent dichotomy of previous workers by (1) placing submergent coasts at a lower level in the

classification and (2) suggesting that emergent coasts can be ignored. The basis (highest-level distinction) in this classification is the differentiation between coasts shaped mainly by terrestrial agencies (**Primary Coasts**) and those modified by

Table 1. *Classification of coasts based primarily on the geodynamic stability of coastal regions and secondarily on features related to relative sea-level change. (After Cotton, 1952).*

- | |
|--|
| I. Coasts of stable regions. (These are all drowned by the recent submergence, but in reality are compound.) |
| A. Dominated by features of the most recent submergence |
| B. Dominated by some features of an earlier emergence |
| C. Miscellaneous—volcanic, fjord, <i>etc.</i> |
| II. Coasts of mobile regions. (These are all compound and affected by diastrophism as well as eustatic changes of base level.) |
| A. Coasts on which the most recent change is submergence |
| B. Diastrophic movements on coasts resulting in emergence |
| C. Fault and monoclinical coasts |
| D. Miscellaneous coasts—volcanic, fjord, <i>etc.</i> |

Table 2. *Classification of coasts based on processes related to changes in relative sea level, i.e. interpretation of features associated with the present coast in relation to the most evident or prominent change in land-sea movement. (After Johnson, 1919).*

- | |
|--|
| I. Submergence coasts |
| A. Ria coasts |
| B. Fjord coasts |
| II. Emergence coasts (with barriers) coastal plain shoreline |
| III. Neutral coasts |
| A. Delta coasts |
| B. Alluvial plain coasts |
| C. Outwash plain coasts |
| D. Volcano coasts |
| E. Coral-reef coasts |
| F. Fault coasts |
| IV. Compound coasts—any combination of the above types |

Table 3. *Classification of coasts as primary (shaped by non-marine processes) and secondary (molded by marine agencies). (After Shepard, 1948).*

I. Coasts shaped primarily by non-marine agencies. (Primary, youthful shoreline)
A. Shaped by terrestrial agencies of erosion (subaerial denudation) and drowned by the Recent (Flandrian) marine transgression or down-warping of the land margin
1. Ria coast (drowned mouths of river valleys)
a. Parallel trend between structure and coast (Dalmatian type)
b. Transverse trend between structure and coast (SW-Ireland type)
2. Drowned glacial erosion coast
a. Fjord coast (drowned glacial valleys)
b. Glacial trough coast
B. Shaped by terrestrial (subaerial) deposition
1. River deposition
a. Delta coast—convex out
b. Alluvial plain coast—straight
2. Glacial deposition
a. Partially submerged moraine
b. Drumlins—often partly drowned
3. Wind deposition
a. Dune coast
4. Vegetation coast
a. Mangrove coast
C. Shaped by volcanic activity
1. Volcanic deposition coast—lava flow—convex out
2. Volcanic explosion coast—concave out
D. Shaped by diastrophism
1. Fault coasts or fault scarp coasts
2. Fold coasts, due to monoclinical flexures
II. Coasts shaped primarily by marine agencies. Secondary or mature coastlines.
A. Shaped by marine erosion
1. Clifed coasts made more regular by marine erosion
2. Clifed coasts made less regular by marine erosion
B. Shaped by marine deposition
1. Coasts straightened by marine deposition
2. Coasts prograded by marine deposition
3. Shorelines with barriers and spits—concavities facing ocean
4. Organic marine deposition—coral coasts

marine processes (**Secondary Coasts**). This classification (Table 3) is somewhat comprehensive and has much to recommend it; however, the lack of a category for emergent coasts, as noted by COTTON (1954), is an obvious disadvantage. Some workers also refer to perceived difficulty in the application of this coastal classification to actual examples. This observation is, however, common to most coastal classification systems for reasons already discussed here. KING (1966), for example, asks the question, "How does one determine the *precise moment* when a coast is sufficiently altered by marine agencies to allow it to be classified in the second major group?" The classification also cuts across the commonly used system of cyclic description. Coasts can be described in terms of the state of development by marine processes, from an initial form which is defined in the classification. This new classification uses what would normally be considered as the youthful stage of development as the second group of the classification, so that a coast which is put into the second group automatically loses any reference to its initial form at the beginning of the cycle, which is running its course at the present time (BIRD, 1976). Shepard modified and elaborated his classification in 1973, but retained its basic structure.

Table 4. *Classification of coasts in relation to shoreline advance (by emergence or sediment accumulation) or retreat (by submergence or erosion). (After Valentin, 1952).*

I. Coasts that have advanced (moved seaward) ¹
A. Due to emergence (Coasts on newly emerged seafloor provided the new coastline has not been eroded back to the original line)
1. Emerged seafloor coasts
B. Outbuilding coasts
1. Organic deposition
a. Phytogenic (formed by vegetation): mangrove coast
b. Zoogenic (formed by fauna): coral coasts
2. Inorganic deposition coasts
a. Marine deposition under weak tides: Lagoon-barrier and dune-ridge coasts
b. Marine deposition under strong tides: tideflat and barrier island coasts
3. Fluvial deposition: delta and outwash coasts
II. Coasts that have retreated (moved landward)
A. Submergence of glaciated landforms
1. Confined glacial erosion: fjord-skerry coasts
2. Unconfined glacial erosion: fjard-skerry coasts
3. Glacial deposition: morainic coasts
B. Submergence of fluvially-eroded landforms
1. On young fold structures: embayed upland coasts
2. On old fold structures: ria coasts
3. On horizontal structures: embayed plateau coasts
C. Coasts of retrogression (Coasts eroded back to a continuous line of cliffs, provided by reversal process has not caused deposition in front of the cliff.)

¹ Features can only be placed in Category I if simultaneous subsidence does not counteract the effect of outbuilding

The way in which base level varies through time is crucial to the problem of coastal classification, as it is to the whole concept of a marine cycle of erosion. The fundamental distinction of process here is between advancing and retreating coasts, noting that advance may be due to coastal emergence and/or progradation by deposition, while retreat is due to coastal submergence and/or retrogradation by erosion. The concept of a changing base level consisting of periods of rapid change alternating with periods of stillstand forms the basis of VALENTIN's (1952) classification (Table 4). This system was devised for use on a map scale (1:50,000,000) of global coastal configurations. The emphasis in this classification is on temporal change. This system features present coastal change rather than the initial form of the coast before modification by marine processes. An important aspect of this classification is the recognition that marine forces are continually active and influence the coast even during changes in base level which should, on the basis of the older classifications, initiate a new cycle of erosion on a new coastal type (BIRD, 1976). According to VALENTIN (1952), the possibility is left open that changes of base level are continually operating and that stillstands are the exception rather than the rule. Valentin's classification is expressed graphically by means of a diagram on which each of four axes represents one of four possibilities, coastal erosion and submergence on the negative side and coastal outbuilding and emergence on the positive side. This classification does not specifically consider coastal morphology nor provide groupings of coastal features in a hierarchical system. Nevertheless, it does provide a rudimentary yet use-

ful frame of reference for conceptualization of the basic role of coastal advance and retreat.

SPECIAL PURPOSE COASTAL CLASSIFICATIONS

In addition to genetic and descriptive approaches to coastal classification, there are practical attempts to map coastal features in relation to some specified purpose. Although not intended to be coastal classifications *per se*, the map units often provide a useful list of "what is" along the coast (see, for example environmental sensitivity index units used by GIBEAUT and GUNDLACH, 1990). The sensitivity of coasts to oil spills, for example, provides the impetus to map coastal features along tanker routes in many regions. Summarized below are two examples, one from a cold region in Canada and the other from a subtropical zone in Florida. Both examples illustrate a potential for classification and the incorporation of mapping units in a relational geomorphological database. The cold-region example from Canada is especially important because the length of coastline (243,791 km, including 52,455 islands) comprises about 29% of the world's coastline (*World Facts and Figures and CIA World Factbook*). The subtropical Florida Atlantic shore, by way of a small-scale comparison, has only 933 km of seacoast based on measurements made with unit a measure of 30 minutes of latitude at a scale of 1:1,200,000 or 5630 km of tidal shoreline (based on largest-scale maps and charts available to head of tidewater or to a point where waters narrow to 30 m). The tidal shoreline is longer because it includes total shoreline length viz. outer seacoast, barrier islands, sounds, bays, estuaries, and tidal rivers. Coastal morphologic units in the Florida example are thus much more detailed than those in the Canadian overview.

Regional or Reconnaissance Classification of Cold Region Coasts in Canada for Sensitivity to Oil Spill Clean-up

The factors that control coastal variability, both in time and space, are outlined by OWENS (1994) as part of an effort to control the fate of spilled oil that reaches the coast. This specialized classification (Table 5) is considered within a framework or context of individual sections of shoreline that have been identified and mapped from regional surveys.

The character of a coast is a function of the existing materials and the processes acting upon those materials. There is a primary distinction between coasts that have sediment in the shore zone and those that do not. In the former case, the primary distinguishing feature between shoreline types is the size of the materials and the presence of vegetation (Table 5). On coasts without sediments, the type of material is the defining shoreline type. Coasts that are entirely without sediment are rare, and many rock cliffs or platforms have pockets of sand or pebbles. The character of the shoreline can be described by the form that results from marine and coastal processes that act on the various materials (Table 5). This approach is rudimentary because many coasts are combinations of one or more basic types. The system is also scale dependent showing only broadly defined units at the regional level.

Table 5. Classification of shoreline types on the basis of materials and coastal configuration. (After Owens, 1994).

I. Solid and Unconsolidated Materials	II. Solid and Unconsolidated Forms
A. Solid Materials	A. Solid Forms
1. Bedrock	1. Anthropomorphic
a. Resistant	a. Bulkhead
b. Unresistant	b. Dolphin
2. Ice	c. Dyke
a. Glacier front	d. Breakwater
b. Exposed permafrost	e. Jetty
3. Anthropogenic	f. Marina
a. Concrete	g. Seawall
b. Metal	h. Revetment
c. Wood	i. Wharf
B. Unconsolidated Materials	2. Cliff
1. Inorganic	a. Vertical
a. Silt/clay	b. Steep
b. Mud	c. Inclined
c. Sand	d. Bevelled
d. Pebble	e. Terraced
e. Cobble	f. Sea stack
f. Boulder	3. Platform
2. Organic	a. Horizontal
a. Sea grass	b. Terraced
b. Marsh	4. Reef
c. Peat	B. Unconsolidated Forms
d. Shell hash	1. Anthropomorphic
e. Vegetated shore	a. Dock/pier
3. Anthropogenic	b. Dyke
a. Concrete forms	c. Breakwater
b. Debris/logs	d. Fill
c. Pilings	e. Marina
d. Rip rap	f. Midden
e. Rubble	g. Seawall
	2. Beach
	a. Attached
	b. Barrier
	c. Spit
	3. Delta
	a. Bird's-foot
	b. Fan/single channel
	c. Fan/multi-channel
	d. Lobate
	4. Channel
	a. Bare
	b. Vegetated
	5. Flats
	a. Creek bank
	b. Levee
	c. River bank
	d. Tidal
	6. Scree/talus

Regional Classification of Subtropical Coasts in Florida for Sensitivity to Oil Spill Clean-up

The SFRPC (1984) prepared an environmental sensitivity atlas which provides priority protection information for spill response coordinators. The information, based on physical, biological, and socio-economic vulnerability to an oil spill, along with the information presented on relative costs and problems associated with different cleanup techniques, provides a basis for decisions on the most effective prevention and cleanup actions.

The shoreline of southeastern Florida is divided into eleven types and each is assigned an environmental sensitivity in-

Table 6. *Classification of shoreline types in southeastern Florida based on environmental sensitivity to soil spill and cleanup. (After South Florida Regional Planning Council, 1984).*

ESI Number	Shoreline Type ¹
1	Exposed, vertical rocky shores and seawalls Steep scarps in limestone bedrock Little or no sediment in intertidal zone Exposed to high wave energy
2	Exposed rocky platforms Intertidal areas of rocky beach cut in limestone platforms Sharp drop-off at seaward margin of platforms Platforms with thin veneer of sediment Sand, gravel beaches on platforms
3	Fine-grained sand beaches Short stretches of beach with low volumes of sand, Fla Keys
4	Moderate to heavy wave activity Coarse-grained sand beaches Renourished beach Steep beach face with wide back beaches Mostly natural beach with biogenic sediment
5	Mixed sand and gravel beaches and fill Natural sand and gravel beach Sand and gravel fill
6	Toe of beach face with coarser, better sorted sediment Gravel beaches and riprap Gravel- to boulder-sized riprap Riprap with narrow beach Fine-grained sediments adjacent to riprap
7	Exposed tidal flats Sand with minor amounts of mud Migrating sand bars Open bays in lee of offshore islands Mangrove fringe
8	Sheltered rocky shores and seawalls Limestone bedrock Manmade concrete seawalls
9	Sheltered tidal flats Fine-grained sediments (mud) Shallow water, even at high tide Fringed by dwarf mangroves
10a	Mangroves High wave activity and currents Sand, mud/Peat/Flat topographic profile
10b	Sheltered mangroves Bays and basins sheltered from waves and tidal currents Thin mud deposits on irregular bedrock surface Thick mud deposits on irregular bedrock surface

¹ From South Florida Regional Planning Council, 1985. *South Florida Oil Spill Response Handbook*. Hollywood: SFRPC, 91p.

dex number. The shoreline types identified for this special purpose classification are listed in Table 6. This kind of shoreline classification is less easily incorporated in a geomorphological classification system. The mapping units do, however, provide information that can be interpreted and re-grouped into units more compatible with geomorphological terminology. This kind of information is now updated by the Florida Marine Research Institute (St. Petersburg, Florida).

Environmental Sensitivity Index Mapping

The most widely used approach in the United States, NOAA's Environmental Sensitivity Index (ESI), systematically compiles information for coastal shoreline sensitivity,

Table 7. *A genetic classification of oceanic islands. (After Nunn, 1994).*

Level One	Level Two
Plate Boundary Islands	Islands at divergent plate boundaries Islands at convergent plate boundaries Islands along transverse plate boundaries
Intraplate Islands	Linear groups of islands Isolated islands Clustered groups of islands

biological resources, and human-use resources. ESI maps identify sensitive resources before an oil spill occurs so that protection strategies and clean-up procedures can be designed in advance. ESI maps include geomorphological classification of shoreline types that are integrated with other coastal resources (BATTISTA and MONACO, 1996) that help define risk during oil spills. These kinds of maps are compiled into atlases that are available for coastal states (including the Great Lakes) in paper and digital formats. The usefulness of these maps is that they provide a standardized approach for coastal geomorphological mapping, including color schemes and symbolization for coastal habitats.

Classification of Oceanic Islands, Exclusive of Coral Reefs

The classification of oceanic islands has always challenged attempts to summarize and group islands according to organizing parameters. As NUNN (1994) points out, in order for a classification of islands to be practical, its purpose and level of generalization must be identified before differentiating characteristics can be selected. Because no single classification of islands meets the requirements of every specialist purpose, none of the attempts to produce a unifying or natural classification of islands provides a suitable basis for general and detailed investigation. Of the numerous island classifications produced for educational purposes, most have antecedents in the seminal works of DARWIN (1842) and WALLACE (1881). Both of their approaches are uncomplicated and intended to be of wide utility. Previous attempts have focused on descriptions of island composition (limestone, basaltic vs. andesitic volcanic islands), geographic occurrence, nature of the underlying lithosphere (oceanic, continental, intermediate) (see discussion in NUNN, 1994). Nunn uses a general genetic classification of oceanic islands based on the location of an island relative to particular physical elements of the earth's lithosphere (plate boundaries). Thus, the distinction drawn between plate-boundary and intraplate (mid-plate) islands forms a high level dichotomy in NUNN's (1994) scheme (Table 7).

Coral reefs are frequently associated with oceanic islands, particularly those of volcanic origin. The model proposed by SCOTT and ROTONDO (1983) explains the origins of all major types of island found on the Pacific lithospheric plate where tens of thousands of seamounts are scattered over the oceanic crust of the plate surface. Because most of these igneous, submergent monoliths never reached the ocean surface, they are

Table 8. *Island types on the Pacific lithospheric plate. (Modified from Scott and Rotonodo, 1983).*

Island Type	Comments
Volcanic Island (No Fringing Reef)	Young, high island subjected to subaerial weathering and erosion
Volcanic Island (with Fringing Reef)	Full development of a typical fringing reef
Raised Volcanic Island (with Fringing Reef)	Original coral reef raised above sea level and a new reef forms at MSL
Almost-Atoll	Submergence has left one or more embayed basaltic islands and stacks in a lagoon surrounded by a barrier reef
Raised Almost-Atoll	Uplift drains the lagoon and a new reef forms at MSL
Atoll	Small low islets formed from coralline and algal rubble separate the reef from the shallow lagoon
Inundated Atoll	Annular reef sand bars only project above sea level at low tide
Part Raised Atoll (Lagoon Open)	Small uplift so lagoon remains tidal
Part Raised Atoll (Lagoon Enclosed)	Atoll uplifted enough for the lagoon to be cut off and reduced in size
Raised Atoll (Dried Out Lagoon)	Karstified landscape (makatea) forms in subaerially exposed lagoon, small ponds in lower depression of former lagoon floor
Raised Atoll (Atoll Form Lost)	Elevated long enough for all remnants of the typical atoll to be lost. Irregular uplift may preserve terraces

protected from modifications induced by subaerial weathering and erosion. Back in 1842 Darwin proposed the elegant explanation that coral atolls resulted from the slow submergence of volcanic islands. His ideas were contested and went unproved until 1951 when drilling through the carbonate platform on Eniwetok in the Marshall Islands encountered volcanic basement rock at depths about 1200 m (LADD, 1973). Despite Darwin's early linkage of intraplate volcanoes to atolls, it was not until the mid 1900's that researchers focused more critical attention on the interwoven histories, building on the work of WIENS (1962) and SCOTT and ROTONDO (1983) to differentiate eleven distinct island types (Table 8). Precursors of island types on the Pacific plate are volcanic islands with no (or incomplete) fringing reef. All other types then depend on the development of a fringing reef and then some degree of subsidence or emergence or some combination of the two. Although many names have been used in reference to island types and specific atolls, these categories provide an indication of important types. The subdivision of coral reefs into distinct categories is thus considered in the following section.

Classification of Coral Reefs and Reef Islands

Following the extremely broad and laconic classification of DARWIN (1842), coral reefs are still divided into three main types: **fringing reefs**, **barrier reefs**, and **atolls**. Within each class of reef there is much morphological diversity and this is particularly true of the reefs of continental shelves which fall generally within the barrier reef division of Darwin. Two significant attempts have been made to produce a genetic

Table 9. *Classification of shelf coral reefs and associated geomorphic features.*

Reef Type	Description
Juvenile Stage of Development	
I. Unmodified Antecedent Platform Reef	All reefs must go through this stage during their initial development. Relief reflects the antecedent platform topography and may include mesoscale karst features. Soil and regolith formed during subaerial exposure will be removed.
II. Submerged Shoal Reefs	Relief enhancement commences as the reef accretes at its maximum rate.
III. Irregular Patch Reefs	Occurs when the reef reaches modern sea level and begins development of reef flat very irregularly.
Mature Stage of Development	
IV. Crescentic Reefs	Coalescence of initial reef patches to form the first hard-line margin to the reef. Lateral movement of sediment forms a prograding sand wedge into the central reef area.
V. Lagoonal Reefs	Closing of the reef flat around the marginal rim on the leeward side creates a lagoonal reef.
Senile Stage of Development	
VI. Planar Reefs	Final choking of lagoons takes place with complete sediment infill and merging of patch reefs.

Terms and descriptions summarized from Hopley (1988)

classification of these reefs. An initial classification by FAIRBRIDGE (1950, 1967) was elaborated by MAXWELL (1968), although both classifications were based on the premise of Holocene origin for the Great Barrier Reef (GBR, Australia). In broad outline, if not in detail, their progressive development of reef forms with time is similar to HOPLEY's (1982) proposal for Quaternary development of GBR coral reefs. GUILCHER (1988) additionally considers **bank reefs** and **patch reefs** to be special types.

Based on criteria considered by previous workers, HOPLEY (1988) developed a classification of **shelf reefs** (Table 9). The basic classification emphasizes small to medium-sized reefs that grow from antecedent platforms with single depressions in the diameter range of 1.75–3.25 km. Smaller reefs, where antecedent surfaces lack a protolagoonal relief, but because the width of reef flat initially developed around the reefal margins occupy such a high proportion of the total reef area, any lagoon that forms will be shallow and quickly filled. The mature phases will be either bypassed or persist for a very short period. In contrast, the largest reefs will remain in mature stages for long periods because of the low ratio of productive margin to lagoon area.

A major subgroup is **ribbon reefs** which grow from linear foundations that are either discrete antecedent platforms or high rims on much larger and usually deeper platforms. The basic feature is depth of water behind the narrow reef flat that develops from the foundations. Although sediment movement is to leeward, accretion is very slow and widening of the reef flat is retarded. Three stages in the development of

Table 10. *Classification of reef islands of the Great Barrier Reef. (After Stoddart et al., 1978).*

-
- I. Unvegetated Solitary Island
 - A. Linear sand cays
 - 1. Small ephemeral cays*
 - 2. Larger oval-shaped islands
 - 3. Cays with extensive relict beach rock
 - B. Linear shingle cays
 - C. Compact sand cays
 - D. Compact shingle cays
 - II. Vegetated Solitary Islands
 - A. Sand cays
 - B. Mixed sand and shingle cays
 - C. Shingle cays
 - D. Mangrove cays
 - III. Multiple Islands
 - IV. Complex Low Wooded Islands
-

ribbon reef can be equated with those in the basic classification.

Reviewing literature on reef islands, STODDART and STEERS (1977) suggest that *cays* and *low wooded islands* of the GBR show greater morphological variety than reef islands of any other coral reef region. Forms range from small ephemeral sand patches emerging only at low water to the complex low wooded islands consisting of leeward sand cay, windward shingle island cemented with rampart rocks, and central mangrove swamp. In the division of island types described by HOPLEY (1988), the numbers of islands on reef tops, their degree of complexity, and the overall morphology in relation to the presence or absence of centripetal processes, are used as additional differentiating factors (Table 10).

GUILCHER (1988) proposes a slightly different classification of reef types which are summarized in Table 11. In addition to the classification of reef types, Guilcher discusses many kinds of surface features that are associated with coral reefs.

Classification of Beaches and Beach Geomorphology

Sandy coasts, which constitute about 20% of the world's coastline, occur juxtaposed to muddy and rocky shores. The term *beach* is traditionally applied to a 'shore with a cover of sand or shingle' (SHEPARD, 1973). Although most classifications deal with sandy beaches (see following discussion), shingle or gravel beaches (e.g. CARTER and ORFORD, 1984; WELLS, 1996) represent coarse-grained end members that are related to morphodynamic properties that are distinct from fine-grained counterparts. JENNINGS and SHULMEISTER (2002), for example, consider the Iribarren number, beach width, average grain size, and storm berm height as discriminating factors in the classification of gravel beaches. For sandy beaches, the **orthogonal system of classification** extends from the landward limit of the swash to the depth at which wave action ceases to be competent to transport non-cohesive seabed sediment (HARDISTY, 1990). Usage of the orthogonal system encompasses the term *shoreface*. Although no permanent lines can be drawn for the boundaries of the orthogonal system because both the landward and seawards limits will move continually under changing wave and tidal

Table 11. *Classification of the main reef types. (After Guilcher, 1988).*

-
- I. Fringing Reefs
 - A. Without boat channel
 - B. With incipient boat channel
 - C. Well-developed boat channel
 - D. Multiple landlocked mini-lagoons
 - E. Reefs intermediate between fringing and barrier
 - F. Asymmetrical fringing reefs
 - II. Bank Reefs
 - A. Patch reefs
 - B. Sand cays
 - III. Barrier Reefs and Associated Features
 - A. Subaerial barriers
 - B. Submerged (drowned) barriers
 - C. Almost-atolls
 - D. Double and multiple barriers
 - E. Sand cay reefs and low isles in lagoons
 - IV. Atolls
 - A. Reticulated
 - B. Drowned
 - C. Double- and triple-ring
 - D. Giant
 - E. Faros
 - F. Elevated
 - V. Ridge Reefs
 - VI. Bahamian Reefs
-

conditions, this definition excludes rocky or muddy shorelines.

Beaches exhibit a more or less smooth profile which is concave upwards and has a more or less straight or gently curved plan shape (RUSSELL, 1958). This worldwide uniformity of form suggests the action of common processes and it is their identification and analysis that leads to an understanding of the general features of beaches (HARDISTY, 1990). These general features are referred to as *first order forms*. The shape of the beach profile is generally due to orthogonal processes, those which operate along a vertical plane in the direction of wave advance (diabathic transport), which is roughly shore normal, while the plan shape of the beach is due to longshore processes which operate in a shore-parallel or coastwise (parabathic) direction.

First order forms often have superimposed on them smaller scale *second order features* (Table 12). If the beach is examined in finer detail, then *third order forms* are revealed which range from wave generated ripples, swash and backwash marks, and drainage channels to the individual grains and internal bedding structures which constitute the fabric of the beach deposit. Second and third order forms are the product of local beach conditions.

Wave-Dominated Beach Types

The term *beach type* refers (according to SHORT, 1975, 1993) to the prevailing nature of a beach, including the waves and currents, the extent of the nearshore zone, the width and shape of the surf zone including its bars and troughs, and the dry or subaerial beach. The first comprehensive classification of beach types (morphodynamic states) (SHORT, 1975) and change was developed by the Coastal Studies Unit at the University of Sydney (New South Wales, Australia) in the 1970's and subsequently modified by WRIGHT and SHORT (1984) and

Table 12. *Glossary of examples for second order beach features.*

Form or Feature	SNP	SPP	Definition
Backshore	X		The zone of the beach lying between the berm crest and the dune, bluff or cliff.
Bar (longshore bar, ball or ridge)	X		An elongate, slightly submerged sand ridge or ridges which may be exposed at low water.
Barrier		X	A sand beach (barrier beach), island (barrier island), or spit (barrier spit) that extends roughly parallel with the general coastal trend but is separated from the mainland by a relatively narrow body of water or marsh.
Beach face	X		Berm crest to low tide waterline, swash zone (morphological term); steeper reflective part of upper beach profile above MSL and typically surmounting the berm. On estuarine beaches, the beach face is adjacent to the MHWL, is planar, and slopes relatively steeply to a broad tidal flat.
Beach ridge (storm beach, chenier)	X		A low lengthy ridge of coarser beach materials (gravels, shells) piled up by storm waves landward of the berm.
Berm	X		The nearly horizontal part of the beach landwards of the sloping foreshore. Accretionary berms have a steep beach face (8–14 degrees) rising to a distinct ridge and a gentle backslope of about 4 degrees. Erosional berms have no clear boundary with the beach face.
Berm crest	X		The seaward limit of the berm; break in slope between berm riser (beach face) and berm tread, terrace.
Cusps		X	A series of arcuate scallops with adjacent horns on the beach face extending normal to the shoreline and recurring at more or less rhythmic intervals.
Foreshore	X		The sloping part of the beach between the berm and the low water line (swash plus inner surf zone).
Low tide terrace	X		An alongshore bar attached to the beach face that becomes a terrace at low water.
Offshore	X		The zone seawards of the low tide mark.
Rip channel	X	X	Channel cut by seawards flow of rip currents which usually crosses the longshore bar.
Shoreface	X	X	Low water line to flatter slope of continental shelf.
Trough (longshore trough, runnel, low)	X		Elongate depressions or series of depressions along the lower beach or in the offshore zone which may be exposed at low water.

Notes: SNP = Shore Normal Processes, SPP = Shore Parallel Processes. Although terms and definitions differ somewhat depending on points of view (e.g. morphology, hydrodynamics), these are meant to be illustrative of guidance based on Shepard (1973), Schwartz (1982), Short (1999), and EM 1110-2-1810 (31 Jan 95)

SHORT (1993). This classification, which is used internationally where the tide range is less than 2 m (microtidal range), recognizes three main beach types: dissipative, intermediate, and reflective (Table 13). The system, as applied to the east coast of Florida (BENEDET and FINKL, 2003; BENEDET *et al.*, 2004a, b), shows a predominance of dissipative beaches north of the Cape Canaveral cusped foreland but intermediate morphodynamic states occur south of the Cape foreland where beaches are characteristically single or double barred, with a well developed berm and rhythmic features (beach cusps) associated with rip currents. Reflective beach morpho-

types occur exclusively downdrift of inlets in wave shadows induced by jetties (BENEDET *et al.*, 2004b).

Reflective Beaches

These beaches are characterized by steep, narrow beaches usually composed of coarser sand and lower waves. Almost all beaches composed of gravel, cobble and boulders are always reflective, no matter what the wave height. These beaches have a steep, narrow beach and swash zone and beach cusps are commonly present on the upper beach face (Figures 3 and 4). The pocket beach near Halifax, Nova Scotia (Figure 3), contains cobble-sized clasts that can range up to 30 cm in diameter. At the lower end of the particle-size scale are reflective sandy beaches such as the one at Taquarinhos Beach on the southeast coast of Brazil (Figure 4). Most reflective beaches containing a range of sand sizes have what is called a *beach step*. The step is always located at the base of the beach face around the low water mark. It consists of a band containing the coarsest material available including rocks, cobbles, boulders and shells. Most steps average a few decimeters in height but some may reach a maximum of perhaps a meter. Immediately seaward of the step the sediments usually fine markedly and assume a lower slope.

Intermediate Beaches

These beach types are intermediate between the lower energy reflective beaches and the highest energy beaches called

Table 13. *Classification of morphodynamic beach types, based on the prevailing nature of a beach, including the waves and currents, extent of the nearshore zone, width and shape of the surf zone with its bars and troughs, and the dry subserial beach. This comprehensive classification of wave-dominated, micro-tidal beach types, first developed for the New South Wales coast, is now used worldwide where the tidal range is less than 2 m. (After Wright *et al.*, 1982; Short, 1993, 1999).*

Wave-Dominated, Micro-Tidal, Beach Types
Dissipative
Intermediate
Longshore Bar-Trough
Rhythmic Bar and Beach (Normal or skewed)
Transverse Bar and Rip (Normal or skewed)
Ridge-Runnel or Low Tide Terrace
Reflective



Figure 3. Cobble beach (allomorphic coast) and sea cliff (automorphic coast) near Halifax, Nova Scotia, Canada. The storm berm is perched on top of bedrock in the back beach area and is separated from the lower berm by a cobble-free zone. A small marine bench lies at the foot of the cliff in the photo center, but most of the cliff faces are steep-to. Meltwater drains across the beach area to the sea in the photo foreground. [Classification (Decametric scale): Cliff—automorphic coast with steep-to cliffs; cobble beach—allomorphic coastal segment with perched gravel beach, reflective morphotype]



Figure 4. Taquarinhas Beach on the south coast of Brazil in Santa Catarina State south of Itajaí. This headland bay coast is marked by numerous granitic promontories that shelter mostly intermediate type beaches that create compositionally unique embayments where the sediment type depends on local provenance. This particular beach contains coarse siliciclastic sand (average mean grain size is 0.8 mm on the beachface) and nonbarred, steep profiles typical of reflective beaches. The granite tors (resistant core stones) were exposed by the erosion of saprolitic materials produced by tropical-subtropical weathering regimes. [Classification (Landscape, scale): Neolittoral pocket beach due to scoliomorphogenesis on a mature or subsiding Atlantic type coast]

dissipative. A characteristic feature of intermediate beaches is the presence of a surf zone with bars and rips. Intermediate beaches are commonly classified into four *beach states*. The lowest energy one is called 'low tide terrace,' then as waves increase the 'transverse bar and rip,' then the 'rhythmic bar and beach,' and finally the 'longshore bar and trough' (SHORT, 1993, 1999).

Low tide terrace (LTT) beaches tend to occur where sand is fine to medium grained and wave heights average between 0.5 and 1 m. These beaches are found toward the lower energy, more protected end of long beaches, in moderately protected embayments, and in more exposed locations where sand is coarse grained. LTT beaches are characterized by a moderately steep beach face, which is joined at the low tide level to an attached bar or terrace, hence the name low tide terrace. Bars usually extend 20 to 50 m seaward and continue alongshore attached to the beach. The bars may be flat and featureless; have a slight central crest, called a ridge; and may be cut every several meters by small shallow rip channels called mini rips.

Transverse bar and rip (TBR) beaches occur where sand is generally fine to medium grained and waves average 1 to 1.5 m. These beaches are thus named in reference to bars that are transverse or perpendicular to and attached to the beach, separated by deeper rip channels. The bars and rip channels are usually regularly spaced every 150 to 250 m, but can reach spacing of 500 m. Their surf zone ranges from 50 to 100 m wide. The longshore variation in wave breaking and swash causes the beach to be reworked such that slight erosion usually occurs in the lee of rips, and slight deposition in the lee of bars. This pattern results in a rhythmic shoreline where the undulations are called megacusp horns (behind the bars) and embayments (behind the rips).

The **rhythmic bar and beach (RBB)** types are associated with dissipative to intermediate the energy states. These beaches are mostly associated with medium-grained sand, but RBB morphotypes may occur where the sand is finer than medium and where waves occur in the general range of 0.5 m as seen, for example, in Florida (BENEDET *et al.*, 2004a). The RBB type has much in common with the transverse type except that waves are usually higher and the bars are detached from the beach. As the name implies both the surf zone and bar are rhythmic as they weave between rips and bars, and the beach is rhythmic as it weaves between megacusp horns and embayments, as described for the transverse beach type.

The **longshore bar and trough (LBT)** beach type is characterized by waves averaging 1.5 m or more, which break over a near continuous longshore bar located between 100 and 150 m seaward of the beach, with a 50 to 100 m wide 2 to 3 m deep longshore trough separating it from the beach. The beach face, unlike the transverse and rhythmic beaches, is straight alongshore and usually has a lower gradient.

Dissipative Beaches

When dissipative beaches occur, the combination of high waves and fine sand ensures that they have wide surf zones and usually two or three shore parallel bars, separated by

subdued troughs. The wide beach with no distinct berm shown in Figure 5, Balneário Camboriú Beach (Santa Catarina State, Brazil), is characteristic of many dissipative morphotypes. The beach face is composed of fine sand, and always wide, low and firm enough to support a 2 WD car. Wave breaking begins as high spilling breakers on the outer bar, which reform to break again and perhaps again on the inner bar or bars. In this way they dissipate their energy across the surf zone which may be up to 300 to 500 m wide. This is the origin of the name 'dissipative.'

Beaches not in present contact with the contemporary coastal regime are referred to as relict or carry a paleo epithet to designate their morphodynamic status in stasis. Progradation of the coast may leave older beaches stranded behind younger ones, for example, as beach-ridge plains. Uplift along neotectonic coasts is another example where the nexus with the present coast is broken and beaches become elevationally stranded by uplift or downfaulting (drowning). There are many mechanisms of stranding and different forms result (see discussions, for example, in TAYLOR and STONE, 1996).

Tide-Dominate Beach Types

Although dissipation of incident wave energy is the most important process that affects the morphology and hydrodynamics of beach environments, the degree to which tide-related processes effect coastal morphodynamics increases with tidal range. Distinctive beach morphotypes can be recognized because (1) the tidal stage determines where certain near-shore processes operate on the shore profile and (2) the tidal translation rate determines how long processes act on the bed and affect beach morphology (MASSELINK and TURNER, 1999). Consideration of tidal cycles (amplitude and duration) adds another level of complexity to beach morphodynamics where beach morphotypes can be differentiated on the basis of breaking wave height and period, the high tide sediment fall velocity, and the mean spring tide range. These four morphodynamic variables were used by MASSELINK and SHORT (1993) to develop a beach morphodynamic classification scheme that incorporates tidal effects. This system recognizes the following main morphotypes: reflective (reflective beachface and reflective high tide beach—dissipative low tide terrace), intermediate (barred: steep beachface with pronounced deep trough, steep beachface with subdued bar morphology, and steeper beachface with low tide transverse bar and rip morphology), and dissipative (barred dissipative and ultra dissipative). The example of a tide-dominated reflective beach on San Salvador Island, Bahamian Archipelago (Figure 6), contains beach rock on the upper beach profile and a low tide terrace.

Classification of Coastal Dune Morphology

There are no major classifications of coastal dunes *per se*. Until very recently, there was a tendency to rely on the seminal contributions of BAGNOLD (1941) together with a small collection of widely cited papers—for example LANDSBERG (1956), COOPER (1958), and OLSEN (1958). Many of the earlier investigators did not attempt to identify the differences between coastal and interior dunes. In the last decade, pro-



Figure 5. Balneário Camboriú Beach (Santa Catarina State, southern Brazil) during low tide. This wide flat beach is characteristic of dissipative states in the morphodynamic classification of beaches, as defined by SHORT (1999), with an average beachface siliciclastic grain size of about 0.20 mm. Note the low gradient of the beachface, lack of a berm, and compacted fine-grained sand that formed ripples during high tide. [Classification (Decametric scale): Scoliomorphogenic dissipative morphotype on a mature or subsiding coast]

cess-based studies of coastal dunes (Figure 7) have begun to revise and even question many long-held views (see, for example, SHERMAN and HOTA, 1990) and there is a noticeable shift towards exploring the morphodynamic status of dunes (SHORT and HESP, 1982). Recent advances in dune geomorphology include the linking of shoreline morphodynamics to dune formation (e.g. SHORT and HESP, 1982; STEWART and DAVIDSON-ARNOTT, 1988; MARTINEZ and PSUTY, 2004), the development of storm-driven cyclic models of environmental change for low barrier dunes (HOSIER and CLEARY, 1977; SORESENSEN and MCCREARY, 1985), and for re-evaluation of many of the long-accepted transport formulae (HORIKAWA *et al.*, 1986; HOTA, 1988). For further consideration of coastal dune morphology, the reader is referred to NORDSTROM *et al.* (1990).

Dunes and beaches are intricately linked as integrated morphodynamic compartments that interact over different spatio-temporal scales. Coastal dune forms are essentially a function of sediment budget where the dune-beach sediment budget evolves, and through feedback mechanisms, new dune forms emerge. Leakage in the system contributes to local site

diversity but the balance between the regional beach budget and regional foredune budget maintain the dune-beach morphological system (PSUTY, 1988, 1994; MARTINEZ and PSUTY, 2004). The range of coastal dune forms is conceptualized by MARTINEZ and PSUTY, 2004) in terms of a foredune developmental sequence that pars foredune and beach sediment budgets. The resulting continuum extends from the condition of an extremely high positive sediment budget to a condition of extreme negative sediment budget where the sequence is highlighted by initial foredune mass increase, attainment of maximum mass, and then a decrease. The spatio-temporal sequencing of coastal foredune development results in a range of morphotypes from accretionary foredune ridges, active foredunes, parabolic dunes, to and sheets. Beach width, which acts both as a major control on sediment supply to foredunes, is in turn often affected by longshore sand waves (DAVIDSON-ARNOTT, 1988) thereby highlighting the beach-dune linkage and spatio-temporal influence of dune morphotypes. SHORT and HESP (1982) and SHORT (1988) clarify the deduction by specifically integrating dune morphotypes with beach states where waves, sediment supply, and grain size



Figure 6. Beach rock on San Salvador Island, Bahamian Archipelago. The beach rock along this leiomorphogenic stretch of carbonate beach dips seaward and is probably genetically related to a higher than present sea level. The average grain size on the beachface is about 0.5 mm. [Classification (Decametric scale): a tide-dominated, low energy reflective beach morphotype, associated with karst seascapes]

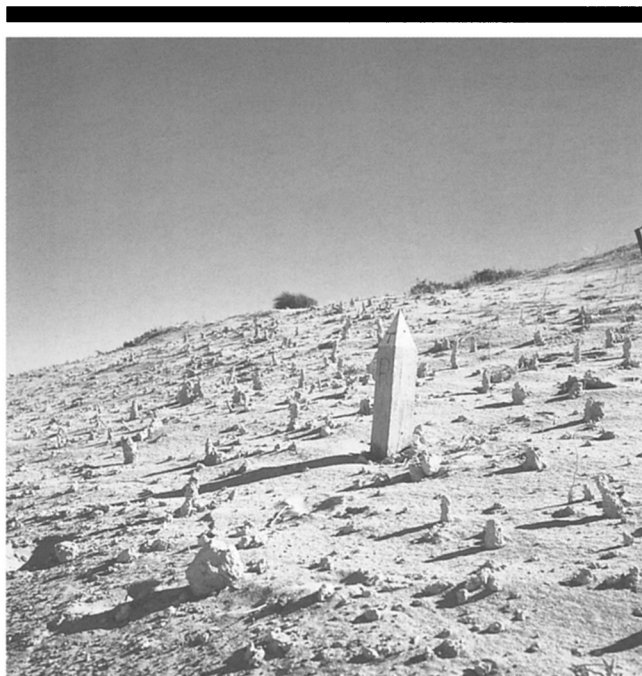


Figure 7. Coastal dune near Pinjarrah (south of Perth), Western Australia. The vegetative cover on this dune was disturbed, allowing destabilization of calcareous sands by eolian activity. The small pinnacles, now exposed from deeper within the profile, are calcareous root casts that formed by dissolution around roots of small trees and shrubs. Some of the larger root casts contain interior linings of travertine, which makes the casts much stronger than those without microcrystalline carbonate linings. Note also the presence of calcareous nodules, now exposed, but which formed in vughs and other small cavities within the dune. [Classification (Decametric scale): Leiomorphogenic (parabathic), Eolittoral carbonate dune on a taphrogenic coast]

affect beach states which in turn affect foredune development and ultimately evolutionary sequences of dune building and degradation.

Classification of Rocky Coasts (Cliffs and Platforms)

A rocky coast may be defined as a coast that is cliffed and yet composed of consolidated material irrespective of its hardness (SUNAMURA, 1992). Rocky coasts (Figures 7, 8, 9, and 10; cf Figures 1 and 2) thus include shores composed of materials ranging from hard rocks such as granite and basalt to relatively soft but cohesive material such as glacial deposits. These shores are thus commonly characterized by cliffs of various types and associated subjacent platforms (GRIGGS and TRENHAILE, 1994). Although cliffs occur behind approximately 80% of the world's coastline (ISAKOV, 1953; EMERY and KUHN, 1982; SUNAMURA, 1992), they have tended to receive relatively little attention in the scientific literature.

Since the postglacial sea-level rise (most recent transgression initiated during the Hypsithermal Climatic Interval in the early Holocene) when the rate of sea level rose initially at an accelerating rate but then began to slow down (6000–5000 YBP), marine processes have been working on rocky coasts to create characteristic shore-zone morphologies.

Rocky coast morphologies are influenced by major variations that reflect: (1) lithological factors (*i.e.* rock types and geological structures, discontinuities, such as bedding planes, joints, and faults), (2) weathering properties of rocks, (3) tides, (4) degree of exposure to wave attack, and (5) the inheritance of minor relative changes in land and sea levels. Recognition of relative land-sea movements was appreciated by many early workers who used various terms in reference to the vertical displacement of coastal features such as terraces and platforms that would today be recognized as polygenetic paleomorphs (see subsequent discussion). Uplift and displacement of coastal features from sea level to higher elevations, for example, form *terraced coasts* (HOBBS, 1921, p. 104) viz. *coastal terraces* of San Clemente Island (California), *raised reef terraces* of Obi (Moluccas), terraces of the Coast Cordillera (Peru), coastal terraces of Oregon, *tilted reefs* on Alu (Solomon Islands), raised reef terraces on Eva (Tonga Islands), terraces on Siompu (Celebes), *etc.* Similar examples are cited from Central America and the Caribbean areas (*e.g.* VAUGHAN, 1919).

Platforms developing around present sea level are frequently classified into: (1) gently sloping platforms without a significant topographic break, extending from the base of a cliff to the nearshore sea floor below low tide level, and (2) nearly horizontal platforms with a marked drop at their seaward edge. There are also steeply descending (plunging) cliffs that pass far below sea level without any shore platform. This classification follows BIRD (1976) who subdivided subhorizontal-platforms into two distinctive types according to the platform elevation, viz. **high-tide and lowtide platforms**.

For sloping platforms, the literature has employed various terms: *abrasion platforms* (JOHNSON, 1919; WEFER *et al.*, 1976); *beach platforms* (WOOD, 1968), *benches* (ZENKOVICH, 1967), *coastal platforms* (SO, 1965), *shore platforms* (BARTRUM, 1916, 1924; BIRD and DENT, 1966; WRIGHT, 1967; BIRD, 1976; ROBINSON, 1977; TRENHAILE, 1987), *submarine platforms* (HEALY and WEFER, 1980), *wave-cut benches* (LEE, 1980), *wave-cut platforms* (BRADLEY, 1958; FAIRBRIDGE, 1968; BRADLEY and GRIGGS, 1976), *wave-cut terraces* (VON ENGELN, 1942), and *wave ramps* (HILLS, 1971, 1972). There are also other terms that describe horizontal or subhorizontal platforms, as discussed by SUNAMURA (1992): *abrasion or denuded benches*, *coastal platforms*, *low rock terraces or platforms*, *rock platforms*, *shore benches*, *shore platforms*, *storm-wave platforms*, *wave-cut benches*, *wave-cut platforms*, *etc.* Some of the nomenclature includes a genetic connotation such as “wave-cut,” “abrasion,” or “storm-wave.” Because the platform genesis and formative processes have not yet been fully elucidated, purely descriptive terms are probably preferable (BIRD, 1976; PETHICK, 1984; TRENHAILE, 1987). Because the term “shore platform” is appropriate and widely used in the modern literature, it is useful to distinguish two basic types on the basis of slope: Type-A (sloping) and Type-B (horizontal).

According to TRENHAILE (1987), **Type-A platforms** are most common in macrotidal environments and **Type-B platforms** (Figure 8) in meso- and microtidal regions (Table 14), as shown in the example of Eva's Cay (Long Island), Bahamian Archipelago. Type-A platforms tend to develop in softer rocks,



Figure 8. Eva's Cay near Saltpond, Long Island, Bahamas. This microtidal tropical marine bench, exposed at low tide, was formed in calcarenite by the combined processes of marine biological weathering and erosion of the honeycomb structures by wave and current action during storms. Note the sandy perched beach sitting on top of the platform in front of the vegetation line. These rocky intertidal platforms provide natural protection against coastal erosion along the shores of many small islands. [Classification (Decametric scale): scoliomorphogenic rocky coast with marine bench, fringing the Bahama Bank Morphotype]

but BIRD and DENT (1966) found that Type-B platforms give place to Type-A platforms at a place where locally derived shingle is available as an abrasive tool for waves. EDWARDS (1951) and HILLS (1972) recognized that Type-B platforms are well developed on headlands, with Type-A in intervening embayments, composed of less resistant materials.

Recession of **coastal cliffs** is essential for both Types-A and -B to develop. Tides are also important in that (1) water level determines the elevation of wave action and controls the type of waves arriving at the cliff and (2) the tidal range may influence weathering and biological activities, although the tide itself has no force to erode the cliff (SUNAMURA, 1992). Cliffs above the shore platforms may take various forms, in part due to inheritance and to marine processes. Some common types include, for example, plunging cliffs, castellated, and slope-over-wall (BIRD, 1976). From a geomorphological point of view, coastal cliffs are commonly grouped into the following main morphotypes (after BIRD, 1976): castellated, plunging, and slope-over-wall (Table 14). Examples of cliffed coasts are shown in Figure 9 (Oregon coast near Tillamook Bay) where

a dissipative beach fronts cliffs of the Coast Range. In the example of northeastern Eleuthera Island (Figure 10), Bahamian Archipelago, steep-to cliffs front the Atlantic Ocean without beaches.

CLASSIFICATION OF COASTAL AND MARINE ENVIRONMENTS

Previous discussion has focused on physical processes and morphologic development of coastal morphologies, shapes and forms. Even though the units of classification were not clearly stipulated in some earlier systems, they were assumed or evident by their description. This section considers alternatives to the initial physically-based approach that considers form and process. Although environmental approaches are relatively new, they offer opportunity or possibilities to evaluate the coast in terms of ecological or biophysical systems.

Development of an internationally consistent world system of coastal classification is scientifically challenging. Terres-

trial, coastal, and marine realms are approached in quite different ways. Thus, terrestrial biotic provinces are classified, for example, by UDVARDY (1975), AXELROD (1958), and ARECES-MALLEA *et al.* (1999) largely on the basis of vegetation. Coastal classification is largely by physical landforms and physical processes (e.g. COTTON, 1954; KING, 1966; BIRD, 1976; DOLAN *et al.*, 1972, 1975); marine realms have been treated both physically (e.g. water masses) and biotically but no one method dominates. Some more recent approaches that focus, for example, on nearshore continental and oceanic island environments, within the littoral zone, are based on the water column and underlying benthic substrate together to form an integrated habitat unit (e.g. ZACHARIAS *et al.*, 1998; ZACHARIAS and ROFF, 2000; ALLEE *et al.*, 2001) as opposed to deeper water environments (e.g. GREENE *et al.*, 1999). In the example of the Bahamian Archipelago, classification of coastal environments is based on combining elements of the NOAA marine classification (ALLEE *et al.*, 2001), Caribbean vegetation classification (ARECES-MALLEA *et al.*, 1999), and COWARDIN *et al.* (1979) to describe ecoregions and smaller ecounits of the natural system. The classification of coastal landscapes is a difficult task because within the general framework of landscape there is no separated definition. Most approaches consider the geographical landscape, geo-complexes, or characteristic complexes of ecosystem that is biocenosis with biotype as environmental approximations. LIND (1969) and FURMANCZYK *et al.* (2002) provide insight into coastal landscape classification by applying a linear approach that differentiates natural components in unit-segments of coast.

DOLAN *et al.* (1972, 1973) provide insight into initial attempts to develop comprehensive classifications of coastal/marine environments. The key element here is the consideration of environments as the objects of classification, not coastal features or morphological properties as discussed previously. The coastal environment is a complex biophysical system in which terrestrial, marine, and atmospheric processes constantly interact. According to these workers, the processes are inseparable but modes of interaction (defined as *natural coastal environmental complexes*) can be identified by analysis of dominant processes. Classification of coastal environmental zones requires systematizing information both *along* and *across* the coast, as also described by LIND (1969). This stratification is based on scale and the natural variability of coastal environments. Because processes operating along-the-coast are mostly global and those operating across-the-coast are regional and local, the development of a classification system demands analysis of relationships between atmospheric and marine processes, organization of geologic materials, and ecological donation within the coastal zone. Environments distributed across the coast are viewed as being within and coupled to environments along the coast. Consequently, the two components of the so-called *orthogonal coastal classification* have a common unit, the *elemental unit*. **Process zones across-the-coast** include: (1) the deep water zone of the outer continental shelf, (2) shallow water zone of the inner continental shelf, (3) zone of intense shoaling and breaking (surf zone), (4) zone of extreme wave energy dissipation (surge zone), (5) zone of maximum tidal and atmo-

spheric penetration, and (6) transitional zone of marine physiographic to continental physiographic dominance. Analysis of the sequence of environmental zones across the coast requires the amassing of data on the physical characteristics and dominant processes of the coastal environment. According to DOLAN *et al.* (1973), most important information sets include: (1) mean and extreme wave climates, (2) tide ranges, (3) submarine topography, (4) terrestrial topography, (5) atmospheric fluxes.

The process of classification along the coast is divided into four steps: (1) analysis of the process, (2) mapping the distribution of geologic materials, (3) analysis of biotic systems in the vicinity of the coast, and (4) integration and assembly of these subunits of the classification. The process context is of two parts and yields the first two levels of the classification: *atmospheric regimes* and the *oceanic subregimes*.

Analysis of the atmosphere is based on air mass climatology whereas oceans are characterized by the analysis of water masses. The materials context is stratified via the information gained through analysis of coastal landforms. This provides the information needed to integrate the principal units of the *coastal interface* with the ocean and atmosphere. The third part of the classification, verification of the regimes, subregimes, and interface units, is achieved through analysis of biotic provinces. The final phase is the integration of all three subunits of the classification.

The Regimes

The dominant characteristics of coastal climates are the consequence of specific atmospheric phenomena. These are: (1) dominant air masses, (2) confluence of airstreams in the coastal zone, (3) the path of the air mass systems, and (4) seasonality of the atmospheric phenomena. An understanding of the spatial and temporal distribution of these phenomena permits inferences about the weather elements: temperature, rainfall, winds, humidity, *etc.*

The Subregimes

Three continuous variables account for differences within the marine fluid environment: (1) water temperature, (2) salinity, and (3) currents. Other phenomena such as waves, tides, and turbidity tend to be discontinuous and are therefore treated at a smaller scale (across the coast).

The Interface

The character of the coastal interface is the consequence of one or more dominant coastal zone processes: (1) marine (waves, tides, currents, *etc.*), (2) biologic (coral and mangrove growth), and (3) fluvial (fresh water drainage). The analysis and subdivision of these interface types requires complete coastal landform analysis and classification which was constructed using topographic, geologic, hydrographic, and vegetation maps and recorded observations in the Sailing Directions Publication.

A means whereby these classifications might be made more compatible is through consideration of physical and biotic properties together, as proposed by HAYDEN *et al.* (1984). At-

Table 14. *Examples of morphological types of shore platforms and marine cliffs, terminology, and classification, and associated features.*

Morphological Types of Shore Platforms

Type A: Gently sloping platforms without a significant topographic break, extending from the base of a cliff to the nearshore seafloor below low tide level

- Abrasion platforms (e.g. Johnson, 1919)
- Beach platforms (e.g. Wood, 1968)
- Benches (e.g. Zenkovich, 1967)
- Coastal platforms (e.g. So, 1965)
- Shore platforms (e.g. Bird and Dent, 1966; Trenhaile, 1987)
- Submarine platforms (e.g. Healy and Wefer, 1980)
- Wave-cut benches (e.g. Barrell, 1920; Longwell *et al.*, 1969; Lee *et al.*, 1976)
- Wave-cut platforms (e.g. Bradley, 1958; King, 1963; Bradley and Griggs, 1976; Sparks, 1986)
- Wave-cut terraces (e.g. Von Engeln, 1942; Leet and Judson, 1958)
- Wave ramps (e.g. Hills, 1972)

Type B: Nearly horizontal platforms with a marked drop at their seaward edge

- High tide platforms (e.g. Bird, 1976)
- Abrasion or denuded beaches (e.g. Zenkovich, 1967)
- Coastal platforms (e.g. Guilcher, 1958)
- Low rock terraces or platforms (e.g. Emery, 1960)
- Marine benches (e.g. Wentworth, 1938; Cotton, 1963)
- Rock platforms (Bartrum, 1916)
- Shore benches (e.g. Stearns, 1935; Wentworth and Hoffmeister, 1939)
- Shore platforms (e.g. Bartrum, 1924; Jutson, 1939; Hills, 1949; Cotton, 1960; Wright, 1967; Trenhaile, 1972; Sunamura, 1978)
- Storm-wave platforms (e.g. Edwards, 1941)
- Storm terraces (e.g. Emery, 1960)
- Wave-cut benches (e.g. Short, 1982)
- Wave-cut platforms (e.g. Johnson, 1931; Fairbridge, 1968; Short, 1982)

Morphological Types of Sea Cliffs

Plunging Cliffs: Steeply descending cliffs that pass far below sea level without any shore platform (Davis, 1928)

- Fault-induced cliff lines (e.g. Shepard and Wanless, 1971)
- Fault-line scarps (e.g. Steers, 1962)
- Lava-flow, dike cliffs (with re-entrants) (Steers, 1962; Paskoff, 1978)
- Buttresses
- Castellated cliffs (Steers, 1962)

Composite Cliffs (Orme, 1962): Range from flat-topped profiles cut into coastal plateaux (Arber, 1911) to gentle slope elements above a steep, wave-cut face (Guilcher, 1958)

- Slope over walls (e.g. Whitaker, 1911)
- Beveled cliffs (e.g. Wood, 1962)
- Coastal slopes (e.g. Challinor, 1931, 1948)
- Hog's back (e.g. Arber, 1911)
- Marginal scarps (e.g. Leach, 1933)
- Two-storied cliffs (e.g. Fleming, 1965)
- Three-storied cliffs (e.g. Savigear, 1962)

Associated Forms

- Notch, visor (Wentworth, 1939)
- Sea caves, tunnels (Wilson, 1952; Guilcher, 1958; Emery, 1960)
- Sea arches, stacks (Johnson, 1925; Snead, 1982)
- Ramparts (Wentworth, 1938; Hills, 1971)
- Ramps (Trenhaile, 1978)
 - Abrasion ramps (Wentworth, 1938; Jutson, 1949)
 - Erosion ramps (Short, 1982a)
 - Wave-cut ramps (Fairbridge, 1968)
 - Wave ramp (Hills, 1972)
- Marine potholes (Bird, 1970)
- Solution pools, pans (Wentworth, 1944)
- Solution basins (Emery, 1946; Emery and Kuhn 1980)
- Solution pits (Guilcher, 1953)
- Pinnacles (coastal lapies) (Guilcher, 1958; Bird, 1976; Tricart, 1962)

tempts to classify environments by species assemblages results in unique 'provinces' that are never exactly repeated elsewhere in the world, and this situation is untenable. As a partial solution, HAYDEN *et al.* (1984) propose a classification system based on physical environments and related marine faunal provinces that come together in a 'zoophysiographic classification of coastal and marine environments'. An important problem concerns the 'coastal zone,' a broad ecotone that both divides and unites marine and terrestrial systems. RAY *et al.* (1981), following KETCHUM (1972), defined the coastal zone boundaries as follows:

- (1) The *terrestrial boundary* is defined by (a) the inland extent of astronomical tidal influences, or (b) the inland limit of penetration of marine aerosols with the atmospheric boundary layer and including both salts and suspended liquids, whichever is greater.
- (2) The *seaward limit* is defined by (a) the outer extent of the continental shelf (approximately 200 m depth), or (b) the limit of territorial waters, whichever is greater.

Definition 2b is jurisdictional, not biogeographical. It should be obvious that the coastal zone is very extensive, and that neither purely terrestrial nor purely oceanic approaches will suffice for its delimitation and ultimate classification.

PIELOU (1979) observes that profound differences in community structure and ecosystem function make the designation of terrestrial and marine *biogeographic regions* by similar methods difficult. She further observed, that: (1) vegetation does not form a structural environment in most marine systems, (2) the oceans are contiguous and marine species have greater ranges than terrestrial species, (3) the boundaries of dispersal are more subtle but the closer to land the clearer are the boundaries between regions, (4) latitudinal zonation is often more marked for marine species than for terrestrial ones, and (5) the ocean is three dimensional and biogeographical zonations are ones of depth as well as location. It thus appears that life forms are more varied in the sea than on land. Consequently, a marine coastal classification should not be approached in the same way as such an undertaking on land (HAYDEN *et al.*, 1984).

HAYDEN *et al.* (1984) provide a classification of marine and coastal areas according to attributes of the physical environment and by the faunal assemblages involved. **Ocean and coastal-margin realms** are defined and mapped with the marginal seas and archipelagos named according to their connections to oceanic realms. For the Atlantic Ocean region, for example, there are four ocean realms (Table 15) and thirteen coastal-margin realms (Table 16). The defining characteristics of these realms are the seasonal variations in ocean sur-

Table 14. *Continued.*

Tafoni and honeycombs (alveoli, alveoles) (Trenhaile, 1987)
This wide range of terminologies that has been applied to the same features, similar forms, or overlapping continuums is based on Trenhaile (1987), Sunamura (1992), Emery and Kuhn (1982), and others, and is not meant to be definitive. This incomplete list is meant to provide examples of the range of complex forms that are associated with cliffs and platforms.



Figure 9. Oregon coast near Tillamook Bay. A dissipative beach fronts cliffs of the Coast Range. Weaker sections of the shorelines have retreated landward from the promontory where this photo was taken. A sea stack, which marks the photo center foreground, is a remnant of a basaltic dike that persisted through prolonged periods of coastal/marine erosion. The seaward extension of the dike occurs in the photo's lower right hand corner. [Classification (Landscape, mesomorphostructural scale): Allomorphic coast, between automorphic headlands and promontories, with leiomorphogenic dissipative beach morphotypes backed by cliffs on a Pacific Type (Cordilleran Subtype) coast; the sea stack (basaltic dike) runs parallel to the plunging cliffs of the promontory but is perpendicular to the beach, cutting across the general parabathic trend.]



Figure 10. Atlantic coast of northern Eleuthera, Bahamian Archipelago. This cliffy coast contains many marine platforms, benches, sea caves, and re-entrants that are developed in eolianite (fossilized calcareous dunes). Bedding planes dipping islandward are clearly visible in the photo center. More than half of these fossilized sand dunes have been eroded away. These dunes contain stratigraphic sequences that were built up during Pleistocene glacial phases when sea level was lower. [Classification (Landscape, mesomorphostructural scale): Rocky scoliomorphogenic coast with benches, sea caves, and re-entrants of Bahamian Bank karst morphotypes on Atlantic Type coast]

Table 15. *List of ocean realms as recognized by Hayden et al. (1984).*

Oceanic Realm	Direction of Surface Currents
I	Variable eastward currents
II	Weak and variable currents
III	Trade-wind currents
III ^e	Strong equatorward currents
III ^w	Westward currents
III ^p	Strong poleward currents
IV	Strong westward and equatorward currents
V	Monsoon currents (seasonal reversals)

face currents and the companion seasonal variations in the main wind currents of the atmosphere (Table 17). While the boundaries between faunal provinces do not always match boundaries between ocean and coastal realms, the foundation is laid for a binomial designation system with the coastal or oceanic realm as 'genus' and the faunal province as the 'epithet' (HAYDEN *et al.*, 1984). This brief summary of *subglobal coastal-marine biogeographic provinces*, following UDVARDY (1975) for the land, provides an example of an attempt that holds promise for rational comprehensive classification of coastal environments.

RAY and HAYDEN (1992) take this approach on step further in their physical approach to classification within-province, *coastal-zone structures* for defining coastal units in which the connections among mass, energy, and biota across the coastal zone are stronger than along the coast. Here they recognize structural subdivisions of the coastal zone with each defined by gradients in ecological processes and attributes with: (a) simple type coastal systems in which the flow of water is restricted to tidelands and the shoreface entertainment volume and (b) complex coastal systems in which a large drainage system has sufficient flow to bypass the shoreface entrainment volume and drains more less directly into the off-shore volume.

Another approach for dealing with coastal environments is

Table 16. *List of coastal-margin realms with dominant directions of currents and windstreams. (After Ray, 1966).*

Coastal Realm	Currents	Windstreams
Arctic (M)	ICE	W
Antarctic (L)	W-ICE	W
Subpolar (A)	W	W
Eastern		
Temperate (B)	P	E
Monsoon (J)	EQ/P	ON/OFF
Subtropical (C)	P	P
Tropical (E)	W	W
Intertropical	W*	W*
Western		
Temperate (F)	P	P/EQ
Monsoon (K)	P/EQ	ON/OFF
Subtropical (G)	EQ	EQ
Tropical (H)	EQ	W/EQ
Intertropical (I)	E/EQ	EQ

Where symbols indicate: ICE = Icemargin coast, P = Poleward, EQ = Equatorward, W = Westward, E = Eastward, ON = Onshore monsoon, OFF = Offshore monsoon, / = Winter-Summer seasonality, * = seasonality in hemisphere source-regions of currents and windstreams.

Table 17. *List of faunal province names used in the subdivision of coastal realms. (After Hayden et al., 1984).*

Map Ref Number	Province Name
Atlantic Ocean Region	
1	Magellan
2	Eastern South America
3	Brazilian
4	West Indian
5	Caribbean
6	Louisianian
7	Carolinian
8	Virginian
9	Acadian
10	East Atlantic Boreal
11	Lusitanian
12	West African
13	Southwestern African
Pacific Ocean Region	
1	Auckland
2	Southern New Zealand
3	Tasmanian
4	Southeastern Australia
5	Indo-Polynesian
6	Japan
7	Oriental
8	Kurile
9	Okhotsk
10	Aleutian
11	Sitkan
12	Oregon
13	San Diego
14	Cortez
15	Mexican
16	Panamanian
17	Peru-Chilean
Indian Ocean Region	
1	Agulhas
2	Western Indian Ocean
3	Red Sea
4	Black Sea
5	Indo-Polynesian
6	Northwestern Australian
7	Southwestern Australian

seen in the comprehensive atlas of the coastal environment (MMA, MINISTERIO DO MEIO AMBIENTE, 1996), a remarkable and exhaustive treatment of coastal features of the Brazilian coast. The length of coast, including only significant embayments and irregular indentations, is about 8500 km and spans more than thirty-five degrees of latitude from 4° 30' N to 30° 44' S Latitude at a scale of 100,000. Characterization of the biophysical environment defines major properties of the continental platform to variable distances inland. Biogeographical classifications as well as geomorphological groupings are included for each folio sheet. Examples of geomorphic units for the Rio de Janeiro littoral include: modern and Holocene fluvial deposits, rocky platforms, sandy shore, coastal plain, dunes, cliffs, coastal valleys and marshy lowlands, littoral plains, mountains and escarpments, *etc.* Many of the classificatory units are combinations of the geomorphic base plus the soil cover, vegetation type, and drainage (hydraulics). For a summary review of this atlas, see

FINKL (2001). The Brazilian classification of coastal environments is comparable to the Canadian effort (OWENS, 1994) as far as length of coastline classified is concerned, but the MMA system is more diverse and comprehends a greater range of environments whereas the geomorphology of Canadian shores is more clearly elucidated. Both schemes interpret coastal environmental resources in terms of susceptibility or sensitivity to perturbation due to anthropogenic input (*i.e.* risks from oil spills). Both the Brazilian and Canadian systems, which have specialized goals and different purposes, contain useful elements that should be considered in the development of geomorphological classification of coasts; neither of these approaches are universal or comprehensive, however.

Method of Coastal Land Systems Mapping

Generalization of map units incurs apparent loss and change in spatial distribution at different scales. Traditionally, an area-class map such as a vegetation or geologic map consisted of a set of map units, or polygons, with a single attribute identifying the predominant class within it. The classes themselves are usually described in terms of the mixture of associated classes that could typically be found in a nonhomogeneous area. Seldom are individual map units characterized more fully in terms of the set of classes within them. If a single-attribute map is generalized, map units are aggregated and the dominant class of the aggregate is assigned as the attribute. Both spatial and taxonomic precision are lost as the result. Similar problems are faced in terrain mapping, land resource assessment, and coastal classification where small or included subsets are unnoticed.

One method used to overcome this problem is seen in the Australian concept of a **land system** (CHRISTIAN and STEWART, 1953; BRINK *et al.*, 1966; SPEIGHT, 1968) where a "land system" consists of a recurring pattern of landforms, soils, and vegetation. The lower order "land facets" which make up the land system are described but not mapped. The concept of a land system has been adapted to coastal conditions extent along the southeast coast of the Florida peninsula in the Broward Coastal Zone (BCZ). Coastal land (hydrologic) systems in the BCZ were reproduced at a scale of 1:24,000 to conform to U.S. Geological Survey topographic quadrangles (FINKL, 1994a). The map units were subsequently digitized and brought into GIS because the ability to store multiple attributes for each map unit in a relational database system is a powerful advantage of modern GIS over traditional map products.

In a simple land system, there is a group of closely related topographic units that are produced by common geomorphological (land-forming) processes. The topographic units thus constitute a geographically associated series that are directly and consequently related to one another. The landscape patterns within a land system are regularly occurring groupings that always exhibit the same spatial interrelationships. The approach used by FINKL (1994a) follows the land-system surveys of the C.S.I.R.O. (Commonwealth Scientific and Industrial Research Organization, Australia) (*e.g.* CHRISTIAN and STEWART, 1953, 1968; BECKETT and WEBSTER, 1965; BRINK

Table 18. *Coastal land systems as applied to the southeast Florida coast. (After Finkl, 1994).*

Coastal Land Systems	Description
Lauderdale Strand	Narrow littoral belt of Holocene shore and beach, including dune fields and overwash fans
Spanish River Sand Hills	Narrow coastal uplands containing Pleistocene parallel dunes, includes ridge and swale topography
St. Mathew Marshlands	Low coastal wetlands that were formerly freshwater marsh but now converting to saltwater marsh
McNab Floodways	Flat lowlands with galeria-like forests that border meandering streams and rivers
Stranahan Prairies	Coast-perpendicular valleys that are broad, flat-floored, and contain sandy lowlands with grassy tracts, flooded part of the year
Himmarshee Sand Plains	Sandy upland terrain characterized by plains of low relief which lack defined drainageways
Miami Ridge	High limestone rockland with undulating relief which rises sharply above the surrounding landscapes, now karstified with solution holes
Mickel Transverse Glades	Coast-perpendicular valleys that are east-west extensions of the Florida Everglades

et al., 1966). This system of land pattern recognition in environmental division is based on hydrologic and climatomorphic principles. The main advantage of this system is that it coordinates all of the major landscape features into one unit rather than separately identifying landforms, soils, vegetation, and hydrology. **Coastal land systems** occurring in the BCZ include subdivisions of low coastal wetlands, alluvial plains and terraces (including floodways), coast-perpendicular valleys, upland sandy terrain, and high limestone rocklands (Table 18).

Primary coastal land systems (combinations of topography, drainage and hydrology, soil associations, geology, and vegetation) were mapped (FINKL, 1994a) from the shore to about 2.5 km inland. The land systems are subdivisions of WHITE's (1970) Everglades, Atlantic Coastal Ridge, and Eastern Valley physiographic units. Identification of natural land units is directly related to the recognition of pre-development natural drainage ways (*e.g.* swales, sloughs, swamps, transverse glades, *etc.*), basin outflow points, soils subject to prolonged flooding, determination of flood prone areas, *etc.* Mapping of coastal environments was based on aerial photointerpretation of *circa* 1940–45 imagery (uncontrolled mosaics and stereo-paired aerial photographs, produced by the USDA Agricultural Stabilization and Conservation Service and available from the National Archives) at a scale of approximately 1:40,000. Aerial photointerpretation was based on older imagery because natural landscape (geomorphic) features are more clearly evident prior to extensive drainage of coastal wetlands (Everglades, transverse glades, wet prairies, marshes, and sloughs), canalization, and urban development. Definitions of the various coastal environmental units incorporates historical (predevelopment) and recent data from

vegetation surveys, particularly those that stress vegetation-soils-topographic-drainage relationships (e.g. DAVIS, 1943; AUSTIN, 1976), soil surveys (e.g. PENDLETON *et al.*, 1984), U.S. Geological Survey topographic maps (AMS4936 IISE-Series V847: Boca Raton, Pompano Beach, Fort Lauderdale, Port Everglades, Hollywood sheets), geological-geomorphological survey reports (e.g. SANFORD, 1909; WHITE, 1970), and ecological and hydrology-climatology maps (e.g. sheets from the *Florida Ecological Atlas*—US Fish and Wildlife Service (FWS), 1984). Primary classical sources of habitat description for southern Florida were generally compiled after 1900 and are summarized in FINKL (1994).

Eight coastal land systems are identified in the BCZ (Table 18). For ease of reference, each land system is identified by a geographic name that precedes a descriptive physiographic term. The named systems listed here, in general order according to their relative elevations above sea level and distance inland from the coast, are as follows: Lauderdale Strand, Spanish River Sand Hills, St. Mathew Marshlands, McNab Floodways, Stranahan Prairies, Himmarshee Sand Plains, Miami Ridge, and Mickel Transverse Glades. Each land system is briefly described in terms of salient natural features and geographic extent in the eastern BCZ.

Lauderdale Strand

The Lauderdale Strand, a coastal unit that makes up the shore and beach, is characterized by narrow littoral belts that are composed of Holocene beaches, dune fields, and overwash fans. Elevations of sand dunes and beach ridges in this narrow coastal belt range from near sea level to heights of about 7 m along dune crests. Vegetation associated with the Lauderdale Strand includes cabbage palm, seagrape, sawpalmetto, cactus, and sea-oats and other grasses. Backdunes that provide some protection from ocean winds and salt spray support dense growths of trees and shrubs. Thin weakly developed, coarse-textured soils are associated with these excessively drained dune sands.

Spanish River Sand Hills

These old coastal dune systems comprise narrow coastal uplands. The older dunes are aligned roughly parallel to the present coastline and form a ridge and swale topography where long, narrow, shallow, trough-like depressions (swampy runnels) occur between dunes. The vegetation that occurs in association with these landforms is distinctly zoned. Low-growing grasses, vines, and stunted shrubs grow in the dry ridge crests whereas larger trees are found in the swampy runnels. Sandy, excessively drained (droughty) calcareous soils with minimal profile development occur along the ridge crests and contrast strongly with the poorly drained organic-rich soils of the runnels.

St. Mathew Marshlands

The St. Mathew Marshlands are low coastal wetlands that were fresh water marsh prior to the cutting of inlets and the Intracoastal Waterway (ICWW), canalization, and digging of drainage ditches for mosquito control in the late 1920's and early 1930's (AUSTIN, 1976; FINKL, 1993). These landscapes have flat to hummocky topographies that lie at elevations generally less than 2 m above mean sea level. Some relict beach ridges occurring inland from the Lauderdale Strand produce a faint linear relief that lies more or less parallel the present coastline. Unconsolidated deposits with lenses of organic materials and buried beach ridges range up to 4 or 5 m in thickness. These sandy and organic-rich materials overlie solution-pitted oolitic and shell-hash limestones in eastern Fort Lauderdale. These marshes occupy broad shallow depressions in the limestones where beach sands, peats, and mucks have accumulated. The natural vegetation

of these marshes (glades) mainly consists of sedges, rushes, and a few hydrophilic trees along the drier margins. Soils in this unit are characterized by very poorly drained mucks or sandy clay loams that overlie loamy sand and organic soils that are in turn underlain by clay or sand.

McNab Floodways

The McNab Floodways are flat lowlands that border meandering streams and rivers. The narrow floodways are usually dry but may become inundated by rising waters at flood stages during the wet season or after high rainfall events. Galeria-like forests containing bald cypress, live oak, gumbo limbo, and palmetto palms flank the sinuous river valleys. These fringing forests apparently impressed early settlers who described the "jungles" for which the region was once known. Organic-rich alluvial soils cover the contemporary floodplain and older terraces. The McNab Floodways link the Everglades, via coast-perpendicular valleys, with the coastal St. Mathew Marshlands.

Stranahan Prairies

The Stranahan Prairies occupy coast-perpendicular valleys that tend to flank the Mickel Transverse Glades. These broad, flat-floored, sandy lowlands are grassy tracts that connect with coastal river floodplains and merge with the Everglades inland. Natural vegetation consists of grasses, rushes, sedges, and other herbaceous plants and low shrubs. The very poorly drained soils are often saturated for two or more months of the year but seldom have ponded water at the surface. The soils are coarse textured or have mineral surfaces that are underlain by clay or sand. These wet prairies occur at somewhat higher relative elevations but flank or merge with the St. Mathew Marshlands, McNab Floodways, and Mickel Transverse Glades. The Stranahan Prairies occur mainly inland of the Miami Ridge except northeast of Fort Lauderdale where they butt up against the backdunes of the Lauderdale Strand. These wet prairies are transitional landscapes that occur between lower-lying wetlands and dry sandplains of the uplands.

Himmarshee Sand Plains

This upland sandy terrain is characterized by plains of low to moderate relief. The sand plains lie at an average elevation of about 2.5 to 4 m above sea level. These sand plains, which lack defined surface drainage networks, are composed of thick accumulations of porous white sands. The deep sands tend to be well drained but in some topographically restrictive situations they may be stained black or red by dissolved iron compounds or organic matter. The vegetation of these dry sandy uplands is dominated by flatwoods, open pine stands with an understory of sawpalmetto and grasses. Thick, strongly developed soils occur throughout the plains. These soils are notable for their dark colored surface horizons that overlie bleached layers that in turn overlie dark brown-colored illuvial horizons that are several meters thick.

Miami Ridge

This land system is a high limestone rockland. The rocky limestone ridges with undulating relief rise sharply above surrounding landscapes to reach extreme elevations of 7 to 8 m above MSL. The ridge is mainly composed of case-hardened oolitic (egg-shaped) calcareous sands that are very porous. The surface of the ridge is often pock-marked by solution holes that extend for several meters below the ground surface (PARKER *et al.*, 1955; PENDLETON *et al.*, 1984). The holes, which are commonly filled by fine-grained materials, now provide good sites for vegetative growth. The predominant vegetation of live oak, laurel, and water oak along with gumbo limbo, mastig, and sable (cabbage) palm continues to form an open hardwood subtropical hammock where left undisturbed. The sandy soils are generally thin and rocky. These lithosols show little modification of their calcareous parent materials and mainly result from meager accumulation of organic detritus from the xerophyllous vegetation. Aside from the occasional massive outcrop, limestone rocks are frequently strewn about the ground surface or occur near the soil sur-

face in many places. Thicker and moister soils occur in large solution pits and karst depressions that are distributed sporadically about the ridge surface.

Mickel Transverse Glades

The Mickel Transverse Glades are cost-perpendicular valleys that are essentially east-west extensions of the Everglades (PARKER *et al.*, 1955). These broad, flat-floored, shallow valleys of low gradient have poorly defined thalwegs. The upper valley side slopes of the shallow depressions merge upstream with the Everglades whereas downstream the diffuent drainage of the floodways merge with prairies and alluvial floodplains. The natural vegetation is predominantly wet grassland (marsh bog) that is composed of sawgrass and other sedges and rushes. The soils are very poorly drained with marly or organic surfaces that are underlain by unconsolidated sediments that in turn overlie limestone.

Ecological Classification of Coastal Environments

Although there are many examples of ecological characterization of localized coastal environments, experience with the Florida Spring Coast (WOLFE, 1990) illustrates the technique. Landscapes of this Gulf-coastal watershed on the west coast of the Florida peninsula are described in terms of *terrestrial, freshwater, saltwater wetland, estuarine, and marine habitats*. The classification system used here consists of 15 general categories of native biological communities, and another three of human-dominated habitat types. This classification (Table 19) is similar to the one used by the FLORIDA GAME AND FRESH WATER FISH COMMISSION (1976), which provides for comprehensive investigation of habitats in north central Florida, and is based in part on information obtained from the CORPS OF ENGINEERS (1978) and U.S. Fish and Wildlife Services' Gulf Coast Ecological Inventory map series (BECCASIA *et al.*, 1982). The advantage of this organized system is that it is open-ended and additions of both general and more specific units can be accommodated. Although no classification systems fits the real situation perfectly, this approach seems to approximate habitats and their interrelationships better than a lengthy list of map units or habitat types (WOLFE, 1990). The main categories of terrestrial and fresh water habitat are listed in Table 19. Classification of saltwater habitats generally follows the scheme of COWARDIN *et al.* (1979). The Springs Coast occupies a zone of transition in coastal vegetation, changing from mangrove dominated coastal habitats in the south to salt-marsh-dominated habitats in the north. The entire coastline, however, discharges substantial quantities of freshwater from myriad streams, springs, and areas of sheet flow. This, coupled with the low-energy regime, yields a coastline that generally has salinities below those considered marine (> 30 ppt) and that is heavily vegetated. The inshore waters of the Springs Coast exhibit typical estuarine salinity patterns, and the flora and fauna found therein are characteristically estuarine (WOLFE, 1990).

More recent efforts at ecosystem-oriented criteria feature the development of a national coastal/marine classification standard for the US (MADDEN, 2003) that can be used across multiple spatial (from micro, 1 m, to continental, 10^7 m) and temporal scales. In this system, relationships between levels of the hierarchy are defined by environmental processes and biological interactions. The goal or purpose of this effort is to support the production of a set of detailed, quantitative GIS

Table 19. *Florida Springs Gulf-coast ecological classification of native biological communities (Wolfe, 1990).*

Terrestrial and Fresh Water Habitats
Coastal Strand
Scrub
Sand Pine Scrub
Oak Scrub
Rosemary Scrub
High Pine Forest (Sandhill)
Longleaf Pine Sandhill
Turkey Oak Sandhill
Longleaf Pine–Southern Red Oak Forest
Pine Flatwoods
Pond Pine Flatwoods
Wet Flatwoods (Slash Pine Flatwoods)
Mesic Flatwoods (Longleaf Pine Flatwoods)
Scrubby Flatwoods
Hammocks
Xeric Hammock
Mesic Hammock
Hydric Hammock
Pioneer Hammock
Sinkholes and Terrestrial Caves
Pine Plantations and Old Field Forests
Pine Flatwoods Plantations
High Pine Plantations
Hammock and Old Field Pine Plantations
Cleared Rural Upland
Developed Areas
Bayhead
Mixed Swamp
Cypress Dome
Freshwater Marshes and Prairies
Ponds
Lakes
Blackwater Streams
Springs, Spring Runs, and Spring-fed Rivers
Aquatic Caves

products that will facilitate understanding of coastal habitats.

Classification of Coastal/Marine Environments Using Digital Aerial Photography and Satellite Remote Sensor Data

Satellite and airborne remote sensors have been used for several decades to map land use and surface cover to assist in the interpretation of natural processes and anthropogenic activities. Environmental remote sensing offers the ability to classify large areas of the earth's surface and provide accurate descriptions of biophysical resources and changing conditions through time. Through NOAA's coastal ocean program, the change analysis project (C-CAP) is designed to determine land/habitat cover and spatial change for sea grass, emergent wetlands and adjacent uplands in coastal regions of the U.S. on a one to five year repeating basis (PATIENCE and KLEMAS, 1993). The advantage of these remotely-sensed systems is that they can provide nearly continuous coverage over large areas and data can be acquired in a timely manner for regional-scale surveys. The C-CAP project uses digital remote sensor data, *in situ* measurement in conjunction with global positioning system (GPS) technology to monitor changes in coastal wetland habitats and adjacent uplands. Landsat

Multispectral Scanner (MSS) data, landsat thematic mapper (TM) data, and spot high resolution visible (HRV) data have been used successfully to detect major categories of coastal wetlands and nearshore bottom (coral reef) features (e.g. FINKL and DAPRATO, 1993). The use of satellite imagery for mapping wetlands provides a number advantages over conventional aerial photographs including timeliness, synopticity, and reduced costs (DOBSON *et al.*, 1995). The C-CAP nationally standardized database is used to monitor land cover and habitat change in the coastal regions of the United States and to improve understanding of coastal uplands, wetlands, and submerged habitats. C-CAP regions (based on NOAA/NMFS administrative regions) are commonly subdivided on the basis of state or other administrative boundaries or ecoregions. Most boundaries encompass coastal watersheds, (e.g. estuarine drainage areas) plus offshore coral reefs, algae, and seagrass beds in the photic zone.

Coastal land cover information is typically stored in the C-CAP database. The **C-CAP Land Cover Classification System** includes three superclasses (KLEMAS *et al.*, 1993): upland, wetland, and water and submerged land (Table 20). These superclasses are subdivided into classes and subclasses that reflect ecological relationships and land-cover classes that can be discriminated primarily from satellite remote sensor data. The system was adapted and designed to be compatible with other nationally standardized classification systems, viz. (1) the U.S. Geological Survey "Land Use and Land Cover Classification System for Use with Remote Sensor Data" (ANDERSON *et al.*, 1976), (2) the U.S. Fish and Wildlife Service "Classification of Wetlands and Deepwater Habitats of the United States" (COWARDIN *et al.*, 1979), and (3) the U.S. Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP) classification system (see discussion in DOBSON *et al.*, 1995). While all categories of the C-CAP classification system can be represented as two-dimensional features at the mapping scale of 1:24,000, some features may be mapped as lines (e.g. rocky shore) or points (e.g. unique landmarks). Most liner and point features, however, can be obtained from nonsatellite sources of information (e.g. aerial photography or *in situ* measurements using GPS).

The upland superclass consists of seven subclasses: Developed Land, Cultivated Land, Grassland, Woody Land, Bare Land, Tundra, and Snow/Ice. These upland classes are adapted from ANDERSON *et al.* (1976). Wetland in the C-CAP Coastal Land-Cover Classification System includes all areas considered wetland by COWARDIN *et al.* (1979), except for bottoms, reefs, aquatic beds, and nonpersistent emergent wetlands. All areas of open water with less than 30% cover of trees, shrubs, persistent emergent plants, emergent mosses, or lichens, are assigned to the superclass Water and Submerged Land, whether the area is considered wetland or deepwater habitat under the COWARDIN *et al.* (1979) classification.

Clearly these kinds of units provide valuable and useful information for the characterization of coastal environments. The C-CAP project provides the added advantage that much data is already archived and if it is not available for a specific area, it can be readily acquired following the C-CAP protocols. Important maps and other sources of collateral data in

the US include the National Estuarine Inventory (NEI), the National Coastal Wetlands Database (in digital format as the *National Estuarine Inventory Data Atlas*), characterization of shoreline types (Strategic Assessment Branch of the Ocean Assessments Division, NOAA) [estuarine shoreline: fringe tidal flat, deep tidal flat, non-tidal flat, fringe marsh, deep marsh, ocean boundary, modified shoreline] (NOAA, 1986).

COASTAL CLASSIFICATION AND MAP LEGENDS: GLOBAL AND CONTINENTAL SCALES

The encyclopedic compilations of BIRD and SCHWARTZ (1985) and relevant topics discussed in SCHWARTZ (1982) and SNEAD (1982) were perused in an attempt to abstract the names of classification units applied to coastal segments. The terms used for the enclosed maps of coastal geomorphology are related to local scales. The *National Atlas of the United States* (1970), for example, bases most of the maps for the conterminous U.S. (exclusive of Alaska and Hawaii) on a scale of 1:7,500,000. The classification is broken down into three parts: (1) Coastal Configuration, (2) Coastal Composition, and (3) Shoreline Characteristics. The coastal maps were prepared by Robert Dolan (University of Virginia) and the logic of the classification is consistent with some of his later reports (e.g. DOLAN *et al.*, 1972, 1973). Map units are listed in Table 21 along with some suggested alliterative approaches that might have more applicability to a world classification system rather than one based on the US shoreline.

Another approach is seen in the *World Ocean Atlas* (1979), published by Pergamon Press and edited by S.G. Gorshkov, the Admiral of the Fleet of the Navy of the USSR, in two large volumes. The atlas is one of the most complete and comprehensive modern studies of the world ocean (GORSHKOV, 1979). [The Russian legend for coastal geomorphology is partially translated and summarized in Table 22]

A PROPOSED NEW SYSTEM OF COASTAL CLASSIFICATION BASED ON GEOMORPHOLOGICAL SITE CHARACTERIZATION

The foregoing examples of different approaches to coastal classification provide a base from which to consider which applications are most relevant to specific needs. Before any conclusions can be reached, it is necessary to briefly review methods and procedures that are specifically related to geomorphological survey and mapping. Previously discussed systems refer to coastal geomorphology or geomorphic features but they are not morphological classifications *sensu stricto*. Fortunately, the International Geographical Union (IGU) has sponsored decades-long research into the philosophy of geomorphological mapping as well as assisted with the development of morphological classification at a variety of scales ranging from global coverage to local plans (GELLERT, 1971). This last bit of information is crucial to the proposed universal approach for a scheme that depends on previous success in coastal classification as well as adapting relevant principles of geomorphological classification as related to the coastal zone. The following, now almost classical works, provide background for conceptualizing what could be done to pro-

Table 20. *Coastal land cover classification system developed for NOAA's Coastwatch Change Analysis Project (C-CAP). (From: Klemas, V.V.; Dobson, J.E.; Ferguson, R.L., and Haddad, K.D., 1993. A coastal land cover classification system for NOAA Coastwatch Change Analysis Project. Journal of Coastal Research, 9(3), 862–872.)*

1.0 Upland
1.1 <u>Developed Land</u>
1.11 High Intensity
1.12 Low Intensity
1.2 <u>Cultivated Land</u>
1.21 Orchards/Groves/Nurseries
1.22 Vines/Bushes
1.23 Cropland
1.3 <u>Grassland</u>
1.31 Unmanaged
1.32 Managed
1.4 <u>Woody Land (Scrub-Shrub/Forested)</u>
1.41 Deciduous
1.42 Evergreen
1.43 Mixed
1.5 <u>Bare Land</u>
1.6 Tundra
1.7 Snow/Ice
1.71 Perennial Snow/Ice
1.72 Glacier
2.0 Wetland (Defined to exclude Bottoms, Reefs, Nonpersistent Emergent Wetlands, and Aquatic Beds, all of which are covered under 3.0, Water and Submerged Land.)
2.1 Marine/Estuarine Rocky Shore
2.11 Bedrock
2.12 Rubble
2.2 Marine/Estuarine Unconsolidated Shore (Beach, Flat, Bar)
2.21 Cobble-gravel
2.22 Sand
2.23 Mud/Organic
2.3 <u>Estuarine Emergent Wetland</u>
2.31 Haline (Salt Marsh)
2.32 Mixohaline (Brackish Marsh)
2.4 <u>Estuarine Woody Wetland (Scrub-Shrub/Forested)</u>
2.41 Deciduous
2.42 Evergreen
2.43 Mixed
2.5 Riverine Unconsolidated Shore (Beach, Flat, Bar)
2.51 Cobble-gravel
2.52 Sand
2.53 Mud/Organic
2.6 Lacustrine Unconsolidated Shore (Beach, Flat, Bar)
2.61 Cobble-gravel
2.62 Sand
2.63 Mud/Organic
2.7 Palustrine Unconsolidated Shore (Beach, Flat, Bar)
2.71 Cobble-gravel
2.72 Sand
2.73 Mud/Organic
2.8 <u>Palustrine Emergent Wetland (Persistent)</u>
2.9 <u>Palustrine Woody Wetland (Scrub-Shrub/Forested)</u>
2.91 Deciduous
2.92 Evergreen
2.93 Mixed
3.0 Water and Submerged Land (Defined to include all deep-water habitats and those wetlands with surface water but <i>lacking</i> trees, shrubs, and emergents.)
3.1 Water (Bottoms and undetectable reefs, aquatic beds or nonpersistent emergent wetlands)
3.11 Marine/Estuarine
3.12 Riverine
3.13 Lacustrine (basin $\geq$ 20 acres)
3.14 Palustrine (Basin $<$ 20 acres)
3.2 Marine/Estuarine Reef

Table 20. *Continued.*

3.3 <u>Marine/Estuarine Aquatic Bed</u>
3.31 Algal (<i>e.g.</i> , Kelp)
3.32 <u>Rooted Vascular</u> (<i>e.g.</i> , seagrass)
3.321 High Salinity (≥ 5 ppt; Mesosaline, Polysaline, Eusaline, Hypersaline)
3.322 Low Salinity (< 5 ppt; Oligosaline, Fresh)
3.4 Riverine Aquatic Bed
3.41 Rooted Vascular/Algal/Aquatic Moss
3.42 Floating Vascular
3.5 Lacustrine Aquatic Bed (Basin ≥ 20 acres)
3.51 Rooted Vascular/Algal/Aquatic Moss
3.52 Floating Vascular
3.6 Palustrine Aquatic Bed (Basin < 20 acres)
3.61 Rooted Vascular/Algal/Aquatic Moss
3.62 Floating Vascular

* The underlined classes are those which C-CAP is committed to include in its data base.

duce a comprehensive coastal classification: *Proceedings of the Meeting of the IGU* (Brno and Bratislava, 27 April–2 May 1965), *Manual of Detailed Geomorphological Mapping* (DEMEK, 1972), *Guide to Medium-Scale Geomorphological Mapping* (DEMEK and EMBLETON, 1976), and the *Proceedings of the 15th Plenary Meeting, Commissions on Geomorphological Survey and Mapping* (Modena—Catania, 7–15 September 1979).

General Principles of Geomorphological Mapping in Relation to Coastal Forms

The subject of geomorphological mapping is the Earth's *relief*, *i.e.* the surface of the Earth's crust at its contact with the hydrosphere, atmosphere, pedosphere, and biosphere. This complex zone of surface amplitudes is what BÜDEL (1982)

refers to as the *relief sphere* of the Earth which, of course, includes the coastal zone. The relief sphere is the subject of geomorphology. Relief is complex and consists of elevations and depressions. The aim of geomorphological mapping is to investigate the morphology, genesis, and age of the relief. The following points are of primary consideration in achieving the goals of geomorphological mapping (DEMEK, 1972; DEMEK and EMBLETON, 1976):

- (1) Effects of structure in terms of lithology and tectonics,
- (2) Dynamic processes (both endogenic and exogenic),
- (3) Development and age of relief,
- (4) Spatial distribution of the different forms and form associations,
- (5) Practical significance of the relief to society.

Principles of Geomorphological Classification

The basis of geomorphological classification is the principle that relief elements of lower order depend on elements of higher orders. That is, morphological continuity throughout the system of classification is achieved by logical transitioning via morphostructures between units of higher or lower order. The *relief forms* are thus a complicated geosystem with numerous feedbacks. The characteristics of different orders, or levels, in a classification system vary according to the properties of the objects being classified. Classifications should reflect both qualitative and quantitative aspects of the objects. The main units of classification must possess unified and distinctive characteristics. These principles apply to each level in the taxonomic hierarchy. Classification must be of a cause-and-effect nature; it must be historic and genetic. Each relief element of any order has its own genesis and history of formation. At each level in the hierarchy, the classification must reflect a regular relationship between the general and the separate (DEMEK and EMBLETON, 1976).

Prerequisites and Bases of Geomorphological Classification

The study of *morphostructures*, morphostructural analysis, is a primary basis of geomorphological investigation. Morphostructures of various taxonomic ranks reflect different degrees of interaction of endogenic and exogenic processes,

Table 21. *Classificatory units used to designate properties of coastal segments, based on the National Atlas of the United States (1970), including suggestions for additional units to accompany the original map units.*

(Slope)†	(Planform)‡	(Relief)‡
Coastal Configuration		
High Cluffed (Steep Slopes)	Rectilinear	Mountains
Low Cluffed (Gentle Slopes)	Curvilinear	Hills
Coastal Plain	Embayed	Terraces
	Crenulate	Plains
	Indented	Submarine
	Rugged	Canyons
Coastal Composition		
Volcanic Rocks†	Rock (by composition)‡	
Older Resistant Rocks	Mixed-Rock, Sediment	
Non-Resistant Rocks	Sedimentary	
Limestone		
Fluvial & Deltaic Deposits		
Glacial & Glaciofluvial Deposits		
Shoreline Characteristics		
Sand Beaches & Barrier Islands†		
Pocket Beaches		
Mudflats & Marshes		
Swamps & Mangrove		
Coral		
Developed		

† Terms used by Dolan in the *National Atlas of the United States*.

‡ Suggested new terms based on revised concept of coastal configuration.

Table 22. *Summary of the Russian coastal classification and mapping units as displayed in the Atlas of the World Oceans (Gorshkov, 1979).*

I. Coasts formed by subaerial and tectonic processes and slightly transformed by the sea
1. Primarily dissected coasts
Coast of tectonic dissection
Coast of erosional dissection
Coast of erosional-tectonic dissection
Dalmation, faulted & embayed
Limans, estuaries
2. Primarily smooth shores
Folded smooth
Downthrown smooth
II. Shores formed primarily by non-wave factors
1. Potamogenic shores
Delta shores
Shores of alluvial flats
2. Shores drained during low tide
Clayey and sandy types
3. Biogenic shores
Coral reefs
Mangroves
4. Thermoabrasive and glacial shores
Thermoabrasive in Quaternary deposits
Glacial Deposits
5. Denudative shores
III. Shores formed primarily by wave action
1. Smoothing coasts
Abrasive bays
Abrasive-accumulative
2. Smoothed coasts
Smoothed abrasive shores
Smoothed abrasive-accumulative shores
Smoothed accumulative shores
Shores of alluvial-marine flats
Smoothed accumulative with cliffs
3. Secondary dissected coasts
Abrasive—indented
Abrasive—accumulative, indented
IV. Miscellaneous
1. Volcanic islands
2. Isolated coral reefs and coral islands
3. Mangroves
V. Materials and rocks
1. Loose, unconsolidated
2. Cemented sediments
3. Volcanogenic materials
4. Crystalline and metamorphic rocks
5. Mainly folded regions
Precambrian
Early Paleozoic
Late Paleozoic
Mesozoic
Cenozoic
VI. Slopes and cliffs
1. Denudational slopes
2. Active cliffs
3. Inactive cliffs
4. Glacial thermoabrasive ledges
VII. Navigational characteristics of the shore
1. Large embayed coasts (baymouth 10 to 50 km wide)
2. Small embayed coast (baymouth less than 10 km wide)
3. Distance of 20 m isobath from shore (<100 m, 100 m–1 km, 1–10 km, >10 km)

Table 23. *Classification of geomorphological maps, for the Geomorphological Map of Europe, as recommended by the International Geographical Union, Commission on Geomorphological Survey and Mapping.*

Map Scale ¹	Type of Map	Scale Range
Large-scale maps	Plans	1:10,000 and larger
	Basic maps	1:10,000–1:25,000
	Detailed maps	1:25,000–1:100,000
Medium-scale maps	Synoptic maps	1:100,000–1:1,000,000
Small-scale maps	Maps of countries	1:1,000,000–1:5,000,000
	Maps of continents	1:5,000,000–1:30,000,000
	World maps	1:30,000,000 and smaller

¹ Based on Gellert (1971)

greater or lesser tectonic activity, and different climatic conditions on the earth's surface.

Morphostructures of the **1st order** represent fundamental units of the Earth's relief, the continents and ocean basins. These are the largest morphostructures, related to differences in the thickness and composition of the Earth's crust and upper mantle. The **2nd order** morphostructures deal with the continents and oceans as a whole which finds its expression in forms such as continental platforms, shelves, slopes, abyssal plains, and midocean ridges. The **3rd order** includes the continental platforms which are subdivided into two separate morphostructures, plains and mountains. Continental plains of the 3rd order are subdivided into **4th order** plains of denudation and deposition. The morphological difference between these depends on whether uplift or subsidence has been dominant in the neotectonic period. In the **5th order**, depositional plains are divided into separate morphostructures according to the type of depression in which sediments accumulated and the depth of the basement complex. Differences between morphostructures in the **6th order** are even more sharply defined. Depositional plains are differentiated according to the character of sedimentation, *e.g.* fluvial, glacio-marine, lacustrine. Classification of megamorphostructures in the first five orders can provide a basis for geomorphological maps of the world and continents on scales smaller than about 1:15,000,000 (DEMEK and EMBLETON, 1976).

The classification of morphostructures is the basis of the legend for medium-scale (1:100,000 to 1,000,000) geomorphological maps. Relief classes are based on relief amplitude, the relative difference between the lowest and highest points in an area of 16 km². *Relief type* refers to a regional unit comprising a distinctive and homogeneous assemblage of forms grouped within a certain altitudinal range. Each unit is characterized by similar morphology and genesis related to a common morphostructural basis, by the same complex of geomorphological processes and by a similar history of development. The relief type is in turn formed of particular *relief forms* such as river terraces, gullies, terminal moraines.

Definition and Classification of Geomorphological Maps

Scale is of considerable significance for geomorphological mapping because at a scale of approximately 1:500,000 the content of the map changes substantially (Table 23). Whereas maps on a scale larger than this (they cover relatively smaller

areas) usually depict relief forms, maps on smaller scales (they cover relatively larger areas) show *form associations* on a morphostructural basis. The scale thus indicates the degree of generalization, synopticity, and the sizes of features represented. On the basis of scale, several types of geomorphological maps can be distinguished. The International Geographical Union (IGU) recommends the scheme in Table 23.

Geomorphological Methods and Procedures in Geomorphological Mapping

Geomorphological mapping, especially at medium scales, is based on one of the following methods of analysis, or on combinations of two or more of them. The **morphological method** consists of (1) determining the limit and dimensions of individual relief elements, (2) defining the component of complete landforms, and (3) establishing the relations between different relief elements for an entire area, the character of their associations and the pattern of their arrangement. The morphological method also includes morphometric analysis.

The **morphofacies method** is used to study relationships between the relief and correlative deposits, as well as detailed investigation of these deposits. The investigations include laboratory studies to determine the age of the deposits and studies of the relation between the deposits and the landforms.

The **morphostructural method** is used to determine relations between the landforms and geological structure. The distribution of relief elements is in direct relationship to the geological structure of the area. The distribution of rocks of different resistance within these tectonic units will also contribute substantially to the relations of the landforms with geological structure.

The **morphogeographical method** is concerned with the study of the relation of the relief with other geospheres of the Earth, mainly atmosphere, hydrosphere, cryosphere, and biosphere. The distribution of exogenic processes on the Earth's surface is controlled by the pattern of latitudinal climatic zonation which is disturbed and complicated by mountainous relief.

The **morphodynamic method** studies the dynamics of present day endogenic and exogenic processes as essential for understanding the genesis and age of landforms, and the direction and intensity of their development. This necessitates observation of processes in the field, especially when their activity is greatest. These kinds of observations are essential for practical purposes, engineering works, *etc.* Several procedures are used to study present relief-forming processes. The most important are those which involve: (1) field observations at fixed sites, (2) prediction of catastrophic exo- and endogenic events on the basis of statistical analysis of their recurrence intervals, (3) experimental study, and (4) comparison of air and space photographs taken before and after particular events.

The **paleogeomorphological method** studies the relief of previous geological periods since remnants of former landscapes are frequently incorporated in the present landscape. In analyzing the present relief, special attention is paid to the stages of transformation of the primary land surface into

the present one. Attempts should be made to fix approximate dates for these major stages in the evolution of relief and drainage.

Generalization of Geomorphological Maps

The purpose of the general geomorphological map is to *express the morphographic and morphometric features of the relief forms*, their genesis and age. The uniform map legend provides for the smooth transition from detailed geomorphological maps to the synoptic ones. The main problem of the construction and generalization of geomorphological maps is that of the classification and systematization of relief forms (*cf.* TRICART, 1955, 1965). The smallest taxonomic unit is the *genetically homogeneous surface* (GHS), a geometrically simple flat area without a more distinct break of slope, generally of a size from some tenths of square meters up to some square kilometers. GHS units combine to create *relief forms*. These forms usually correspond to longer stages in the relief development (DEMEK, 1967). Their dimensions vary over a relatively large range from some hundreds of square meters up to hundreds of square kilometers. The forms compose the *relief type*, a complex of forms on a more or less distinctly limited area, noted for the same absolute elevation and the same genesis depending on the same morphostructure, the same complexes of morphogenetic agents, and the same history of development. The relief type is not a concrete unit, but an abstract unit established deductively.

Detailed Geomorphological Maps (1:10,000–1:50,000)

The main contents of detailed geomorphological maps are the concrete relief forms and their parts. The decomposition of relief forms into GHS units appears to be a practical solution (DEMEK, 1967). These surfaces are mapped in the field by noting the edges and breaks of slopes bordering them. The GHS units are divided into groups according to their inclination, origin, and age. The representation of morphostructures in the geomorphological maps provides a basis for incorporating dependence of relief on geomorphological structure, prevailing rock type, and as well as helping to establish the direction of the general development of the relief reflecting the development of the structural-geological units. The morphostructures thus allow for a transition to small-scale maps, the main contents of which are relief types defined in relation to morphostructure (DEMEK, 1967). These maps are built up from plans and basic geomorphological maps that contain form elements, miniforms, and microforms (*cf.* Table 24). These maps show genetically homogeneous and independent forms where the dominant process acts without morphographically recognizable interruption (DEMEK and EMBLETON, 1967).

Medium-Scale Geomorphological Maps (1:200,000 to 1:500,000)

The concept of medium-scale maps is that they should be similar to detailed maps but the contents of these maps, concrete relief forms, are suitably simplified according to the scale. These maps are analytical and contain all the neces-

sary data that would enable the delimitation of relief types and thus the transition to small scale maps. Experience has shown that maps of concrete relief forms are more practical than maps of relief types because practice reckons with concrete surfaces (DEMEK, 1967). These maps show mesoforms that are comprised by genetically independent cyclic forms that represent partial integration of a number of microforms. The dominant factor acts with one or several effective breaks conditioned tectonically or climatically (DEMEK and EMBLETON, 1976).

Small-Scale Synoptic Maps (1:1,000,000 and less)

These maps are usually constructed on the basis of the relief type representation. These are maps of geomorphological regions completed with selected relief forms. These maps of countries, continents, and the world integrate macro- and megaforms. They show the largest, continuous, form complex of individual character predominantly controlled by tectonics (DEMEK and EMBLETON, 1976).

STRUCTURAL ORGANIZATION OF THE NEW UNIFIED GEOMORPHOLOGICAL COASTAL CLASSIFICATION SYSTEM

The purpose of presenting summaries of prior coastal classifications was partly review, a reminder of what has been done before, according to the philosophy that the present can not be built without reference to the past. The point of that effort was to briefly summarize the main features of extent systems being sure to indicate advantages of each classification as well possible deficiencies. From some of these systems (*e.g.* SUESS, 1888; JOHNSON, 1919; SHEPARD, 1973; COTTON, 1952; VALENTIN, 1952) it is apparent that with time the coastal classifications became more comprehensive and sophisticated in approach because increasingly numerous parameters were considered in the characterization of coasts as shown by the evolutionary trends implied in Table 24. Because the list of individual parameters grew with time and experience, many researchers came to appreciate critical categories (structures, processes, materials, *etc.*) that were necessary to achieve more complete understanding of coasts. One of the most important properties of coasts is, for example, associated with antecedence, the inherited characteristics that give the present-day coast its distinctive appearance (*e.g.* EVANS *et al.*, 1985; HINE *et al.*, 1988; RIGGS *et al.*, 1996; FITZGERALD and HETEREN, 1999) as recognized in emergent or submergent categories in the classifications. Because most coasts are now seen as having a polygenetic history, *i.e.* they retain component features (forms or materials) left over from previous cycles of development associated with changes in relative sea level, modern coastal classification is inherently complex. The degree of complexity depends in part on the width (across-the-shore component) of the coastal segment being classified, age of the coastal zone, and whether previous sea level stands are revisited by younger fluctuations to produce palimpsest patterns. Superimposed on complex inherited coastal morphologies is the imprint of more recent marine processes as they affect the erodibility of different kinds of materials under different climatic regimes.

Table 25 lists some of the more important parameters that have been considered in previous systems, whether the coastal property was given a high or lower position in the classification scheme, and how these parameters relate to the proposed classification system outlined in Table 24. The JOHNSON (1919) and SHEPARD (1948, 1973) systems were perhaps intended to be comprehensive global classifications but they lacked scope, flexibility, and the degree of specificity that is now possible through modern data acquisition techniques such as satellite remote sensing. More recent coastal classifications abandoned some of the more subjective aspects of previous systems (*e.g.* interpretations of emergence, submergence) by focusing on coastal materials and forms (*e.g.* SFRPC, 1984; OWENS, 1994; SUNAMURA, 1992; SHORT, 1999) that could be observed in the field, summarized from existing topographic-geologic maps, from aerial photographs, or from space imagery. Some of the specialized classifications, as opposed to the global schemes, which concentrated on specific kinds of features such as coral reefs, beach types, cliffs and platforms, islands, and coastal habitats (including coastal zoogeographic provinces and realms) are useful but limited schemes.

Thus, from these different kinds of coastal classifications, it is clear that a new scheme is required, one that is unified, comprehensive (global in scope), and structured. It is suggested that the unifying property in the new scheme should be coastal morphology; morphometry (in a range of scales) will provide transitioning from one categorical level to another and is the thread or theme that will run through the system from highest to lowest levels. This new geomorphological classification of coasts needs to embrace all important factors that are related to the identification and classification of coastal features in terms of: shape or form, lithic composition, susceptibility (or resistance) to erosion, effects of lithospheric (geotectonic, isostatic movement) and oceanic modulation (eustasy, steric effects, tides, *etc.*), antiquity of coastal landforms as related to hypsometry and order of sedimentary sequences, paleogeography of global shorelines, and erosional (destructural) and depositional (constructional) process, among others. These disparate factors or considerations can be grouped in a more orderly fashion under the general headings of: lithic criteria, chronometric parameters, geodynamic and climatomorphogenic processes, morphogenetic (morphodynamic) relief features, and polygenetic forms.

With these thoughts in mind, the new system is based on the principles and practices of geomorphological mapping that have been worked out for the geomorphic map of Europe (see previous discussion). This multinational project, which was initiated through the International Geographical Union (IGU) in the early 1960s and largely completed in the late 1980s, provides a sound basis for devising a comprehensive classification of coastal landforms. The essential principles laid down in the manuals for geomorphological mapping are thus adapted to special needs in coastal areas. There are many problems associated with coastal classification (see previous discussions) and perhaps the most important or overriding problem is that coasts tend to be complex with older and younger features occurring in close proximity to produce a palimpsest pattern of forms. Two or more shorelines of dif-

Table 24. *Organizational structure of considerations for a proposed approach to a comprehensive coastal classification based on morphological units that are hierarchically subdivided in terms of rock type, age, geodynamics, climate, relief, erosional-depositional forms, and relief elements.*

I. Lithologically Controlled Morphostructures	
(Most "hard rock" coasts; produced by automorphism) [Scales: Myriametric—local to global coverage, modifiers of coasts on any scale]	
A. Lithic Criteria for Hard Rock (Automorphic) Coasts	[Primary, basic, self-derived coasts formed by magmatic, geotectonic, or subaerial processes; includes most coasts that are composed of terrestrial morphostructures with little or no modification by marine activity]
1. Petrology/Structure of Crystalline and Indurated Materials	
a. Massive (e.g. granite, basalt)	
b. Cemented (e.g. coral limestone, eolianite, beach rock)	
c. Banded (e.g. Flysch, turbidite)	
2. Competance (Resistance) [Based on Exogenic Mechanical Factors]	
a. Abrasion (Crystallinity)	
b. Percussion (Friability)	
c. Thermal Processes	
d. Cryoclastic Susceptibility (frost)	
3. Environmental Determinants	
a. Igneous (Fissure or Flow) Eruptions (Endogene)	
b. Biogenic Constructors (coral, corallgal reefs; Exogene)	
4. Geodynamic Determinants for Clified Coasts	
a. Lithospheric Modulation (geotectonic, isostatic movement)	
b. Oceanographic Modulation (eustatic, steric, tides, tsunamis, fluvial inputs)	
B. Lithic Criteria for Soft Rock (Allomorphic) Coasts	
(Most "soft rock" coasts; produced by allomorphism) [Created by marine processes of erosion and deposition; relief forms and types comprised by uncemented sedimentary materials]	
1. Petrology/Structure of Sedimentary Materials	
a. Gravel and Boulders (e.g. steep beaches)	
b. Sand and Silt (e.g. moderate slope beaches, littoral dunes)	
c. Mud (e.g. tidal flats, saline marsh)	
2. Competance (Resistance) [Based on Endogenic Physico-Chemical Factors]	
a. Diagenesis and Lithification	
b. Water Saturation (mud; flowage potential)	
c. Compaction (pore spaces)	
3. Environmental Determinants	
a. Igneous (Cone or Ejecta) Eruptions (ash/cinders, clastics; Endogene)	
b. Sedimentological Input (marine, fluvial, eolian, biogenic; Exogene)	
II. Chronometrically Determined Morphostructures	
A. Rates of Erosion versus Accumulation	
1. Erodability (cf IA2, B2)	
2. Preservation Potential	
B. Rates of Coastal Retreat versus Progradation	
1. Ephemeral Events	
2. Controls of Longevity	
C. Antiquity of Littoral Landforms (Neomorphs vs Paleomorphs)	
1. Hypsometry (Paleogeography over Phanerozoic time: high/low envelope constraints)	
a. Panthalassic (e.g. mid Cretaceous)	
b. Intermodal (e.g. Holocene)	
c. Pantelluric (e.g. Triassic)	
2. Eustatic Sequence Orders (based on Vail/Exxon system)	
a. Protolittoral (<100 years) (Protomorphostructural units)	
b. Neolittoral (~1000 years) (Neomorphostructural units)	
c. Eolittoral (~10,000 years) (Eomorphostructural units)	
d. Pliolittoral (~100,000 years) (Pliomorphostructural units)	
e. Meiolittoral (~1 million years) (Meiomorphostructural units)	
f. Paleolittoral (>1 million years) (Paleomorphostructural units)	
3. Paleogeography of Global Shorelines	
a. Neomorphogenesis (e.g. newly created volcanic material)	
b. Paleomorphogenesis (e.g. ancient crystalline rocks, exposed by structural or eustatic processes)	
III. Geodynamic-Climatomorphogenic Process Zones	
[Myriametric scales, but mostly megametric scales for regional and continental coverage]	
A. Geodynamic Provinces (Plate Tectonics)	
(Broad differences in tectonic style, form and outline of rock coasts) [Note: Convergent, divergent, translation, island arc—types after Emery & Uchupi (1984); epicontinental, mobile belt, quasiratonic, volcanic island types after Fairbridge (1968)]	
1. Divergent (Passive) Continental Margins (Atlantic Type Coast)	
[Transverse or discordant coasts that truncate the tectonic grain of the hinterland; truncated peneplains, Precambrian to Cenozoic] [Type Sites: New Foundland, Brittany, Ireland, NW Spain]	
a. Juvenile (or rising) Coasts	
b. Semi-stable (or neutral) Coasts	
c. Oscillatory Coasts (block-faulted coasts, e.g. Rio de Janeiro to Recife, Brazil)	
d. Mature or Subsiding Coasts	

Table 24. *Continued.*

2. Convergent (Active) Continental Margins (Pacific Type Coast) [Longitudinal coasts that run parallel to the structural grain; parallel or concordant coasts; including collapsed innerarc basins]	
a.	Cordilleran Subtype (Associated with subduction zones and deep sea trenches; California Subtype, western sides of North and South America)
b.	Dalmatian Subtype [Turkey, partially drowned basins (Gregory, 1920)]
3. Taphrogenic (Rifted) Coasts (Associated with transform faulting) [Type Sites: Offshore islands of Mediterranean or continental borderland, <i>e.g.</i> southern California, Balearic Islands, Corsica, Sardinia; Sea of Okhotsk Basin (Gavrilov, 1999)]	
4. Island Arc Coasts	
a.	Volcanic areas (<i>e.g.</i> Java)
b.	Non-volcanic areas (<i>e.g.</i> Timor)
5. Sediment-Loading (Alluvial) Coast	
B. Climatomorphogenic Provinces	
1. Humid Tropical (deep chemical weathering, extreme fluvial activity, continuous flux of sediments, especially 1:1-type clays, to coast)	
2. Tropical Wet-Dry (episodic fluvial activity, sheet floods, discontinuous supply of siliciclastic sediments to coast)	
3. Savanna (episodic fluvial activity, sheet wash, etchplanation)	
4. Tropical/Subtropical Desert (eolian activity, episodic floods)	
5. Humid Subtropical (monsoonal areas; periodic heavy flux of sediment to the coast)	
6. Humid Mesothermal (extensive but slow valley formation; 2:1-type clays in alluvium)	
7. Humid Microthermal (taiga zone with valley formation, permafrost, periglacial activity, thermokarst; feldspars and 2:1-type clays reach the coast)	
8. Polar/Subpolar (tundra, ice rafting and frost debris; seasonal sediment flux to coast during spring thaw)	
9. Glaciated, Nivation (ice, snow-related geomorphic processes)	
IV. Relief Types (Morphoregions)	
(Major Regional Morphostructure, Morphosculpture Complexes; from a few tens to a few hundreds of km; regional units comprising distinctive & homogeneous assemblages of forms characterized by similar morphology and genesis; synoptic units) [Hectometric to kilometric and larger for regional, subregional coverage]	
A. Mountains (Hills)	
1.	Lithologic Dominance [Type Site: Do]
2.	Structural Dominance [Type Site: Do]
B. Plainlands	
1.	Plateaus (Truncated to form coastal cliffs > MSL)
a.	Limestone Morphotype [Dover, U.K.]
b.	Weathered Morphotype [Charles Point near Darwin, NT (Hays, 1967)]
c.	Volcanic Rock Morphotype [Giants Causeway (Steers, 1962), Easter Island (Paskoff, 1978)]
2.	Coastal Plains (~ MSL)
a.	Arctic Morphotype [Alaskan-Canadian Beaufort Shelf (Hill <i>et al.</i> , 1994)]
b.	Mid-Latitude Morphotype [U.S. Atlantic Coastal Plain]
c.	Tropical Morphotype [Type site: Do]
3.	Submerged Plains (< MSL) [Type Sites: Do]
C. Valleys	
1.	Glacial (Ice-carved)
a.	Rock-cut Morphotype [Fjord, fjard, sea lochs—Norway, Sweden]
b.	Sedimentary (infilled) Morphotype: [Sandur coast, SE Iceland (Forbes and Syvitski, 1994)]
2.	Fluvial & Alluvial (Funnel-shaped sea inlets formed by drowned river valleys; rias, voes, abers)
a.	Chesapeake Bay Morphotype [Incised valley or ria (Evans and Prego, 2003)]
b.	Barrier-fronted Morphotype [Type site: Albemarle Sound, USA]
c.	Boreal (Arctic, seasonal) Morphotype [Mackenzie, Lena]
3.	Submarine (Complex genesis: gravity slides, turbidity currents)
a.	La Jolla Morphotype—Scripps Canyon, La Jolla, California (Shepard, 1973)
b.	Rhone Morphotype (O'Connell <i>et al.</i> , 1995)
D. Continental Freeboard & Relief Roughness	
1.	Elevation of hinterland summit within 5 km of coast
2.	Slope (MSL to summit)
3.	Roughness (D = 2.0 v. smooth, D = 3.0 v. rough)
V. Morphogenetic Relief Features	
(Macro- and Mesomorphostructures and their elements; a few tens of km) [Decametric to hectometric scales for subregional to local coverage; range in area from 100s m ² to 100s km ² ; concrete units]	
A. Erosional (destructural) Process-Forms	
Morphodynamic Process	
1.	Hydromechanical
	(Wave-worn benches, including differential erosion of variegated lithology, hard & soft bands, and prior-weathering of joints in massive lithology such as granite & basalt)
2.	Mechanical
	(Sea-ice, "glacial", seasonal freeze-up, grounding of ice flows & bergs; frozen spray; strandflat formation)
3.	Chemical and Biological
	(Water-level weathering & notch cutting of calcareous rocks including differential erosion of polygenetic calcarenites by boring algae, gastropods, boring clams, echinoids, crabs, fish, <i>etc.</i>)
Morphometry (Shape and orientation of landforms, relative to the present coastline)	
1.	Linear Shapes (due to leiomorphogenesis: from Gr. <i>leios</i> , connotative of smooth or straight; coastal planforms that are broadly smooth or straight)

Table 24. *Continued.*

a. Shore Parallel (Parabathic) Morphostructures	
Beach scarp	
Boat channel	
Caves	
Interbar depression	
Lagoon	
Lithogenic reef	
Marine terrace	
Moat, coral reef	
Marginal channel, coral reef	
Palanga, sharp ground	
Palve (blowaway plain)	
Peat scarps, eroding tundra scarps (Arctic)	
Sea cliffs	
Shore platforms (Rock platforms, ramps)	
Stacks & related features (Type sites: Twelve Apostles, Port Campbell, Victoria; Duncansby Head, NE Scotland)	
Submarine abrasion step, terrace	
Wave-cut (abrasion) platform (rock pavements), bench, terrace (rasas) (Type-A, Type-B platform)	
a. Transverse (Diabathic) Morphostructures	
Chute, coral reef	
Hanging valleys on cliffs (V-shaped, flat-floored, broad)	
Inlet, pass, colk, entrance	
Overflow channel	
Rip current channel	
Surge, tidal channel	
Washout	
Wave-cut (cross-shore) fissures	
2. Curvilinear (due to scoliomorphogenesis: from Gr. <i>skolios</i> , connotative of curved, wavy, or crooked; coastal planforms that are uniformly curved or wavy)	
a. Shore Parallel (Parabathic) Morphostructures	
Sea caves	
Sea stacks	
b. Transverse (Diabathic)	
Blowout depressions	
Sea arches, bridges	
B. Depositional (constructional) Process-Forms	
Morphodynamic Process	
1. Hydromechanical (Wave-, current-, tide-built)	
2. Mechanical (Ice-push)	
3. Biogenic (Coral, calcareous algae, mangrove)	
4. Anthropogenic (Archaeological midden hills & ridges)	
Morphometry (Shape and orientation of landforms, relative to past/present coastline)	
1. Linear Shapes (due to leiomorphogenesis)	
a. Shore Parallel (Parabathic) Morphostructures	
Aggradation terrace	
Baymouth, barrier, longshore bar	
Beach	
Arctic (ice-affected) Morphotype (Taylor and McCann, 1983)	
Temperate Morphotypes: Dissipative, Intermediate, Reflective—NSW, Australia (Short, 1993); Florida (Benedet, Finkl, and Klein, 2004)	
Tropical Morphotype: Plage Blanche, Fom el Oued, southern coast of Morocco (Russell, 1958).	
Beach ridges (Chenier plains, foredunes)	
Arctic Morphotype—Radstock Bay, EC Arctic archipelago, Canada (Taylor and McCann, 1983)	
Temperate Morphotype—SW Louisiana (Howe <i>et al.</i> , 1935)	
Tropical Morphotype—Tarfaya, Morocco (Stapor, 1982)	
Continental shelf, platform reef systems (Spalding <i>et al.</i> , 2001)	
Barrier Morphotype—GBR, Australia (Hopley, 1994)	
Fringing Morphotype	
Patch Morphotype—Florida Reef Tract (Agassiz, 1852; Jones, 1977)	
Bank Morphotype—Bahama Platform (Cant, 1977), Florida Keys—Dry Tortugas	
Dunes	
Climbing Morphotype—Fonte de Telha, Portugal (Jackson and Nevin, 1992)	
Transgressive (frontal dune) Morphotype—Stradbroke Island, S. Qlds (Bird, 1969)	
Lagoons (Cooper, 1994)	
Peat-covered seabed, peaty flats	
Reef cap	
Ramparts (algal, shingle)	
Sabkha, salinas (smooth, hummocky) (Barth and Böer, 2001)	
Abu Dhabi Morphotype—Abu Dhabi, Persian Gulf (Evans <i>et al.</i> , 1969; Kendall and Harwood, 1996)	
Tunesian Morphotype (Cramer, 1982)	

Table 24. *Continued.*

-
- Spits (barrier)
 - Swamps, bogs, marshes
 - Tidal flats
 - b. Transverse (Diabathic) Morphostructures
 - Coral reef, spur and groove topography—Florida Reef Tract (Shinn, 1963)
 - Dune-fed fan (Persian Gulf, Senegal)
 - Overwash fan, field, splay
 - Transverse bars
 - 2. Curvilinear Shapes (due to scoliomorphogenesis) Morphostructures
 - a. Shore Parallel (Parabathic)
 - Crescentic bars
 - Pocket beaches
 - b. Transverse (Diabathic)
 - Deltas (fan-like)
 - River-dominated morphotype: Mississippi (Coleman *et al.*, 1998)
 - Tide-dominated morphotype: Ganges-Brahmaputra
 - Wave-dominated morphotype: Brazos (Galloway, 1975)
 - Dunes
 - Parabolic Morphotype—Ninety Mile Beach, Victoria (Bird, 1969)
 - Spits (loped, recurved, serpent, compound)
 - Tombolo
 - C. Polygenetic (complex) Forms**
 - (*e.g.* drowned, submerged landscape and seascape features)
 - 1. Ingressional (Submerged) Relict Forms [Initial topography of continental shelf and landward portion of coastal zone]
 - a. Karst Landscapes (blue hole doline, poljes, caves)
 - Belizian Shelf Morphotype (Purdy, 1974)
 - Bahamian Bank Morphotype
 - Palau Morphotype
 - b. Glacial Landscapes (erosional and depositional terraines)
 - Moraines, Outwash Plains (incl. palimpsest glacial dispersal trains—Newfoundland to New York (Grant, 1972)
 - Glacially Eroded Basins—Gulf of Maine, Scotian Shelf (Grant, 1972), Norwegian Sea (Mörner, 1978); Strait of Magellan (Bird, 1969)
 - Tunnel Valleys—North Sea (Vanney, 1972)
 - Drumlin Coast—Boston Harbor (Forbes and Syvitski, 1994)
 - c. Fluvial Landscapes (stream channels, incised valleys)
 - Hudson Morphotype (Veatch and Smith, 1939)
 - Atlantic Shelf Morphotype—Long Island to Cape Hatteras (Field, 1980)
 - Guinea Shelf Morphotype (McMaster *et al.* 1970)
 - d. Eolian Landscapes (submerged dunes on the Campeche Shelf, Logan *et al.*, 1969)
 - e. Alluvial Landscapes
 - Deltas—Texas–Louisiana shelf (Curray, 1960)
 - Alluvial Channel Systems
 - Atlantic Shelf Morphotype—Long Island to Cape Hatteras (Field, 1980)
 - Guinea Shelf Morphotype (McMaster *et al.*, 1970)
 - Bay of Biscay Morphotype (Vanney, 1972)
 - f. Coastal Seascapes
 - Beaches, Barrier Islands, Lagoons, Shorelines, Spits
 - [Type site—Middle Atlantic Bight: Nicholls, Franklin, Fortune shores, and Block Island shore] (Emory & Uchupi, p. 58)
 - Cliffs (wave-cut)
 - Plunging Morphotype—Banks Peninsula, Christchurch, New Zealand (Davis, 1928; Cotton, 1968)
 - Coastal Swamp Drainage Systems
 - Florida Bay Morphotype (Price, 1967)
 - Coralgal Reefs
 - Miami Morphotype—Cape Hatteras to Miami (Emory & Uchupi, 1972; Marszalek *et al.*, 1977)
 - Mayotte Morphotype—Mayotte drowned barrier reef system, Indian Ocean (Guilcher *et al.*, 1965)
 - Sea Caves [Honduras and Bahama Bank: Pratt and Dill, 1974]
 - Shoal Retreat Massifs [US Atlantic shelf: Swift *et al.*, 1972]
 - 2. Egressional (Emergent) Relict Forms [Emergent, elevated landscape and seascape features]
 - a. Barrier Shorelines (incl. paraglacial & non-paraglacial barrier coasts, barrier islands, mainland-attached barriers, perched barriers, barrier island facies, lagoon-salt marsh facies) [Central and Southern US Atlantic Coastal Plain: Hails and Hoyt, 1969; Davis, 1994; Glaeser, 1978; FitzGerald and Heteren, 1999; Pilkey, 2003]
 - b. Beach/beachridge [Boxgrove, Sussex Coastal Plain, UK; Carnlough Coastal Peat and Raised Beach Ridges, County Antrim, Northern Ireland]
 - c. Cliffs
 - Tropical Reef Morphotype—Makatea Island, S. Pacific (Pirazzoli, 1994)
 - Castellated Morphotype—Lands End, England (Bird, 1969)
 - Columnar Morphotype—Cape Pillar, SE Tasmania (Bird, 1969)
 - Slope-over-wall Morphotype (periglacial)—Cornwall, England (Bird, 1969)
 - d. Coral Reef
 - Fringing Reef Morphotype—NE Papua New Guinea (Bloom *et al.*, 1974; Webster *et al.*, 1998)
 - Barrier Reef Morphotype
-

Table 24. *Continued.*

e. Marine Planation Surfaces (incl. terraces) (Type sites: N&W Britain: Hollingworth, 1938; S. California: Shepard and Wanless, 1971)
f. Seabed Features (Uplifted marine terraces: Shellmann and Radtke, 2003)
g. Sea Stacks (kerkurs)
VI. Relief Elements (RE) and Genetically Homogeneous Surfaces (GHS) (Units)
[Metric to decametric scales for local area coverage; smallest taxonomic units of some tenths of m ² up to some km ²]
A. Elements
1. Solution Pits (Limestone corrosion morphotypes)
2. Pinnacles (Limestone corrosion morphotypes)
B. Miniforms
1. Tidal Pools (mediolittoral rock pools: Molinier and Picard, 1959)
2. Honeycomb Weathering Fields
3. Micro-atoll (Contrabandiers, near Rabat, Morocco; Russell, 1967)
4. Algal Rims (Palmas Atlas, Puerto Rico; Russell, 1967)
C. Microforms
1. Rillen and Karren
2. Tafoni, Lapies

References for Table 24

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Table 25. *Materials, processes, forms, or coastal environmental properties that are considered in some selected classification systems and compared to this proposal.*

Authors	Suess (1888)	Cotton (1952)	Johnson (1919)	Shepard (1948)	Valentin (1952)	Owens (1994)	Finkl (2004)
Features							
Geodynamics	H	H		L			H
Tectonics	H	H		L			H
Structure (faults, folds)	H	L	L	L	L		L
RSL Change		H	H	H	L		L
Marine Processes				H	L		H
Terrestrial Processes			L	H	L		H
Shoreline Position		L	L	L	H		
Materials			L	L		H	H
Form (Morphology)			L	L		H	H
Environmental						L	L
Organic			L	L	L	L	L
Erosion–Deposition					L	L	H
Climate							L
Polygenesis		L	H	L			H
Tides					L	L	L
Anthropomorphic						L	L

H = Parameter or characteristic considered at a high (prominent) level in the classification system. Such consideration is usually explicit but may be implicit based on recent interpretations. L = Parameter or characteristic considered at a lower (subordinate) level in the classification system or the concept is implied or inferred. Blank = Parameter or characteristic not specifically considered or inferred in the classification system.

ferent ages and type may, for example, occur in the same coastal position. An example would be a younger Holocene sea level revisiting the approximate level previously occupied by a Pleistocene sea level, as commonly seen along tectonically stable shores in the Bahamian Archipelago and Australia. The question thus arises as to which shoreline feature is being classified and to which 'coast' does it belong? Further, in order to comprehend present coasts it is necessary to understand the relevance or impacts of the hinterland on the coast. One possible solution is to follow the suggestion of McGILL (1958) and classify the **coastal fringe**, a zone about 5–10 km wide that includes both landscapes and seascapes.

The unifying concept of the classification is based on morphostructures, which may be large or small and which cut across all taxonomic levels in the system. Because the system is geomorphic, it focuses on the shape (morphology) of landforms or individual features and provides for consideration of the processes responsible for their formation, age of the forms, and their relationships with adjacent or juxtaposed morphostructures.

The main taxonomic levels in the coastal geomorphic classification system summarize as follows: (1) control of coastal morphostructures, (2) morphostructural process types, (3) geodynamic-climatomorphogenic process zones, (4) relief types (morphoregions), (5) morphogenetic relief features, and (6) relief elements and genetically homogeneous surfaces. Each of these main groups is briefly described in what follows (see Table 25), along with indications of subdivision within the main categories.

The system thus first considers the lithic competence of the material comprising the coast. Mechanical and chemical factors that affect the stability of rock units are related to thermal, abrasion, percussion, and cryoclastic processes (the mechanical factors) and water-saturation, cementation, and compaction (the chemical factors). Lithic competence is a primary criterion for all coastal rocks, soft and hard, as it is directly responsible for the stability (ease of development and preservation potential) or degradation (physico-chemical breakdown) of coastal forms. Next in importance and closely related to lithic properties and coastal forms are the chronometric constraints on the feature. Morphostructural units are separated into broad age groups that progress from youngest (less than 100 yrs old) to oldest (more than 1 million years) by orders of magnitude. This grouping, although arbitrary, provides for a coastal chronology that is useful for general age comparisons. Many coastal features have been dated by radiometric methods (*e.g.* coral reefs, beach ridges) and chronometries are available along some well-studied coasts, both contemporary neomorphogenic shores and older (raised or submerged) paleomorphogenic shoreline features (*e.g.* BLOOM, 1965, 1978; STAPOR, 1975; TAYLOR and STONE, 1996; RINK and PIEPER, 2001; RINK, 2003). Other environmental factors that influence the character of the coast include volcanic activity, isostatic adjustment (*e.g.* neotectonic movements or glacial rebound), eolian deposition, and biogenic development that results in accumulations of reef corals, shell middens, or mangrove muds.

In this morphogenetic system, all coasts are broken out into two hierarchical orders that define the most basic types

of coast. The **allomorphic order** embraces most soft rock coasts that are created by marine processes of erosion and deposition. Allomorphic relief forms and types are comprised by mostly uncemented sedimentary materials. Most hard rock coasts belong to the **automorphic order**. These are primary, self-derived coasts that are formed by magmatic, geotectonic, or subaerial processes. Automorphic coasts include terrestrial morphostructures that have been modified by marine processes.

Suborders refer to geodynamic and climatomorphogenic process zones. The bicameral grouping recognizes suborders associated with geodynamic continental margins and climatomorphogenic provinces. There are a variety of continental margins, which define broad differences in the structure, form, and outline of coasts, with the Atlantic and Pacific types being well established in the literature. To those coasts that truncate the tectonic grain of the hinterland (transverse coasts) and which run parallel to the structural grain (longitudinal coasts) (after SUESS, 1888) we add taphrogenic and sediment loading (after FAIRBRIDGE, 1992) coasts. These suborders incorporate rifted coasts and continental borderlands. The sediment loading suborder embraces large alluvial accumulations associated with basin subsidence. The great deltas of the world, coastal plains, and partially drowned sedimentary basins are characteristic of this suborder.

Climate exerts such a strong imprint on coastal development that the same geomorphic features such as coastal plains, sea cliffs, and beaches have distinctive morphotypes in polar, mid-latitude, and tropical regions (*e.g.* BIRD and HOPELEY, 1969; BÜDEL, 1982). Different climatic regimes can also produce characteristic forms in the same rock type; granites on tropical coasts are quite different than granites along Arctic coasts. Another important factor is deep chemical weathering that produces a variety of alterites and hard duricrusted residual covers (FINKL, 1994b). Erosion of deeply weathered landscapes brings predominantly kaolinitic clays to the coast whereas sediment transport in arid regions feeds feldspathic sediments to coastal margins. In mid-latitude humid climatic regimes, smectitic-type (montmorillonoid) clays are common erosional products that are transported to coastal regions (see FAIRBRIDGE and FINKL, 1980). The climate factor is so strong that many researchers recognize a range of climatomorphogenic regions where the morphology of the landscape and its weathering products can be arranged in sequence, for example, from physical weathering in Polar Regions to intense chemical weathering in the tropics. The continuum of climatomorphogenic regimes is organized here into nine discrete provinces viz. (1) humid tropical, (2) tropical wet-dry, (3) savanna, (4) tropical-subtropical desert, (5) humid subtropical, (6) humid mesothermal, (7) humid microthermal, (8) polar/subpolar, and (9) glaciated.

Relief types are grouped into morphoregions that include morphosculpture complexes, as defined by DEMEK (1972) and DEMEK and EMBLETON (1976). These regional units that comprise distinctive and homogeneous assemblages of forms and which are characterized by similar morphology and genesis are broken down into mountain (hill), plainland, and valley morphostructures. Mountains in contact with the sea form distinctive coasts depending on dominant lithologies or

geological structure. Plateaus (uplifted plainlands) that are truncated to form coastal cliffs are subdivided, for example, into distinctive limestone, weathered, and volcanic morphotypes. Plainlands at or near present sea level are likewise subdivided but in this case on the basis of climatomorphogenic zones to give Arctic, mid-latitude, and tropical morphotypes. Similar subdivisions of valleys obtain various types of drowned or partially drowned morphotypes. Continental freeboard and relief roughness, the latter based on fractal analysis of surface contours, provide a basis for morphometric analysis and classification at hectometric to kilometeric scales.

Morphogenetic relief features (macro- and mesomorphostructures and their elements) are divided into three groups on the basis of whether they are dominantly erosional (destructive), depositional (constructional), or polygenetic process-forms. The erosional and depositional taxonomic categories are subdivided on the basis of shape, *i.e.* whether the morphostructures are linear or curvilinear in planform and broken down again on the basis of whether they lie parallel or transverse to the shore. The polygenetic or complex process-forms essentially boil down to submerged (or partially drowned) landscape features or emerged seascape features. A wide range of morphotypes are recognized for classes of ingressional and egressional relict forms. Examples of submarine morphostructures on the inner continental shelf off southeast Florida are given in FINKL and KHALIL (2000) where reef structures, calcareous hardground exposures, inter-reefal sedimentary troughs, and bar systems are correlated with coastal process zones *viz.* bioconstructor barriers, para(dia)bathic sediment transport zones, hydrodynamic barriers, log-spiral eddies, transverse bars, and coastal ocean process zones.

Geomorphic features classified at the lowest level in the proposed scheme are relief elements (RE) and genetically homogeneous surfaces (GHS). RE and GHS units commonly occur in nature at metric to decametric scales and range in the extreme from some tenths of m² to some km². These kinds of features (*e.g.* solution pits, rillen and karren, micro-atolls, honeycombs) are usually mapped at the largest of scales.

DISCUSSION

The proposed considerations for a new comprehensive scheme (Table 24), that make up a *de facto* system, do not represent a new classification *per se*, but rather an integration of many properties that are already included in other systems, descriptions, or analogs. The system is an approximation that has benefited from contract work (YUHR *et al.*, 1997; FINKL *et al.*, 1997), collegial inputs, and suggestions for improvement (see *Acknowledgements* section). It is thus regarded as organic, a work in progress that can be modified as new information or insight becomes available. The nested hierarchy is deliberately designed to be open ended so that it can accommodate additions, subtractions, and transformation without destroying the overarching layout. The scheme is a broadly bottom-up approach that moves from specific features or forms to more inclusive or comprehensive categories *viz.* relief elements > morphogenetic relief features > relief types > geodynamic-climatomorphogenetic process zones >

chronometrically determined morphostructures > lithologically controlled morphostructures. This sequencing thus migrates from a simple relief form to a linear or curved shape to a form-producing process to a relief type (mountain, plain, valley) as influenced by plate tectonics and climate, age, and lithology.

Descriptions of specific coastal features or shore segments do not necessarily have to follow the outline because scales of observation are variable and therefore categorical levels are flexible. Notes to assist observational criteria are thus provided as guides as in the case of rock type, which can be important at myriametric scales. Geodynamic and climatomorphogenic processes, on the other hand, are operational mostly at megametric scales for regional and continental coverage. Some smaller units for local area coverage are best related at metric to decametric scales (*e.g.* solution pits, limestone pinnacles).

An example of the flexibility of the system can be illustrated by walking a southeast Florida beach scarp through the hierarchy. This protolittoral (<100 years old) feature belongs to the class of erosional linear parabathic morphostructures associated with coastal plain relief in a humid subtropical environment on a semi-stable (or neutral) divergent continental margin containing allomorphic sandy deposits. The complete hierarchical sequence would not normally be given for a small scale morphological feature as in the case of the Linnaean system where genus and species identifiably is normally adequate for most purposes. Related attributes of a feature may be additionally referred to when relevant and warranted, however.

The overall design of the system is based on the relative or combined influence (power) of materials that affect the character of the coast (Category I) (Table 24). Geological inheritance is thus built into the system by incorporating rock type, its durability, and age of the material upon which coastal processes act. Because the coastline, and by inference the coastal zone, always transits preexisting landscapes, seascapes, or seabed in response to relative fluctuations in sea level (eustatic or geodynamic changes) it is important in the first instance to consider the nature of the material that is being converted into a coastal feature, as has been recognized in many prior systems (*e.g.* JOHNSON, 1919; VALENTIN, 1952; OWENS, 1994) (*cf* Table 24). In this regard, the relegational role of lithologic control is broadly likened to SHEPARD's (1973) primary and secondary coasts where hard rock coasts are regarded as automorphic, because they are primary, and secondary soft rock coasts that are produced by allomorphism (allomorphic coasts) as marine products.

The age of morphostructures (Category II) (Table 24) relates to the paleogeography of global shorelines, rates of retreat versus progradation (erodability, preservation potential), and antiquity of the littoral landforms that are in turn related to hypsometry and eustatic sequence orders. The system thus embraces coastal forms of all ages *sensu lato* and is not limited to Holocene shores. This is advantageous because most coasts are complexly developed, polygenetic with palimpsest features and patterns, as recognized in other systems *viz.* JOHNSON (1919), COTTON (1952), SHEPARD (1948, 1973) (*cf* Table 25). Additionally, paleo- or miolittoral shore-

lines and associated morphostructural units could be stranded and reside great distances inland from present-day land-sea boundaries (e.g. JOHNSON and LIBBEY, 1997; LIBBEY and JOHNSON, 1997).

Plate tectonics and the large-scale coastal morphologies associated with them are embraced at the third categorical level in terms of geodynamic and structural provinces as divergent (passive) continental margin (Atlantic Type Coast) and convergent (active) continental margins (Pacific Type Coast), following the lead of INMAN and NORDSTROM (1971), and building on seminal works (e.g. SUESS, 1888; COTTON, 1952; SHEPARD, 1948, 1973) (cf Table 25), with modifications and updates from FAIRBRIDGE (1992, 2004). The climatomorphogenic provinces are patterned after BÜDEL's (1982) perception and understanding of climatic geomorphology.

The fourth categorical level deals (Table 24) with relief types or morphoregions that are major regional morphostructures or morphosculpture complexes that range from a few tens of kilometers to hundred of kilometers, hence hectometric to kilometric scales and larger for regional and sub-regional coverage. Types of mountains, plains, and valleys are modified by the height of continental freeboard and relief roughness, where appropriate. The cliffs of Dover are a good example of a plateau that is truncated by marine erosion to form coastal cliffs. Glacial fjords and fjards or deeply and shallowly incised valleys (e.g. Chesapeake Bay Morphotype) can be modified by terms in Categories I, II, or III as required. These kinds of large, as well as small-scale features noted in Category V, are consistent with types included in other classifications (e.g. JOHNSON, 1919; SHEPARD, 1948, 1973; OWENS, 1994).

Morphogenetic relief features (Category V) (Table 24), macro- and mesomorphostructures and their elements occur on the order of a few tens of kilometers and are thus relevant to decametric and hectometric scales for subregional to local coverage. The units are subdivided in terms of erosional (destructive), depositional (constructive), or polygenetic (complex) process forms. These units make up the vast majorities of coastal forms that are so commonly referred to in the literature. Their morphometry is described in terms of shape and orientation relative to the coast as linear (due to leiomorphogenesis) or curvilinear (due to scoliomorphogenesis). Diabathic and parabathic modifiers are recognized. Morphotypes are identified for many units as suggested exemplars, which can be changed or added to as more information becomes available.

CONCLUSIONS

Over the last century numerous types of coastal classification have been put forward. These attempts at organizing knowledge in the littoral were mainly based in the physical sciences, although there are now more numerous biological classifications for littoral systems and subsystems (e.g. rocky intertidal zones, coastal salt marsh) as habitats, ecosystems, faunal-floral realms or provinces, etc. In a way, it is surprising that there is no comprehensive classification of coastal landforms and yet, on the other hand, it is understandable because "the coast" is a transitional zone between

terrestrial and marine systems to which coastal specialists have laid claim only relatively recently. With increased interest in the coastal zone due to population pressures, demand for integrated resource management through integrated coastal zone management (ICZM) practices, and recently as littoral battle space (e.g. FINKL, 1997), the time has come for clearer integration of understanding of coastal materials, landforms, processes, and their dynamic interactions. Such perception and appreciation derives from classificatory efforts which attempt to organize these factors or parameters into a logical, interrelated, and universal system.

Although prior needs for systematization of coastal geomorphologies were not as pressing as it is now, there are other factors driving the issue today. There are now, for example, large relational databases and GIS frameworks for many coastal sectors that compile inventories of coastal features. Remote sensing (multispectral space-borne and hyperspectral aerial platforms) also brings to the arena a whole new field of data that is synoptically valuable on a range of scales never before possible. So, it is perhaps prudent to consider that: (1) the time has come for comprehensive and integrated classification, (2) there exist huge coastal databanks (in analog and digital form), and (3) new techniques are available for classifying the world's shoreline. All that is required is development of a suitable framework that is appropriate for a universal, global system of coastal classification.

It is not that previous systems were no good or lacked merit, for the questions to be asked should evolve about purposes and goals of the systems in hand and the kind of information that was available at the time of formulation. Today's complicated issues in the coastal zone require sophisticated resolution; it's a case where preliminary or rudimentary solutions no longer meet newer complex demands. In a sense, prior systems of coastal classification are *apophoreta*—appetizers for the main course yet to come. Thus, a new system of coastal classification needs to be developed and it is apropos to consider the purpose of the new system and determine exactly what is to be classified. The purpose of this proposal is to organize a smorgasbord of coastal landforms in terms of a multipurpose, comprehensive, and unified classification scheme.

The subject of classification is geomorphological units (taxons); therefore, following the lead of the IGU Commission on Coastal Survey and Mapping, morphostructures provide the linking theme of the classification system and facilitate transitioning from one taxonomic level to another. Morphostructures exist at all scales within the spectrum of mapping. In addition to the purpose, theme, and units there are (classificatory and mapping) constraints related to the definition of coast and this has to be comprehended in the scheme. To be useful in a broad or universal context, the new system must classify more than the shore- or coastline *per se*. The system must apply to a "zone" and not a line. The classification procedure must allow for "across-the-shore" variation as well as "along-the-shore" extent, similar to what DOLAN *et al.* (1972) refer to as the orthogonal approach. LIND (1969) applies a similar approach in his distribution of coastal profile types where cross-shore profiles are given alongshore distributive properties so that diabathic sequences are parabathically

linked. Due to the complexity of antecedence (inheritance) in coastal landforms, the classification system needs to consider a swath of certain dimension along the shore and not just the length and width of a particular landform. Because most coasts are the result of polygenesis (multicyclicity) over a range of time frames, composite classifications are required to consider rather broad areal extents both above and below present sea level along coasts. MCGILL (1958) refers to the area or zone that should be classified as the "coastal fringe" and this is adopted here as a swath along the coast that extends for several kilometers on either side of the shoreline to include subaerial and submarine features. Finally, in addition to being comprehensive and unified, the classification system needs to be open ended so that new information can be added as required. The scheme presented here is preliminary and should be considered as a work in progress. The usefulness or value of a classification system can only be determined in the fullness of time by use in the field. And finally, no classification is a completely accurate representation of Nature and, no matter how well conceived and constructed, the scheme is morphologically both an ontological and phylogenetic approximation of macro- and micro-developmental forms. The contribution offered here is thus an approach or approximation of what is yet to come. Whatever the form of subsequent efforts towards development of a comprehensive coastal classification scheme, the evolving systems should in one way or another deal with the criteria outlined here.

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