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Geomorphological Mapping of Mediterranean Coastal Features, Northeast Spain

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ABSTRACT

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This study proposes a method for the cartographic reproduction, in a single map, of natural features, coastal dynamics, and artifical structures. The test site focuses on a sector of the Spanish Mediterranean coast, from Barcelona to Comarruga. The different variables are represented in successive coastwise bands. This method permits: (a) analysis and visualization of relationships between the variables, (b) the incorporation of new variables in additional bands, and (c) the cartographic representation of temporal variations. The features mapped include backshore forms and the shoreline morphology. Other variables mapped in successive bands correspond to seawater dynamics (1st band), coastal processes (2nd band), artificial structures (3rd band), and lithology (4th band). This coast has undergone important transformations during the last few years. Because littoral drifts in this sector are dominated by southwesterly flows, breakwaters and other coastal works have caused a progressive advance of erosion downstream of these works.

ADDITIONAL INDEX WORDS: *Backshore morphology, beach material, coastal mapping, coastal processes, rocky platforms, shoreline morphology, Spanish Mediterranean.*

INTRODUCTION

In the last twenty-five years, the Spanish Mediterranean coasts have undergone important transformations in their configuration. Industrialization, progressive regulation of hydrographic basins, as well as the utilization of the littoral by tourism, are the main causes of coastal change. Until recently, activities along the coast have been localized, always following the same general sequence. Projects at one point along the coast including construction, development of coastal protection works, extraction of building materials, invariably affect other coastal segments requring additional protection of the littoral.

It is informative to document, for a long stretch of coast, natural biophysical characteristics as well as human interventions that bring about more change in natural systems. These observations are interesting because they provide an encompassing view of the littoral system. That is to say, the impacts of human intervention seem to surpass the local dynamics that are part of a much larger framework, both in space and in time.

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COASTAL MAPPING

A Review

Before developing the preliminary map that is presented here, we reviewed many papers that dealt with cartographic representation of coastal areas. Most of the papers, depending on the scale and objectives, emphasized various aspects of the problem.

Models most relevant to this study include, among others, the observations of DUBOIS and BRIARD (1979, 1980) for the north coast of Saint Laurent and HEYDORN and TINLEY (1980) for a sector of the South African coast. The studies of DUBOIS and BRIARD include a series of schemes that incorporate sedimentological units in which they place the main morphological and dynamic features (*i.e.*, tides, littoral drift, wave fronts) at scales on the order of 1:300,000. In another series of figures, at a more detailed scale (1:140,000), they cartographically display shoreline stability, temporal erosion or accretion, in addition to the type of coast. In order to accurately represent the erosion, stability, or accretion, the following symbols are respectively employed: triangles, circles and squares. These symbols are drawn at the ends of lines drawn perpendicular to the shore at points studied. If data for different time frames are available, symbols for each period may be combined with rates of change for each period. This system permits the visualization of variations in rates of coastal processes for specific time frames. It is difficult, however, to establish relations between these and other variables (*i.e.*, currents, waves, structures) because they are represented on other maps.

HEYDOR and TINLEY's (1980) synopsis of the Cape Coast (South Africa) shows natural features, coastal dynamics, and shoreline utilization. This important study includes maps (at a nominal scale of 1:3,000,000) which variously show relief and rainfall profiles, geology and fault patterns, soil patterns, wind directions, climographs, vegetation, bathymetry, and utilization of the coastal region by humans. They also show (scale 1:500,000) dynamic features of the Cape Coast that HEYDOR and TINLEY recorded on 1:50,000 topographical maps during a low level air survey. Coastal types and surfaces were charted on an outline of the shoreline as was coastal stability in another identical outline, at about 5 cm from the former.

COASTAL MAPPING BY SUCCESSIVE BANDS

Characteristics, Limitations and Advantages

The method of cartographic display reported here shows selected variables in a single map. These variables are represented in successive bands that are drawn parallel to the coast. This method makes it possible analyze different variables without simultaneously consulting several different maps. Similar techniques were used by GREEN *et al.* (1975) for a sector of the Amerla coast, Spain, and also in the Indicative Plan of the Uses of Public Dominion of the Spanish Littoral (Plan Indicativo de Usos del Domino Público Litoral de España) of the Ministry of Public Works at a scale of 1:5,000. The public works plan included two figures for specific coastal segments. One figure is a map derived from the other, the photoplan. In both figures bands containing different concepts or variables are projected along a horizontal line that runs parallel to the coast.

The variables that are represented depend on the goals of special purpose mapping or on characteristics features of the area. Perhaps one of the most interesting aspects in this mapping technique is the possibility of displaying a range of new variables or showing temporal changes in coastal processes.

Variables that are subjected to larger changes include coastal processes and artifical (man-made) structures. The representation of temporal variations in coastal stability includes different alternatives: (A) Every time period may be represented by a separate band. In this way a map can by updated by adding new bands. After construction of man-made structures the newly modified coastal processes can by shown in another band. (B) The time periods may be indicated by different symbols, patterns, or letters. This method works well for the depiction of man-made structures but poses problems for the representation of coastal processes because they are variable in time and space. (C) To each symbol the date may be added to its corresponding band. This method poses the same problems as (B) and it may become cumbersome as there are limitations of available space for many dates.

Consideration of temporal variations in coastal processes indicates another aspect of thee maps, the distribution or arrangement of the bands. After having prepared the maps, it seems more convenient to draw the long-lasting variables (*e.g.* lithology) in the more internal (landward) bands, and locate the coastal processes and the artifical structures in the more external (seaward) bands. Of all the variables that we have considered it seems more useful to include bathymetric data that could be shown in a more external part of the map.

Limitations of this method for cartographic representation of coastlines stem from the type of coast and from the scale. Because the irregularity of the shoreline tends to be amplified as more external bands are added, we recommend this system for coasts with few indentations. As to mapping scales, the validity of this method of coastal representation is largely a function of the characteristics of the coast. More regular and homogenous coasts allow the use of larger scales. More detailed scales

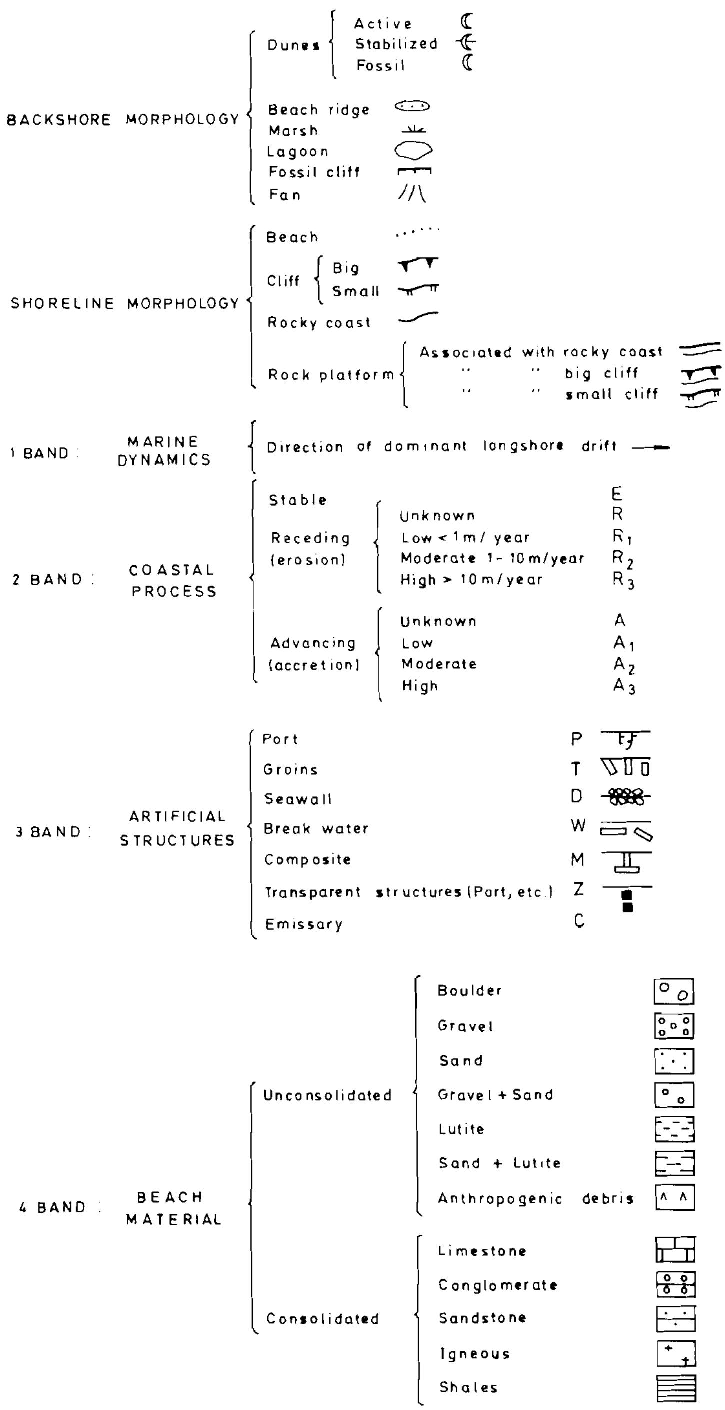

Figure 1. Key to cartographic symbols used in maps deploying coastwise bands for marine dynamics, coastal processes, artificial structures, and beach material.

require some simplifications. For the coastal segments described in this study, we think that the scale limit is about 1:200,000.

Selected Variables and System of Representation

In this study we have selected and represented the following variables: (a) backshore morphology, (b) shoreline morphology, (c) marine dynamics, (d) coastal processes, (e) artifical structures, and (f) beach material (Figure 1).

The backshore morphology is represented by a series of conventional symbols specific to each form. They are printed on the land side of the shoreline. In this study of the Spanish Mediterranean coast the following forms have been specified: dunes (active, stabilized, or fixed), beach ridges, marsh, lagoon, fossil cliff, alluvial fan. Just as several types of dunes have been identified on these maps so can other types of marshes or other forms be incorporated. The shoreline morphology is drawn with different kinds of dashes at the edge of the land. We have pointed out beach, cliff (big or small), rocky coast, and rock platform (associated with rocky coast, big cliff, or small cliff). Other variables are represented on the successive bands parallel to the coast. The first corresponds to seawater dynamics *viz.* waves, tides, and currents. In this study, only the direction of the dominant longshore drift has been mapped. This mapping procedure was due in part to the lack of tides as well as the scarcity of available current and wave data.

The second band identified coastal processes in terms of erosion, accretion, or stability. For each process several rates are distinguished (high, moderate and low) and their range is shown in the key.

The third band shows the man-made structures that include for example, ports, and protective works such as groins, seawalls, breakwaters, composite structures, transparent structures and emissaries. We do not know if there is an exact English term for *transparent structure* (a sort of pier). It refers to a port situated on the sea and linked to the coast by means of a bridge designed so as not to hinder coastwise sand drift.

Finally, the fourth band depicts the type of beach material where unconsolidated materials are separated from those that are consolidated. Within the unconsolidated category the subdivision corresponds to grain size but the consolidated category refers to rock type.

THE N.E. SPANISH MEDITERRANEAN COAST

This coastal sector serves as an example for the cartographic representation described above and corresponds generally to the Catalan coast (Figure 2, a, b). The littoral region is included on sheets 447 and 448 of the Spanish topographical map series (scale 1:50,000) between the Llobregat River and Comarruga village. This coastal section has a variable morphology of structural origin; its NE-SW orientation corresponds to the structural alignments of the Catalanides.

The morphological elements which form this sector are basically defined by the structural history, the lithology, sea level oscillations, and sand movements. The cliffy coast corresponds, for example, to outcrops of the calcareous Mesozoic while the long beaches without deltaic developments are formed on the edges of Neogene depressions.

Backshore and Shoreline Morphology

Cliffs

Both fossil and active cliffs are distinguished in reference to the present shoreline. Development of subvertical slopes along active cliff bases makes it possible to differentiate cliffs with a large proportion of subvertical slopes (decameters or hectometers in length) from those with less developed short steep slopes (up to several meters in length) which occur infrequently in this zone.

One of the main fossil cliff systems forms the landward limit of the delta plain of the Llobregat River. The other paleo cliff system is developed in the Cubelles-Calafell zone (Figure 2a). Preservation of these old cliffs depends on human activities and the materials in which they are developed (mainly Neogene and Pleistocene materials). These old cliff lines mark the landward limit of the Versilian transgression.

Active cliff systems are developed in calcareous Miocene and Mesozoic outcrops. These cliffs are characterized by a subsequent development of subvertical slopes which fall directly to the sea without a basal subaerial platform. These so called plunging-type cliffs with the best development occur in the Garraf Massif between the villages of Garraf and Vallcarca.

Rocky Platforms

The well developed rocky platforms of the Catalan Mediterranean coast are associated with

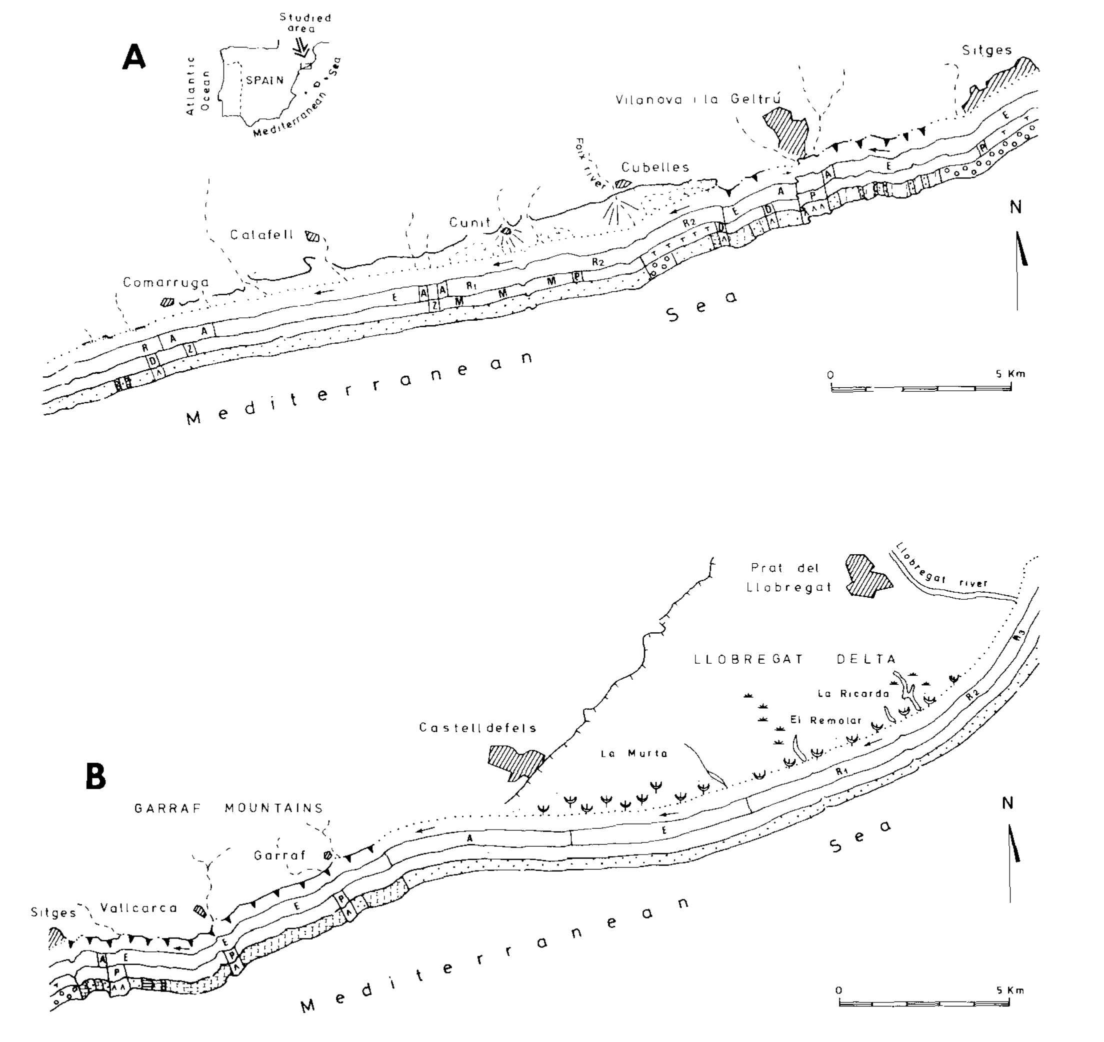

Figure 2. Preliminary maps of coastal features: dynamics and artifical structures, Catalan coast: (A) Comarruga-Sitges, (B) Sitges-Llobregat River.

Pliocene and Quaternary alluvial fans and also with Tyrrhenian deposits. The presence of soft strata between strongly cemented conglomerates in the fans generally favors the development of submerged platforms. Rocky platforms are mainly associated with Tyrrhenian deposits in the southwest part of the study area.

Beaches

Beach zones are developed from fluvial deposits. Extension of sandy beaches is conditioned by the longshore dynamics as well as the natural or man-made morphology of the shoreline. In general, the beaches are made up of siliceous sands but locally limestone shingle may predominate. Two examples of the latter type are the Sitges beach and the one developed in the cone of the Foix River.

The most important source of sediment supply is the Llobregat delta (Figure 2b) where the shore is formed by coastal dunes that are stabilized by *Pinus pinea*, lagoons (La Ricarda, El Remolar, and La Murtra), beaches, and bars.

A different type of accretionary beach is related to the evolution of bars. These bars may have become welded to prograding aluvial fans or to rocky headlands. Bar development tends to close the depressed lateral zones which are eventually converted into lagoons (Figure 3). The remains of three lagoons between Cubelles and Cunit are presently dried and largely occupied by urban landscapes.

Finally, there are small beaches that occur in coves (locally called Calas), structural indentations, along cliffy coastal sections. The main concentration of cala beaches is localized between Sitges and Vilanova i La Geltrú.

Present Evolution of the Coast

Reconstruction of major events in the shoreline evolution was achieved by analyzing a series of aerial photographs and topographic maps. This reconstruction is not complete due to the diversity and discontinuity of spatial and temporal information. The trends in this report correspond to the period 1957-1978.

Marine Dynamics

Currents along this microtidal coastline show a predominant circulation from the northeast to the southwest, flowing practically parallel to the coast. This circulation involves a littoral transference which is predominant in this direction. Nevertheless, the sediment intake and transfer, depending on the marine regime, undergo remarkable fluctuations over time. Thus, during some parts of the year currents flow in the oposite direction. Another important component in the marine dynamics of this zone are the so-called Eastern storms. These storms are associated with ENE winds that achieve maximum strengths in October and March. During these intense storms the littoral transport and marine erosion is affected down to the base level of the waves.

These combined processes result in the net transport of sediments to the southwest. The construction of screens or barriers of different types along the coast contributes to (a) a blocking of the sedimentary flow to both sides of the barriers but with a marked accumulation on the northeastern part of the works and (b) to the development of progressive erosion downstream of the coastal engineering works. These factors have caused the construction of successive protective works that extend from the initial blocking points in a northeast-southeast direction. The erosive chain reaction caused by the construction of engineering works generally extends to the limits of the physiographic unit in which they are built.

Coastal Processes

Data relating to erosion and accumulation in the

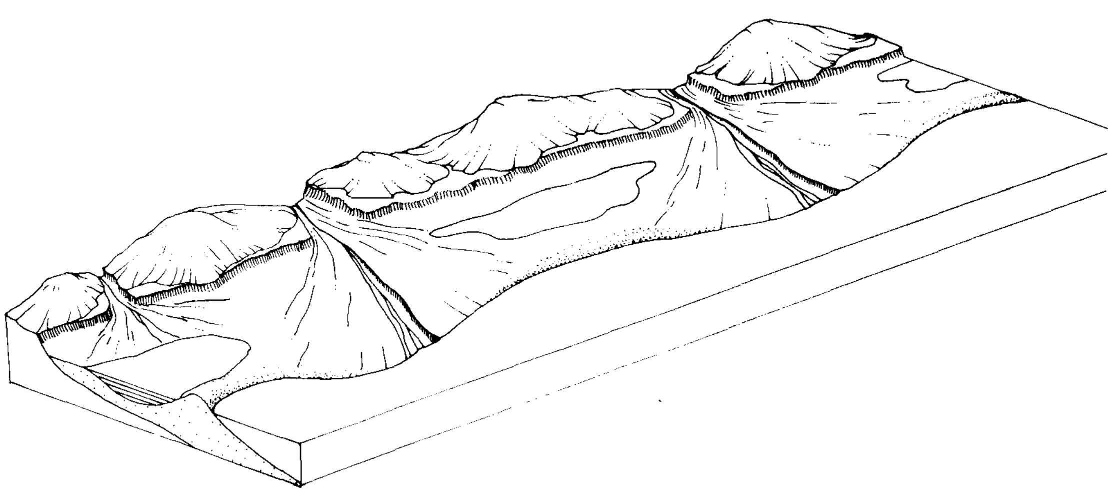

Figure 3. Example of an accretionary beach that is related to the evolution of bars. Coastwise depressions between alluvial fans or rocky headlands are eventually cut off and converted into lagoons, as between Cubellas and Cunit.

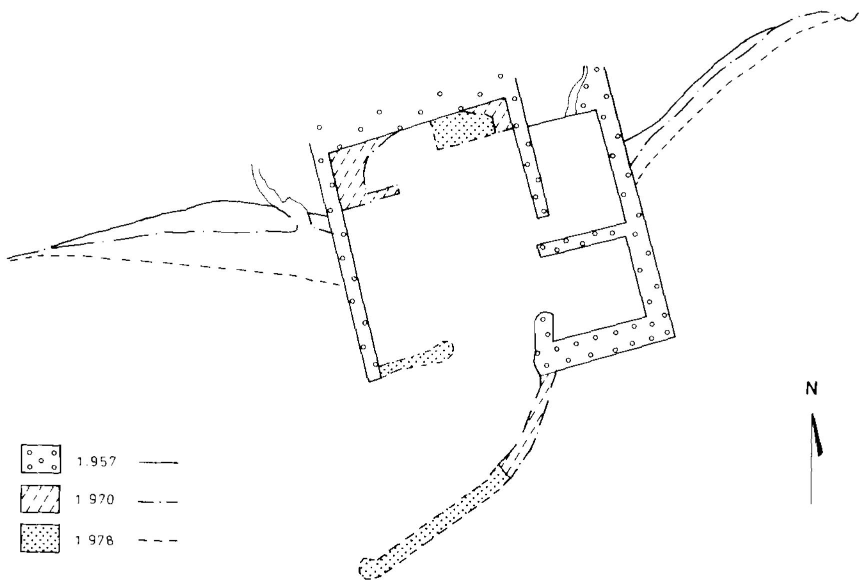

Figure 4. Port facility near Vilanova i La Geltrú.

coastal zone prior to 1957 are derived from specific examples but indicate that until the 20th century the general trend has been one of growth. Since then the process has reversed and a generalized erosion is now observed all along the coast. Progradation now only occurs on the updrift sides of protection works or ports. The predominance of southwest currents causes asymmetrical accumulations on both sides of coastal works with a shift towards the south of the erosive processes that originate from the works.

This study identifies three discrete coastal zones. The central zone, formed by cliffs of the Garraf Massif, acts as a sand transfer zone. The development of a cliff-foot platform 2-4 km wide between the shoreline and the 20 m isobath permits the transfer of sand coming from the Llobregat delta.

The northern zone forms the southwestern part of the Llobregat delta which is developed just south of Barcelona between the Montjuic headland (northeast of the mapped area) and the Garraf Massif in the southwest. The maximum erosion in the Llobregat delta occurs at the river mouth and progressively decreases toward the southwest. Maximum recession rates are 30 m/year for the period 1953-1957 and 12 m/year for the period 1957-1965 (MARQUÉS, in press). Basic causes of this rapid rate of coastal recession (MARQUÉS, 1984) include (a) the construction of the Barcelona port, (b) the extraction of sediments for construction from the Llobregat River bed and from the coast, (c) regulation of river discharge through the construction of dams and reservoirs, and (d) subsidence of the Llobregat delta caused by compaction and drops in hydrospheric pressure, among other factors.

The southern zone, extending in a north-south direction from Vilanova i La Geltrú to Comarruga, experienced severe erosion after the expansion of the port facility near Vilanova i La Geltrú (Figure 4). This port, acting as a barrier, caused the formation of two triangular beaches on both sides of the port entrance. The rates of growth from 1970-1978, subsequent to the main extension of the port, are about 3,600 m^2/year and 7,000 m^2/year in the northern and southern zones, respectively (MARQUÉS and JULIÁ, 1980). The retention of sand is the main cause of the coastal recession in the outskirts of Cubelles. The first protective works, seawalls and groins, were constructed in the northeast zone of the Foix River. The great distance between some groins allowed the erosion of beaches between groins. For this reason, a series of recent modifications have mainly consisted of the construction of terminal hooks on the external-most parts of the groins. The construction of these T-groins reduced the erosion but it was then shifted towards the southwest by the dominant SW current. During the 1980's, the protection works were extended to the outskirts of Cunit. In this zone the breakwaters are formed by stone blocks, placed parallel to the coast, and with a submerged peduncle. In addition, between each pair of breakwaters and the beach, a small mole has been constructed, also in blocks, in order to attenuate the impact of the waves which penetrate separations between breakwaters.

Finally, the port of Cunit, which has a "U" shape (open towards the coast) should be mentioned. It was constructed at 200 m from the coast and linked to it by a causeway on piles. Although the purpose of this unusual construction was not to interrupt the passing of sand, a cuspate spit has invaded the port enclosure. A corrugated metallic vertical screen has been constructed in an effort to prevent sedimentary infilling of the port. It is hoped that this screen will help reduce the frequency of maintenance dredging.

CONCLUSION

Several cartographic representations have been considered in the development of practical techniques that integrate variables in the littoral environment. From this study it is concluded that the cartographic reproduction in the form of successive coastwise bands is the most successful. This mapping technique facilitates the analysis of different variables involved in the coastal framework in a single map. New variables or changes in space and time are easily incorporated. Limitations of the method arise from the type of coast and from scale. The irregularity of the shoreline tends, for example, to be amplified as more external bands are added.

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□ RESUMEN □

El presente estudio propone un método para la reproducción cartográfica, en un único mapa en el que se recogen: caracteristicas naturales, dinámica costera y estructuras artificiales. El lugar del test se localiza en el sector de la costa mediterránea española comprendido entre Barcelona y Comarruga. Las diferentes variables son representadas en sucesivas bandas paralelas a la costa. Este método permite: (a) análisis y visualización de las relaciones entre las variables; (b) interpretación de nuevas variables en bandas adicionales y (c) representación cartográfica de las variaciones temporales. Se incluyen en el mapa las formas de la playa emergida y de la morfologia de la linea de costa. Asimismo se representan en sucesivas bandas las variables correspondientes a la dinámica marina (1ª banda), procesos costeros (2ª banda), estructuras artificiales (3ª banda) y procesos litológicos (4ª banda). Esta costa ha sufrido importantes transformaciones durante los últimos cercanos años como consecuencia de la interposición, a la corriente litoral del Sur-Oeste dominante en la zona, de diques y ostras obras maritimas que han detenido el flujo de sedimentos causando el progresivo erosionamiento de los lugares situados aguas-abajo de las citadas obras.

□ ZUSAMMENFASSUNG □

Diese Forschung schlägt ein Verfahren der kartographischen Wiedergabe vor, wodurch Bodengestaltungen, Küstendynamik und Bauwerke auf einer einzelnen Karte eingeschlossen sind. Die Forschungslage ist ein Bereich der mittelmeerischen Küste Spaniens, das von Barcelona bis Comarruga streicht. Die verschiedene Veränderlichen sind durch aufeinanderfolgende küstenweise Bänder dargestellt. Die folgende sind durch diese Verfahren ermöglicht: (a) die Analyse und die Veranschaulichung der Beziehungen zwischen der Veränderlichen; (b) die Einschliessung neuer Veränderlichen in zusätzliche Bänder, und (c) kartographische Wiedergabe der Zeitveränderungen. Die gezeichnete Gestaltungen schliessen Formen hinter dem Strand und die Küstenmorfologie ein. Andere in aufeinanderfolgenden Bänder gezeichnete Veränderlichen übereinstimmen mit der Seewasserdynamik (1. Band), Küstenprozesse (2. Band), Bauwerke (3. Band), und Gesteinskunde (4. Band). Diese Küste ist in Laufe der letzten Jahre wichtige Verwandlungen erfahren. Weil die Küstendriftströmung in diesem Gebiet von südwestliche Zuflüsse vorherrscht ist, haben Wellenbrecher und andere Küstenbauwerke eine stromabwärts von der Bauwerke laufende Auswaschung verursacht.