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COASTAL GEOMORPHOLOGY OF MAJORCA

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THE large-scale morphology of the Balearic Islands is divisible according to two basic structural units. Some areas are composed of folded Palaeozoic, Mesozoic, and Lower Tertiary rocks, which form most of Ibiza, the Majorcan Highlands, and the northeastern half of Menorca. The physiographic characteristics of these areas, like the Mediterranean rough lands in general, display conspicuous effects of linear fluvial erosion, a process responsible for a jagged dissection only incompletely masked by veneers of Quaternary sediments. Other areas, including the island of Formentera, the Majorcan plains, and southwestern Menorca, are composed of horizontal Cenozoic bedrock, and evidence of fluvial dissection is absent or of limited importance. Instead, features produced by wave action and other littoral processes are prominent if not dominant. The purpose of this paper is to describe these marine-littoral features, analyze their evolution on the island of Majorca, and indicate their reflection in the cultural landscape.

The previous geomorphological literature on the coasts of the Balearic Islands is limited to a few remarks by A. Penck,[1] P. Fallot,[2] J. Carandell,[3] O. Mengel,[4] A. Muntaner Darder,[5] and L. Solé Sabarís.[6] In contrast, stratigraphic work applied to Pleistocene beaches has a considerable tradition and a sizable literature.[7] The field investigation on which the following remarks are based was carried out during 1959, 1960, and 1961. The study involved (1) mapping of the surficial deposits, geomorphology, and soils of a 350-sq. km. section of southern Majorca at 1:50,000, (2) a survey of the modern and Pleistocene coasts of Majorca and Formentera, (3) study of soil erosion problems, and (4) micro-stratigraphic and subsequent laboratory analysis of sediments and soils.[8]

GEOLOGY

Although Majorca very probably rests on a Palaeozoic basement, the oldest exposed bedrock, of a dominantly limestone facies, is of Mesozoic and Lower Tertiary age. An initial orogeny, during the Upper Oligocene (Chattian), subjected the southeastern part of the island to thrust faulting,[9] and a second phase, at the close of the Lower Miocene (Burdigalian), modified the remaining surfaces into

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[1] A. Penck, *Morphologie der Erdoberfläche* (Stuttgart, 1894), Vol. II, pp. 568–569, 579.

[2] P. Fallot, "Esquisse morphologique des îles Baléariques," *Révue de Géographie Alpine*, Vol. 2 (1923), pp. 421–448.

[3] J. Carandell, "Movimientos lentos en el litoral este de Mallorca," *Boletin*, Real Sociedad española de Historia natural, Vol. 27 (1927), pp. 468–473.

[4] O. Mengel, "Mouvements quaternaires dans l'île de Majorque," *Comptes rendus sommaires*, Société de Géologie de France, 1934, pp. 84–86.

[5] A. Muntaner Darder, "Las formaciones cuaternarias de la Bahia de Palma (Mallorca)," *Boletin*, Sociedad de Historia natural de Baleares, Vol. 3 (1957), pp. 77–118.

[6] L. Solé Sabarís, "Le quaternaire marin des Baleares et ses rapports avec les côtes méditérranéennes de la péninsule ibérique," *Quaternaria*, Vol. 6 (1961), in press.

[7] See the pre-1957 bibliography compiled by J. Cuerda in the *Livret-Guide de l'excursion L. Levant et Majorque*, V. Congrès Internationale de l'INQUA (Madrid and Barcelona, 1957), pp. 49–52. For a later bibliography see K. W. Butzer and J. Cuerda, "Coastal stratigraphy of southern Mallorca and its implications for the Pleistocene chronology of the Mediterranean Sea," *Journal of Geology*, Vol. 70 (1962a), in press.

[8] Part of the field work was carried out together with the palaeontologist J. Cuerda of Palma, and valuable discussion and information was provided by A. Muntaner Darder (Palma), V. M. Rosselló (Valencia), and B. Vidal y Tomás (Santanyí). The field and laboratory work were made possible by the generosity of the Akademie der Wissenschaften und der Literature, the University of Wisconsin Research Committee, the Geography Department of the University of Wisconsin, and the Geographisches Institut of the University of Bonn. R. E. Dott and David Ward carefully read the manuscript.

[9] B. Darder, "La tectonique de la région orientale de l'île de Majorque," *Bulletin*, Société géologique de France, Vol. 25 (1925), pp. 235–278; B. Darder and P. Fallot, *La Isla de Mallorca*, Guida de la excursion C-5, del XIV Congrès Geologique International de Madrid (Madrid, 1926), pp. 12 ff.

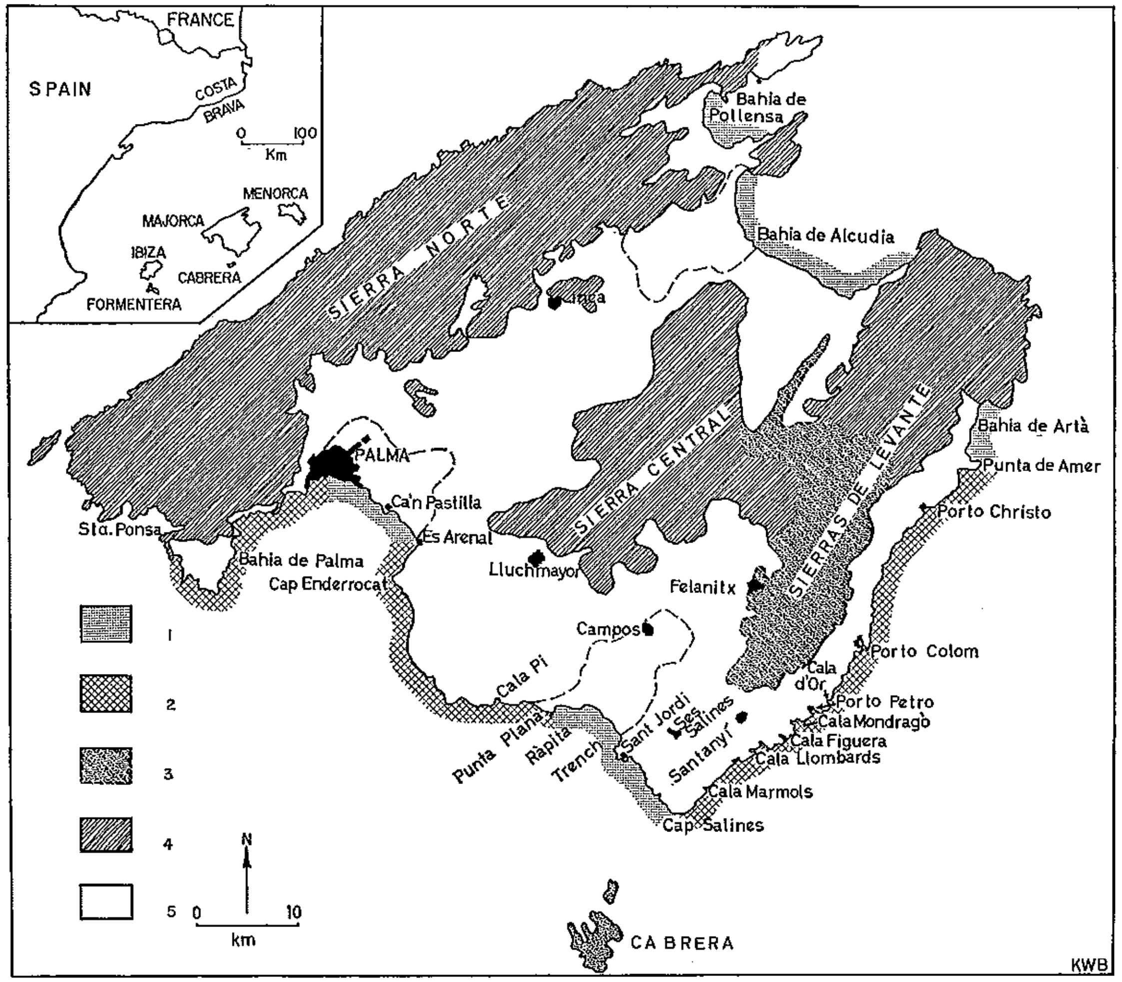

FIG. 1. Structure and coastal features of Majorca. 1 = shallow-water coasts of nip, shingle-beach and beach-ridge types; 2 = cliff coasts; 3 = Mesozoic and lower Tertiary beds folded during Upper Oligocene orogeny; 4 = Mesozoic and lower Tertiary beds folded during Lower Miocene orogeny; 5 = horizontal Cenozoic strata. The heavy broken line delimits the lowland plains of Palma, Alcudia, and Campos. (3–5 simplified and modified after Darder and Fallot.)

a complex mountain system of folds and faults.[10] Three major anticlinal axes, oriented northeast to southwest, were formed: the mountainous northern ranges or Sierra Norte (with a maximum elevation of 1,445 m.), the discontinuous hills or low mountains of the Sierra Central (maximum elevation 549 m.), and the irregular hill and low mountain complex of the Sierras de Levante (maximum elevation 560 m.) (Fig. 1).

During the Middle and early Upper Miocene (Helvetian-Tortonian), a marine transgression deposited a series of massive epicontinental sediments in the intervening synclines and around the margins of the central and eastern sierras. Undisturbed horizontal beds of these calcarenites and algal limestones rise to about 150 m. above sea level, and show no evidence of major tectonic deformation apart from limited synclinal depressions apparent at the foot of the Sierra Norte.[11] The primary origin of the lowland plains of Campos, Palma, and Alcudia can be explained satisfactorily by reference to gradational agents. Deformation of the Cenozoic bed-

[10] Fallot, *Etude géologique de la Sierra de Majorque* (Paris, 1922).

[11] A. Muntaner Darder, personal communication.

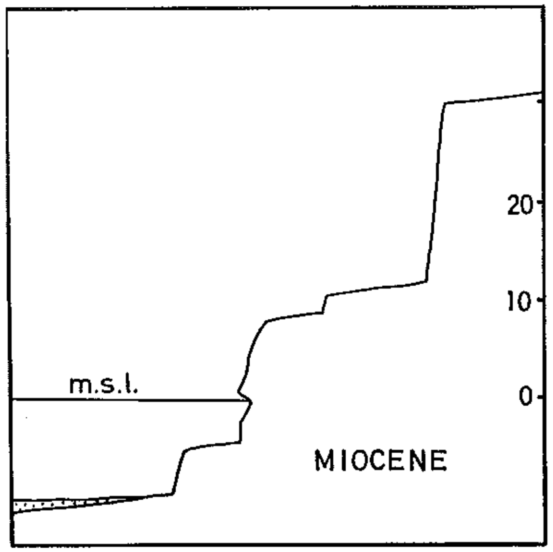

FIG. 2. Profile of a cliff coast at Es Tamarimar, Cala Figuera. No vertical exaggeration. Note the well-developed older platforms and cliffs.

rock is limited to irregularities resulting from sag or collapse around present or former sea caves. In view of this almost general tectonic stability in Cenozoic times, there is little effect of structure upon landforms in the areas under consideration. These coastal sectors of Middle or Upper Miocene and Pleistocene strata include the whole modern littoral of Majorca, with the exception of the northwest coast and the northeastern flank of the Sierras de Levante (Fig. 1).

MODERN COASTAL FORMS

Cliff Coasts

Cliff coasts are characteristic of a large part of the Majorcan littoral. They are associated almost exclusively with deeper waters offshore, and the –20 m. isobath is generally found at distances considerably less than 500 m. from the shoreline. Shelf gradients exceed 1 per cent.

Plunging cliffs, extending to 5 or 10 m. below sea level, are most characteristic of this coastal type, whereas beach platforms cut into Miocene limestones are rare. The general picture is one of a small notch, averaging some 20–30 cm. wide, and 30 to 50 cm. high, cut into almost sheer cliffs (Figs. 2, 3). The

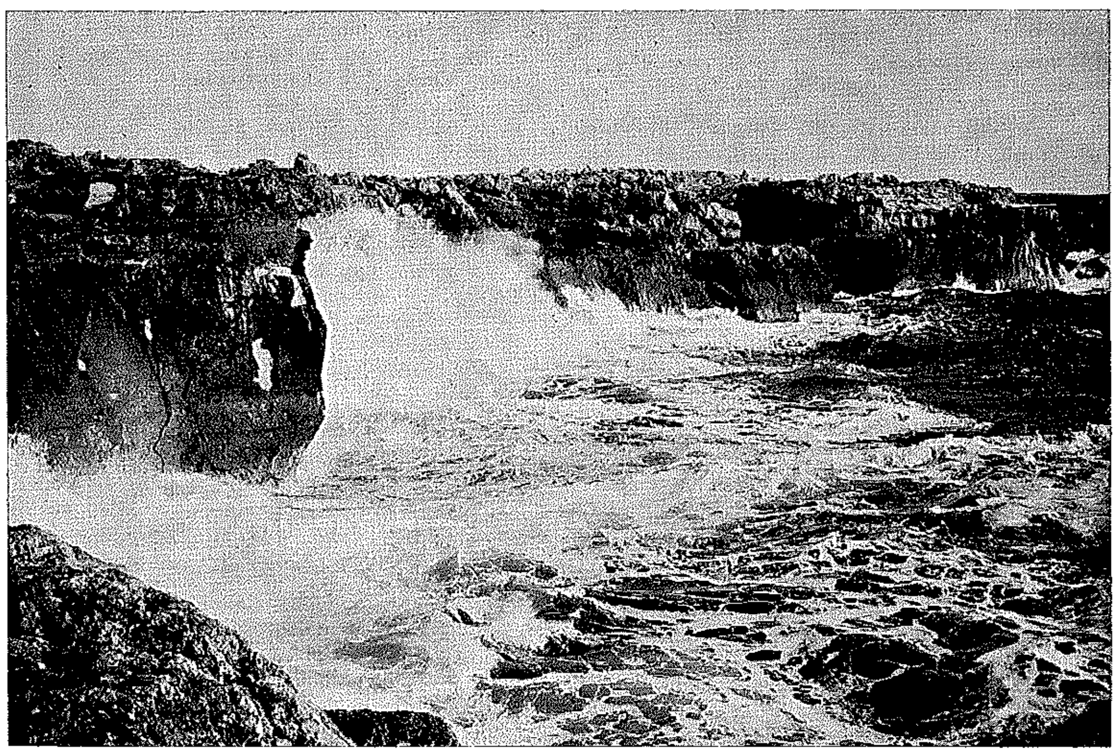

FIG. 3. Low cliff coast between Cala Pí and Punta Plana. The notch is cut into Miocene calcarenite at the base of the 8 m. cliff, which is capped by Pleistocene silts and horizontal aeolianites.

morphology of the submerged cliff base is dominated by fossil benches of several meters width at -4.5–5 m., -7–10 m., and well-marked grotto base levels at 2–3 m. and 4–5 m. below mean sea level. The cliff face varies locally from 3 to over 30 m. in height, and frequently shows abrasional platforms related to higher Pleistocene sea levels.

The limited height of the notch can be explained by the small tidal amplitude of the Mediterranean Sea (15–30 cm.). However, the effects of storm waves are noticeable to a considerable elevation. Chemical solution resulting from sea spray is conspicuous to 10–12 m. above the watermark, and solution cavities with brine, averaging 15–25 cm. in depth and 50 cm. in diameter, are found on high platforms to about +8 m. These cavities are associated with a jagged microkarstic surface (*réseaux de lapiés* or *Karren*), which marks the highest levels attained by occasional storm waves.[12]

Beach platforms cut into Miocene bedrock are found only at the mouths of small inlets (*calós*), and were therefore probably formed by fluvial processes. Wave-cut platforms of 10 to 20 m. or more in width are common in softer Pleistocene sediments. These benches culminate in notches, with little or no overhang, and a water depth of about 10 to 100 cm. Frequent colonies of *Littorina neritoides* aid grain-by-grain disintegration of the consolidated to fully cemented aeolianites, and coarser clastic materials, derived from cemented colluvial deposits of Pleistocene age, provide a potent erosive tool for mechanical wear. The development of platforms in the small inlets is at least partly associated with the presence of clastic materials and mechanical erosion, which is indicated by the occurrence of frequent potholes.

Presumably, then, the differential development or absence of modern abrasional platforms is largely a reflection of both the degree of mechanical weathering and the durability of the bedrock. Mechanical weathering along the deep-water cliff coasts in Miocene bedrock is limited to pressure, suction, and the shock impact of oncoming waves. There seems little reason to doubt Guilcher's suggestion that chemical solution is a factor frequently dominant in notch and platform development in limestone bedrock.[13]

A question is posed by the more distinctive development of elevated and submerged platforms along cliff coasts that do not have modern platforms.[14] Similarly, sea caves are insignificant at modern sea level, yet frequent at other levels. Possible explanations are suggested by the comparative inconstancy of sea level in the Recent period[15] and by possible unknown differences among the biological prerequisites[16] for carbonate solution at the watermark.

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[12] In general wave heights in the open Mediterranean are not thought to exceed 8 m. and wave lengths 50 m. On the coasts these maximal values are considerably reduced. During gales of Beaufort 6–8, the wave height observed during storms in the autumn of 1960 seldom exceeded 4 m., and wave lengths in deep water seldom exceeded 30 m.

[13] A. Guilcher, *Morphologie littorale et sous-marine* (Paris, 1954), pp. 43–46.

[14] A. Guilcher ("Essai sur la zonation et la distribution des formes littorales de dissolution du calcaire," *Annales de Géographie*, Vol. 62 [1953], pp. 161–179) even characterizes modern shorelines on limestone bedrock in the Mediterranean area by a notch without a corresponding abrasional platform. This seems an over generalization, however, in view of well-developed platforms in Pleistocene limestones of aeolian (aeolianite) or marine (calcarenite) origin. For the latter case in northern Egypt, see K. W. Butzer, "Quaternary Stratigraphy and Climate in the Near East," *Bonner Geographische Abhandlungen*, Vol. 24 (1958), pp. 37–38. Similarly, the calcareous deposits of the limestone alga *Tenarea tortuosa*, described by J. M. Pérès and J. Picard ("Les corniches calcaires d'origine biologique en Méditérranée occidentale," *Recueil Travaux Station Marine Endoume*, Marseille, Vol. 4 [1952], 34 pp.) for the Provence and Languedoc coasts, cannot be considered a characteristic Mediterranean feature. Such deposits are generally absent on the coasts of the Balearic Islands.

[15] See the data compiled by R. W. Fairbridge, "Eustatic changes in sea-level," *Physics and Chemistry of the Earth*, Vol. 4 (1961), pp. 99–184. Many of these materials are of dubious value and the assemblage shows a lack of critical evaluation. But broad lines of repeated glacial-eustatic fluctuations of sea level in an 8 m. range do seem to emerge for the last 6,000 years. In a more specific way some of these fluctuations from about -4 m. to +3–5 m. have been recognized by detailed work in the Mediterranean area (D. Hafemann, "Die Frage des eustatischen Meeresspiegel-anstieges in historischer Zeit," *Abhandlungen*, Deutscher Geographentag, Berlin 1959 [Wiesbaden, 1960], pp. 221–231; K. W. Butzer and J. Cuerda, "Nuevos yacimientos marinos cuaternarios de las Baleares," *Notas y Communicaciones*, Instituto Geológico y Minero de España [1962b], 60 pp., in press).

[16] See K. O. Emery, "Marine solution basins," *Journal of Geology*, Vol. 54 (1946), pp. 209–228.

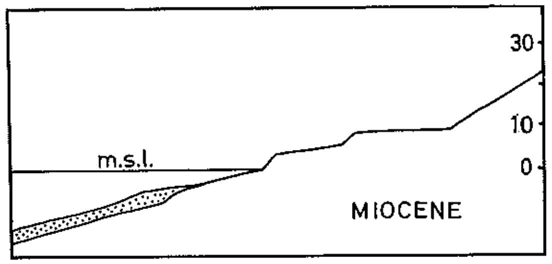

FIG. 4. Profile of a nip coast at Estanyol, west of Rapitá. Vertical exaggeration 10×. Note the older benches.

Nip Coasts

Less conspicuous coastal forms, consisting of a nip incised into a gently sloping bedrock surface, are common along many of the shallow-water coasts of Majorca. The nip face or cliff many be about 0.5 to 2 m. high, and the gradient of the shelf, as well as of the land surface beyond the nip, is in the order of 0.5 to 1 per cent (Figs. 4, 5).

This nip-coastal type has a surprisingly well-developed, shallow beach platform, which extends with little topographic variation up to 10 km. out to sea. Bedrock varies from cemented Pleistocene (continental or marine) conglomerates, siltstones, and aeolianites to Miocene limestones and calcarenites. However, there is no difference in coastal evolution corresponding to Pleistocene or Miocene facies. Except in areas of ancient conglomerates, the shelf is covered by 10 cm. or more of coarse sand. These lime sands are largely derived from mechanical disintegration of the rich bivalve and less plentiful gastropod fauna inhabiting the littoral zone.

Storm waves break more than 1 km. offshore, although moderate waves may break less than 100 m. away from the nip zone. It is difficult to determine whether rare storm-wave action or considerably more frequent rough seas of moderate wave height and length is more significant in coastline sculpture. When waves break immediately offshore they strike the nip zone as horizontal translational waves, whose erosive force is generally greater than that of waves striking a cliff coast in deep water. (The latter are diminished in their effectiveness by standing waves produced by reflection.) This appears to be one major explanation why the nip coast platforms are better developed than those of cliff coasts cut into identical bedrock. Another explanation involves the longer preservation of slightly higher and lower-lying platforms along a coast of gentle gradient, for the undercutting which may destroy higher terraces above a cliff coast is largely absent on such gently sloping nip coasts. Accordingly, modern sea level coincides quite closely with that of one or more nearby Pleistocene shorelines, and the platforms are essentially the sum of several periods of wave action.

FIG. 5. Nip coast near Rapitá. The scattered boulders are occasionally moved during storms.

Aeolian mantles, without great morphological significance, have accumulated up to 1 km. inland, where coasts are cut into Pleistocene aeolianites. These aeolian features will be discussed below.

Shingle-Beach Coasts

A number of rocky coasts of very gentle slopes, and shallow waters offshore, do not have a nip zone in the sense described above. The "cliff" is limited to a small step about 10–40 cm. high. Coarse blocks and other marine eroded detritus are thrown up and accumulate as a shingle beach in the rear (Fig. 6). This depositional activity of storm waves is limited to areas of Pleistocene bedrock where the direct impact of wave shock is only moderately effective. Other characteristics of these shingle-beach coasts are identical to those of the nip coasts outlined above.

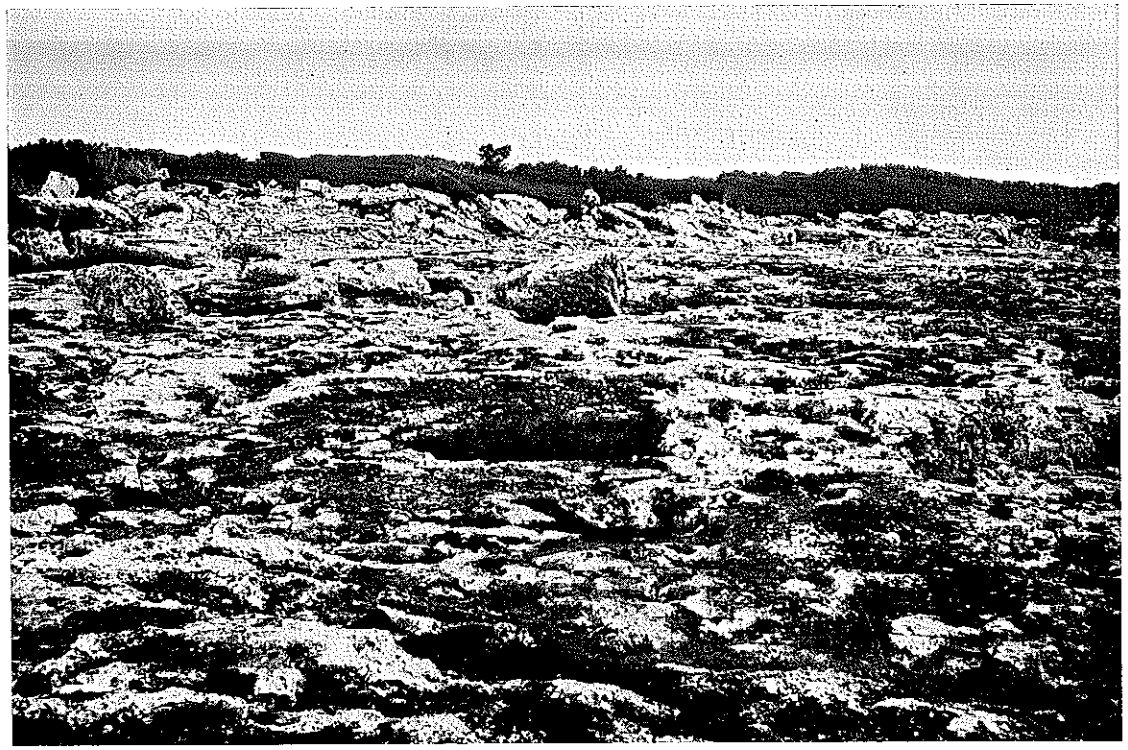

FIG. 6. Tyrrhenian shingle beach near Cala d'Or. The top of the platform in the foreground is at + 12.5 m. above and 50 m. inland from the modern coast. The vegetation beyond the shingle beach shows wind deformation.

Beach-Ridge Coasts

Shorelines of sandy, shallow-water coasts[17] have similar offshore characteristics, as have the rocky variety, although deposition now completely outweighs erosion in the immediate beach zone. Shelf and inland gradients are similar, but the "cliff" is replaced by a sloping surface of beach sand, and the shingle beach by a ridge of semi-aeolian lime sand (Figs. 7, 8). The coarse beach sands form a slope of 8–12 per cent about 20 m. above and below the watermark. Fossiliferous deposits

[17] Known in Mallorquin as *platjas* (Castilian *playa* = beach) and *arenals* (sand surface).

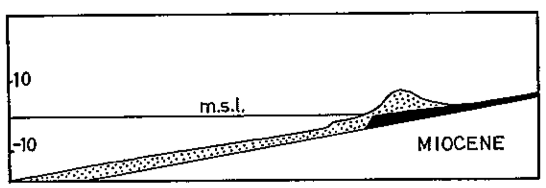

FIG. 7. Profile of a beach-ridge coast at Arenal de la Rapitá. Black = consolidated Pleistocene silts. The Miocene surface is inferred from indirect evidence. Vertical exaggeration 20×.

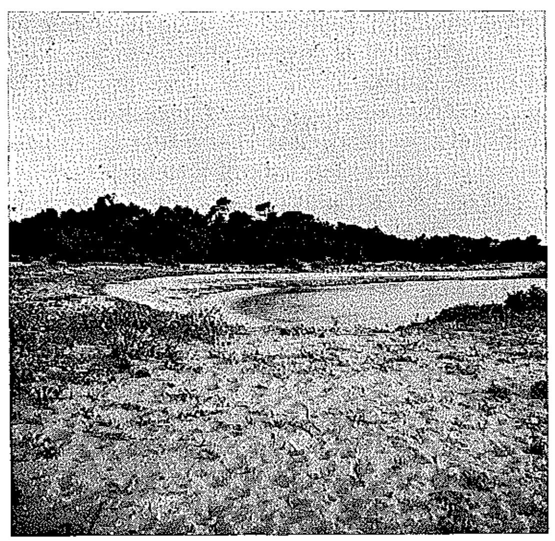

FIG. 8. Beach-ridge coast west of Colonia de Sant Jordi. A semi-aeolian ridge is conspicuous at the edge of the pine forest. The irregular dark embankments just above the watermark are of dead algae.

FIG. 9. Bar-and-lagoon coast in Cala Mondragó. Miocene limestone is exposed to the right of the drowned torrent valley, and sub-recent dunes veneer Miocene bedrock in the left background.

of this type are often preserved on Pleistocene beaches.

The beach is backed by a low ridge of subdued dunal topography, averaging 3–10 m. in height. Bedding shows alternations of water stratification from times of high seas and either inconspicuous stratification or topset or cross-bedding from the intervening periods of aeolian accumulation. This sub-aerial beach ridge is very frequently followed by a complex of littoral dunes, which extend as far as 2 km. inland. In other instances, coastal lagoons or swamps lie immediately behind the beach ridge or in the rear of the littoral dunes. However, such lagoons are not part of a genetic offshore-bar-and-lagoon or "emerged" coast. On the contrary, as is outlined below, they are caused by marine transgressions of both Pleistocene and Recent date.

Bar-and-Lagoon Coasts

A last, highly localized coastal type occurs in well-developed open *calas* (drowned valleys) of the southeastern coast of Majorca. It is a miniature and special form of the offshore-bar-and-lagoon coast represented by a shallow marine-deposited sand bar cutting off a brackish or salt water lagoon in the interior parts of such bays. Slopes at the watermark average 2–5 per cent, or a little less than that of the beach-ridge coasts (Fig. 9). Like the beach ridges, the marine bars are composed partly of clastic products of limestone disintegration, and partly of finely ground organic rubble. About 97–99.5 per cent of this material is calcareous, and about 80–90 per cent of the grains are in the 0.06–2.0 mm. size fraction. The lagoonal waters are caused largely by seepage of sea water, although a weak subterranean inflow of fresh or brackish water is noticeable at the mouths of the larger, dry-stream valleys.

This coastal type is produced by direct onshore wave action rather than centrifugal currents. Since the –5 m. isobath is located 100–200 m. offshore, higher waves break at a distance of about 100 m., and translational waves pound the sand bars if the wind direction is right. The great quantity of lime sand present in such inlets is largely a product of the abundant bivalve fauna harbored in the shallow and otherwise calm waters.

REGIONAL SURVEY OF COASTAL TYPES

The preceding description of coastal landforms gives only limited consideration to overall evolution. It seems particularly important in coastal geomorphology to treat basic units and concepts empirically and descriptively, and not "put the cart before the horse," as Guilcher has characterized the common usage of genetic terminology in the classification of coastal types.[18]

The distribution of coastal types for Majorca can be summarized approximately as follows for the areas of Cenozoic bedrock (Fig. 1):

(1) *Cliff coasts*, including (A) "high cliffs" (over 30 m.): Porto Christo to Porto Colom, Cala Llombards to Cala Marmóls, Cala Pí to Cap Enderrocat, Palma to Santa Ponsa; (B) "medium cliffs" (15 to 30 m.): the area northeast of Porto Christo, Cala d'Or to Cala Llombards, Cala Marmóls to Cap Salines, and the Cala Pí area; (C) "low cliffs" (3–15 m.): Porto Colom to Cala d'Or, Punta Plana to near Cala Pí, Cap Enderrocat to Es Arenal.

(2) *Nip coasts*: sections of the eastern Bahia de Alcudia and the Bahia de Artá, Rapitá to Punta Plana, and Ca'n Pastilla to Palma.

(3) *Shingle-beach coasts*: sections of the Cap Salines to Sant Jordi coasts.

(4) *Beach-ridge coasts*: parts of the bays of Pollensa, Alcudia, and Artá, most of the littoral from Cap Salines to Rapitá, and the sector from Es Arenal to Ca'n Pastilla.

(5) *Bar-and-lagoon* coasts: located in a number of *calas* of the southeastern and eastern coast.

Employing this information, the existing Majorcan coastlines in horizontal strata and of identical petrological properties can be classified in terms of relief, shelf-gradient, and ratio of erosion to deposition at the watermark (Fig. 10). This more general classification avoids certain unnecessary genetic connotations, such as emergence or submergence.

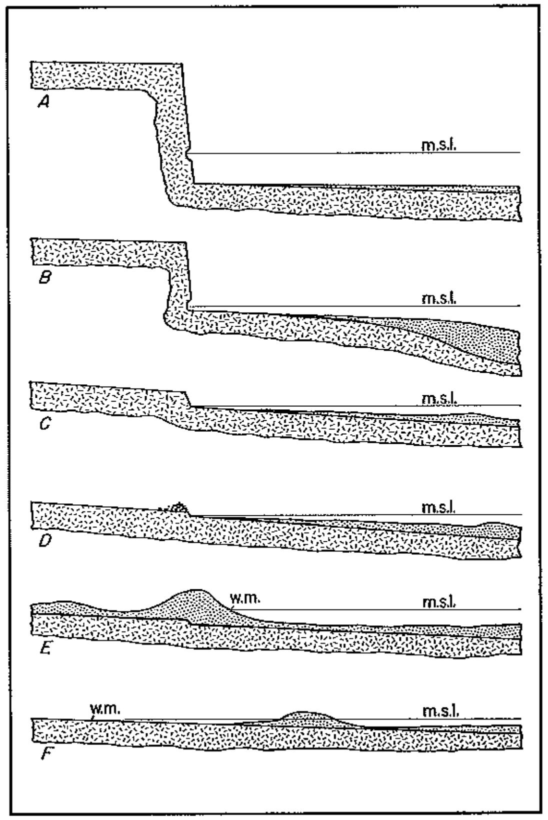

FIG. 10. Classification of Majorcan coastal profiles. From top to bottom these profiles show (A) medium to high cliff coast, (B) low cliff coast, (C) nip coast, (D) shingle-beach coast, (E) beach-ridge coast, and (F) bar-and-lagoon coast. wm = watermark.

Given comparatively uniform bedrock characteristics, it may indeed be possible to classify coasts accurately on the basis of morphometric criteria. A descriptive classification of this type is not, however, designed to answer the genetic problems presented by the Majorcan coasts. In the subsequent sections aeolian deposits are considered, and the morphological significance of successive Pleistocene sea levels is assessed.

RECENT LITTORAL DUNES

Widespread coastal dunes and aeolian mantles appear to be associated with the various types of shallow-water coasts. They occur in association with nip and shingle-beach coasts cut into Pleistocene aeolianites, invariably with the beach-ridge coasts, and frequently

[18] Guilcher, *op. cit.* (1954), p. 41.

with the bar-and-lagoon types as well (Fig. 9). Such aeolian deposits are of two major types.

Most frequent are amorphous sheets of sand accumulated on smooth ground, in hollows, or behind more varied topography. Any dune-line morphology is caused here by the subsurface material, which is frequently formed of fossil Pleistocene dunes. These sheets average 1–2 m. in thickness, and occur in association with each of the above-mentioned coastal types. They are all stabilized by woodland or grassy-herbaceous vegetation or are in furrows. A xerorendzina soil type is characteristic. The light brown A-horizon attains an average depth of 40–65 cm., and is of *moder* to *mulliform-moder* humus type with a fine granular structure. The clay fraction content is only about twice that of the underlying C_2-horizons, i.e., about 5–10 per cent. This soil type proves that the aeolian mantles are essentially "fossil."[19]

Limited to the beach ridge and bar-and-lagoon coasts are another class of aeolian deposits, with true dunal morphology. Such dunes usually follow the shoreline in irregular, parallel ridges 2 to 10 m. high, although massive dunes with older cores may attain 15–25 m. Sand sheets are usually attached to littoral dunes. Halophile plants are the only colonists in the area still affected by occasional sea spray, whereas the crests and lees of the dunes are under woodland or maquis scrub.[20] Although the dunes are apparently fixed, deposition and internal transport of sand still persists, as is shown by occasional half-buried pines or junipers. Soil horizons are limited to immature rendzina (A) horizons under a litter of needles.

Both classes of deposits are unstratified and have a grain-size texture almost identical to that of modern beach sand. On the average, 80 per cent (by weight) of these 95–98 per cent calcareous sands are in the 0.2–2.0 mm. size class. About one-half of the rare grains of quartz are windworn, and about 15 per cent show clear evidence of water action. Wind-polished or wind-scoured molluskan fragments or intact shells are frequent, and numerous foraminifera are visible in thin section. The derivation of this material from nearby beaches is obvious.

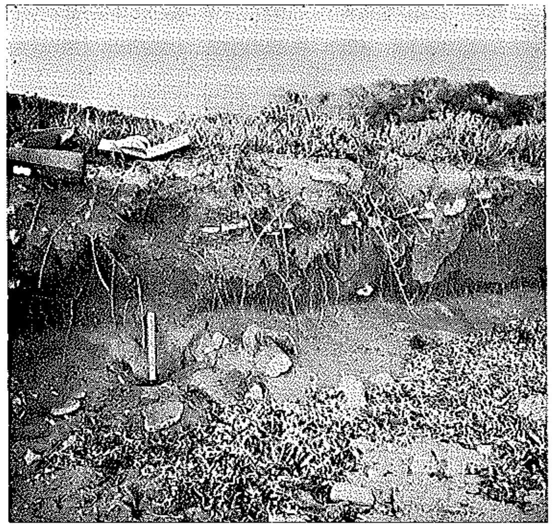

FIG. 11. "Fossil" Recent littoral dune near Platja del Trenc. Unweathered dune material is exposed to the rear of hammer. Roman potsherds were found over a horizontal disconformity (not visible in this view) a little below the level of the stratified shingle.

The absence of any exposed beach sands along the nip or shingle-beach coasts appears paradoxical in view of the nearby aeolian beds. Even along the beach-ridge coasts the amount of sand available for deflation is limited, for moderately spaced woody halophiles take over almost immediately where the sands are no longer more or less permanently wet. This lack of an adequate sand source today, further confirms the fossil character of the sand sheets and most of the dunes. Archaeological evidence of chronological value is available at one site near the Platja del Trenc, on the southern coast, where the following section is exposed (cf. Fig. 11):

(A) 40 cm. (base not seen) of unweathered, medium grained, very pale brown (10 YR 8/3 according to the Munsell Color Code) aeolian sand.

[19] "Fossil" is here used to express the idea that landforms may represent another climatic or topographic environment and consequently not be products of contemporary processes. Fossil landforms need not imply burial. There seems to be no generally accepted English term to express the German *vorzeitlich* or *Vorzeitsform*.

[20] Tree growth on the various aeolian beds described is largely confined to stands of aleppo pine (*Pinus halepensis*) or juniper (*Juniperus phoenicea*) without undergrowth. Most important component of the maquis scrub or dunes is the pistacchio bush (*Pistacia lentiscus*) while frequent grassy vegetation on sand sheets consists of the wire grass (*Cynodon dactylon*).

(B) 30 cm. of weathered brown (10 YR 5–6/3) sand with rendzina *moder* humus. This soil is truncated by a disconformity on which numerous water-laid pottery sherds were found.

(C) 35 cm. of weathered aeolian sand of light brown (10 YR 6/3) color, rich *moder* humus, and marine deposited beach shingle (angular detritus of Pleistocene sediments). Surface under herbaceous vegetation.

The pottery sets an upper limit to at least 1 m. of littoral sand deposition, and may give some approximation for the later, modestly developed horizon. The sherds comprise fragments of several vessels and have been dated as Roman, probably Republican, age,[21] i.e., presumably from the last century B.C. It is known that Mediterranean sea level was at least 2 to 3 m. lower during an eustatic regression in Graeco-Roman times.[22] Such a regression would have exposed a considerable area of shelf and littoral sediments to deflation along the shallow-water coasts. With the possible exception of some of the littoral dunes accompanying the beach-ridge coasts, the littoral aeolian deposits are thus not functionally related to coastal types. Instead they are mainly regressional dunes or aeolianites as described by R. W. Sayles.[23]

The fact that the Recent littoral-aeolian features of the Balearic Islands are largely "fossil," may have wider significance in the Mediterranean area. This suggestion should in no way cast doubt on the significance of aeolian processes at the shoreline. Nevertheless, it may be useful to reassess some of the assumptions widely made with reference to coastal dunes.[24]

PLEISTOCENE LITTORAL DUNES

Pleistocene regressional dunes or aeolianite deposits are closely analogous to the Recent deposits described above. However, in proportion to the amplitude of glacial regressions (about –100 m.), the Pleistocene dunes are better developed and extend 10 km. or more inland. Such fossil dunes are a characteristic subtropical littoral facies, and they have recently been described in detail from a morphological, sedimentological, and palaeoclimatic perspective.[25]

Aeolianites developed in typical aeolian facies may be found as (1) steeply inclined, foreset-bedded dunes embanked against coastal cliffs with a typical seaward dip of 40–60 per cent and landward dip of 60–80 per cent (Fig. 12); (2) free longitudinal dunes of subdued morphology on coastal plains, where they may form littoral cordons. The local relief of one dunal generation may be in the order of 5–25 m., while slopes are gentle, and seldom exceed 25 per cent; (3) undulating sand sheets with longitudinal affinities to subdued dunal topography, which are concentrated in the face and lee of minor surface irregularities. These sheets are found beyond the rims of coastal cliffs and well inland on coastal plains or level uplands. However, the morphology is still controlled by bedrock.

Grain-size distributions of the typical coastal facies of aeolianite include a 70 per cent coarse sand (0.2–2.0 mm.) component, whereas in aeolianites of interior facies this proportion may be reduced to an average of 40 per cent. Clay and fine silt (0.002–0.006 mm.) components usually account for 5–15 per cent. Grain-size characteristics of *continental dunes* are quite distinct: coarse sand components are

[21] The pottery was kindly studied by a qualified specialist, Sr. D. G. Rosselló Bordoy, Director of the Provincial Museum of the Balearic Islands. His commentary (translated) is as follows: "Roman pottery of unprecise date, probably Republican according to the material and shape, not very clear due to lack of spouts and well defined handles." As Majorca was conquered by Rome in 123 B. C., a fair approximation in time is given.

[22] D. Hafemann, *op. cit.;* Fairbridge, *op. cit.;* and K. W. Butzer, "On the Pleistocene shore lines of Arabs' Gulf, Egypt," *Journal of Geology,* Vol. 68 (1960), pp. 626–637. Local evidence is also available on Formentera where a late Carthaginian or very early Roman (2nd or 1st century B.C.) sepulcher is cut into aeolianite *at the present watermark.*

[23] "Bermuda during the Ice Age," *Proceedings,* American Academy of Arts and Sciences, Vol. 66 (1931), pp. 382–467.

[24] See, for example, H. Louis, *Allgemeine Geomorphologie* (Berlin, 1960), p. 214.

[25] K. W. Butzer, "Climatic-geomorphologic interpretation of Pleistocene sediments in the Eurafrican subtropics," in F. C. Howell, ed., *African Ecology and Human Evolution, Viking Fund Publications in Anthropology,* 1962, in press. This publication contains two 1:50,000 surficial geology maps of typical aeolianite areas of southern Majorca. A simplified distribution map of aeolianites and Recent aeolian beds of southern Majorca is given in Figure 1 of Butzer and Cuerda, *op. cit.* (1962a).

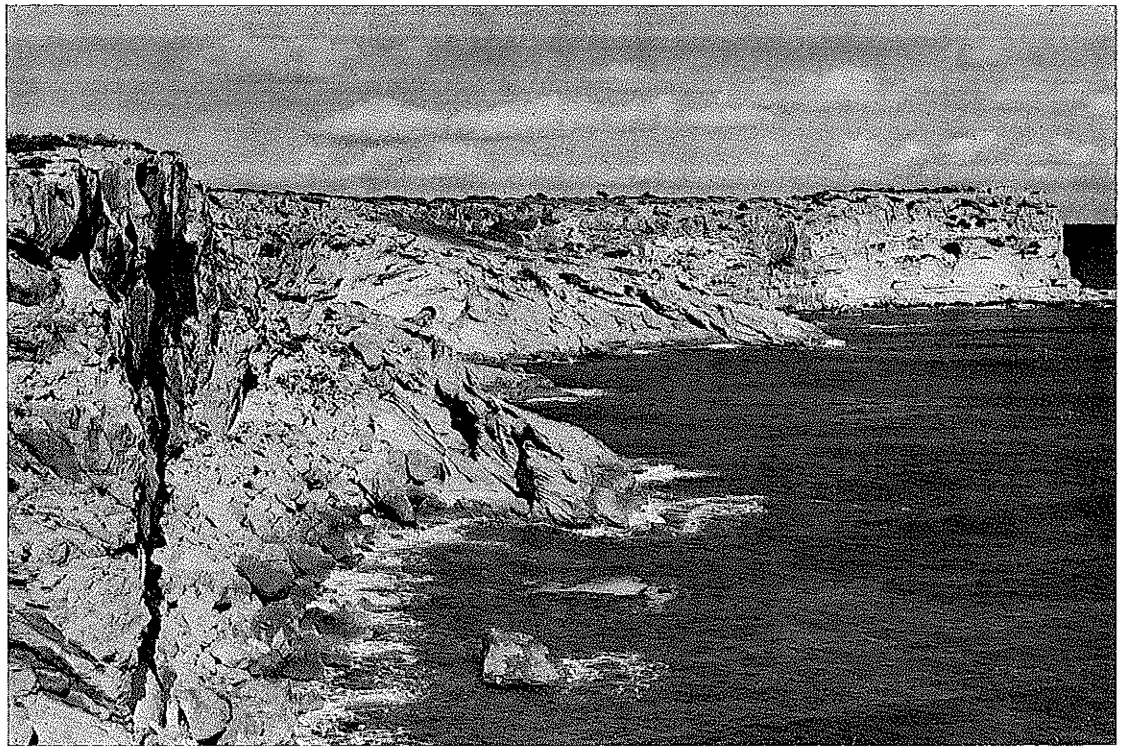

FIG. 12. Upper Pleistocene aeolianite in the foreground and center embanked at 18° to vertical limestone cliffs (Pta. d'es Baus). The low Tyrrhenian platform at the base of the headland (right background) is at + 3 m., and a sea-cave entrance is noticeable in the cliff face at + 17 m. nearby.

small, while medium sands (0.06–0.2 mm.) average 20–90 per cent (over double that of aeolianites), and there is an almost complete absence of any component under 0.003 mm. Littoral and continental dunes are quite distinct both morphologically and sedimentologically.

Three major aeolianite generations, each with several subdivisions, can be recognized on Majorca and some other Balearic Islands.[26] These fossil dunes can be fixed stratigraphically in the last three major regressional phases of the Mediterranean Sea, i.e., "Mindel," "Riss," and Würm in the conventional sense. However, they are no more a functional part of the respective Pleistocene shorelines than are the Recent littoral dunes in relation to modern sea level.

"FOSSIL" BEACHES

Pre-Tyrrhenian Platforms of the Upland Plain

Marine erosion has greatly modified the surface of the horizontal Miocene limestones of Majorca.[27] Marine platforms are frequent and are preserved as shallow, level hollows, or flat plains bounded by low steplike echelons running roughly parallel to the coasts. The underlying Miocene strata have been planed off to slopes of less than 1 per cent. Veneers of colluvial *terra rossa* sediments usually mask the bedrock and, along with aeolianite mantles, often obscure specific littoral features, such as nip zones or low cliffs with former sea caves. Even where these common shoreline features can no longer be found, the extensive flat platforms must be of marine origin, since no other gradational agent is capable of producing such planation. These surfaces are sufficiently conspicuous in the cultural landscape to merit the local name of *camp*.[28]

[26] Butzer and Cuerda, *op. cit.* (1962a, b).

[27] This was first recognized in a general way by J. Carandell (*op. cit.*), who visited the upland plain briefly in 1926. His references are to visual impressions of the landscape and not to specific features, which can only be recognized and demonstrated by considerable patient field work. Solé (*op. cit.*) discounts Carandell's suggestions entirely.

[28] Mallorquin for the Castilian *campo* or field.

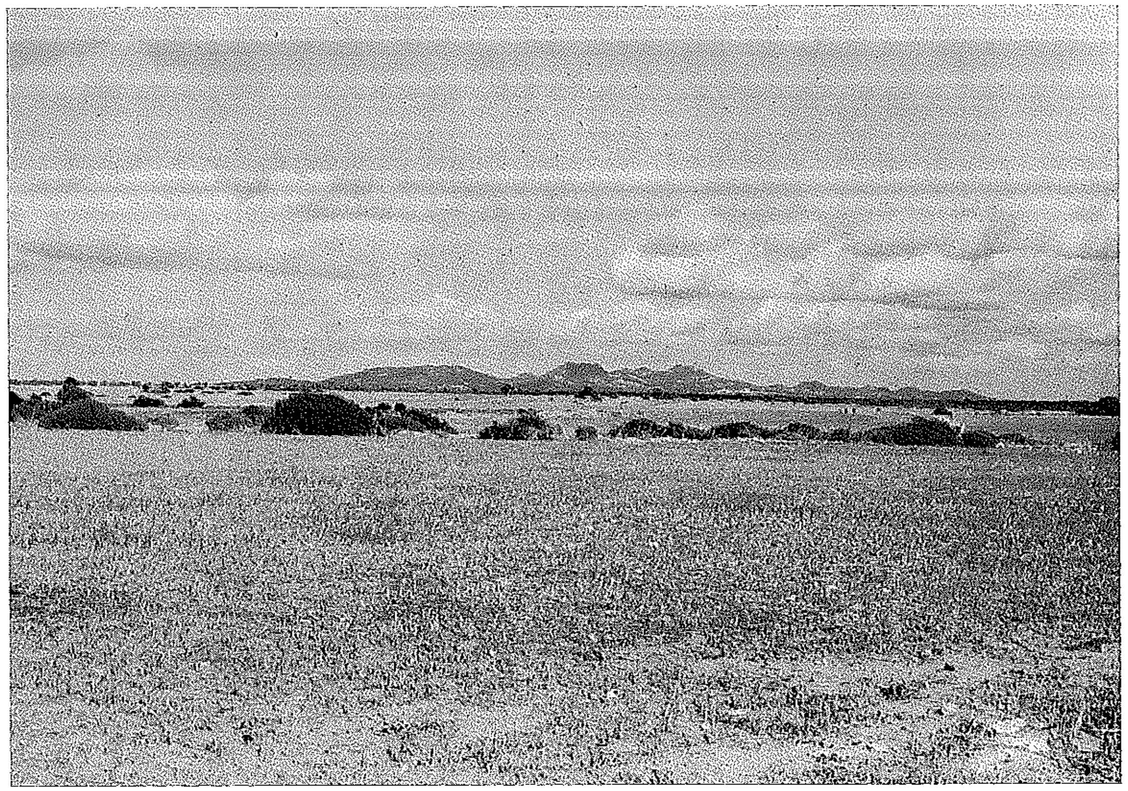

FIG. 13. Marine abrasional platform at 56–60 m. between Cala Llombards and Son Coves. The Sierra de Levante appears on horizon.

Such levels are observed regularly at 40–46 m., 58–60 m., 65–68 m., and 100–108 m.; they also occur sporadically between 70 and 95 m. The actual beach platform, with its somewhat greater slopes, can often be located at 2–4 m. above these flattish shelf or marine platforms. In many instances, classical coastal features enable precise determinations of former sea-level. On this basis general shorelines can be identified at 48–50 m.,[29] 60–62 m., 70–72 m., and about 110 m. (Figs. 13, 14). The age of these shorelines is difficult to determine with precision. The youngest at 48–50 m. briefly antedates the major regressive complex preceding the Tyrrhenian I, and hence qualifies as pre-Mindel or pre-Elster in the conventional sense. Altimetrically, all of these shorelines fall into the range of the Early and Later Sicilian,[30] i.e., the Basal Pleistocene.

The widespread occurrence of marine sculptured surfaces on the basic structural platform of Miocene limestones, and the extensive veneers of fossil littoral dunes, illustrate the dominance of marine-littoral processes in modifying the landscape of the Cenozoic bedrock of Majorca (Fig. 15). In fact, fluvial features are merely incidental details in a morphology of coastal landforms created during the time span of the Pleistocene.

Origin of the Lowland Plains

Three major lowland plains are found in the regions of Palma, Alcudia, and Campos. Each of these plains, resting on Middle Miocene bedrock, occur at elevations 50–80 m. below the general level of the surrounding upland of Cenozoic strata. The question arises whether these features are produced by tectonic de-

[29] See also the stratigraphic and palaeontologic evidence for this shoreline in Butzer and Cuerda, *op. cit.* (1962b).

[30] Cf. F. E. Zeuner, "Pleistocene shore-lines," *Geologische Rundschau,* Vol. 40 (1952), pp. 39–50; Butzer, *op. cit.* (1958), pp. 26–42; and Butzer, "Das Wenner-Gren Symposium über Quartärstratigraphie im Mittelmeerraum, Burg Wartenstein, 1960," *Eiszeitalter und Gegenwart,* Vol. 13 (1962), in press.

FIG. 14. 50 m. beach platform and cliff of Morro de Son Coves. Note the sea-cave entrance to the left of the tree.

formation or exogenic forces. A cover of alluvial deposits, generally about 5 m. in depth, but also developed to depths of 100 m. below the surface, obscures the bedrock in most areas. The Campos Basin, studied in 1960, may be considered as a type example.

This basin consists of a rectangular area of about 7 by 12 km., which is bounded by a gently sloping upland to the northwest, and a prominent escarpment of some 60 m. to the north and southeast. The floor generally has a slope of less than 1 per cent, and consists of planed bedrock under a veneer of several meters of fluvial silts or gravels. Occupied by a lagoon in its lowest parts, it is separated from the sea by a belt of littoral dunes, both of Pleistocene and Recent age. This gradient persists offshore for more than 10 km.[31]

Tectonic downwarping of the basin can be excluded, since the underlying Miocene strata are apparently horizontal and undeformed,[32] and those exposed at the escarpment are cut in steps, obviously by gradational processes. The question remains whether marine abrasion or stream erosion of Pliocene or Pleistocene date was responsible for the formation of the basin. Stream gradation cannot be excluded automatically, because of the presence of a well-developed Pleistocene river network (reconstructed by mapping of gravels vs. silts). Torrent valleys run into the basin in radial pattern, but the 0.8 per cent gradients would not give the ancient watercourses sufficient energy to erode an almost flat lowland plain of such dimensions.

Although no marine beds have yet been found, all of the features can be explained adequately by marine erosion. The basin floor can be interpreted as an epicontinental platform, the northeastern and southeasterly escarpment as a great marine cliff, the steps of the escarpment as temporary beach platforms, and the caves in it as marine grottoes at the notch mark of stages of higher sea level (Fig. 16). These suggestions are supported by unequivocal evidence in the form of massive aeolianites, which extend semi-continuously around the escarpment base and occur sporadically on the basin floor, where they are older than the alluvial deposits. These dunes have a coarse

[31] 0.6–0.8 per cent slopes are generally characteristic on both the southwestern and northeastern coastal quadrants of Majorca.

[32] Comment is necessary on the mineral well of San Juan, located near the southeastern edge of the basin. The waters have a temperature of 38–47°C., which is proportional to the height of the water head. The well is 380 m. distant from the Salobrar lagoon and 2.75 km. from the coast, yet the level of the water head fluctuates with sea level according to storm periods or calm sea low water. In other words, it behaves like the normal ground-water table, which is also more or less at sea level here. The analysis of R. Codina Länglin (*Aqua minero termal clorurada-sódica de San Juan de Campos.* [Palma, 1894], 52 pp.) includes the following comparison of mineral waters with sea water:

minerals (grams per liter)	Local sea water	Mineral water
bicarbonates, silicates, alcalines	0.04318	0.15584
potassium chloride	0.14106	0.12061
sodium chloride	24.74013	21.09186
calcium chloride	0.00428	0.00353
magnesium chloride	3.69761	3.30549
sodium sulfate	10.10025	0.98419
calcium sulfate	2.15502	1.98707
magnesium sulfate	0.98373	0.79662
iodides, bromides, and other salts	traces	0.02122
Total	32.86526	28.46243

The mineral waters must be derived from salty marine sediments at great depth (local geothermal gradient unknown), i.e., within the folded and faulted pre-Cenozoic basement of Majorca. They probably move upward from the folded series by a joint or fissure in the overlying horizontal limestone strata. Here they are not fully isolated from the standing, rather saline water table and fluctuate along with it. The fountain carries no implication of post-Lower Miocene tectonics.

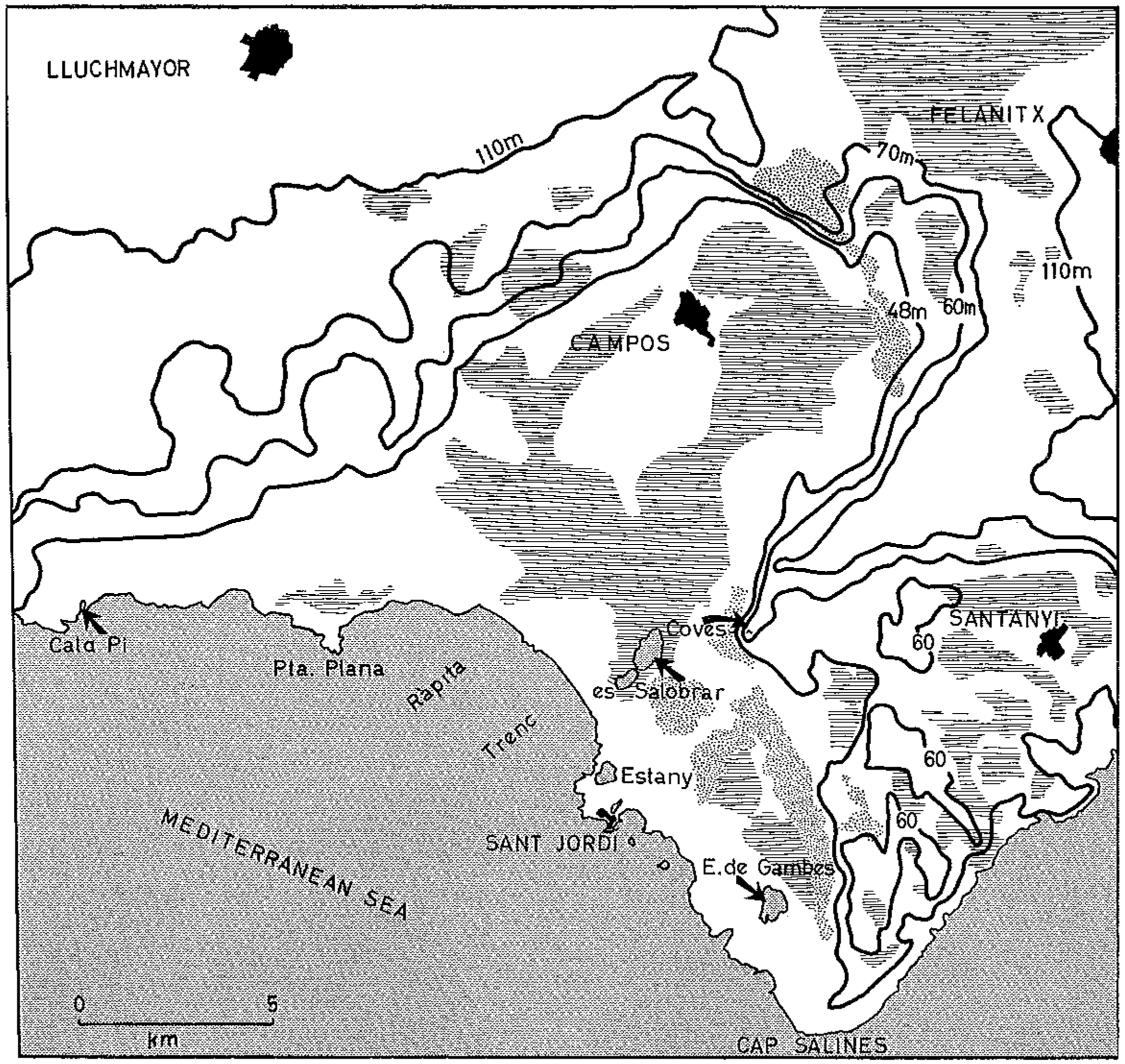

FIG. 15. Location of pre-Tyrrhenian shorelines on southern Majorca. Levels are only approximate. The shaded areas represent marine platforms and hatched areas indicate locations of pre-Tyrrhenian aeolianites. (Platforms and aeolianites were not mapped west of the longitude of Lluchmayor.)

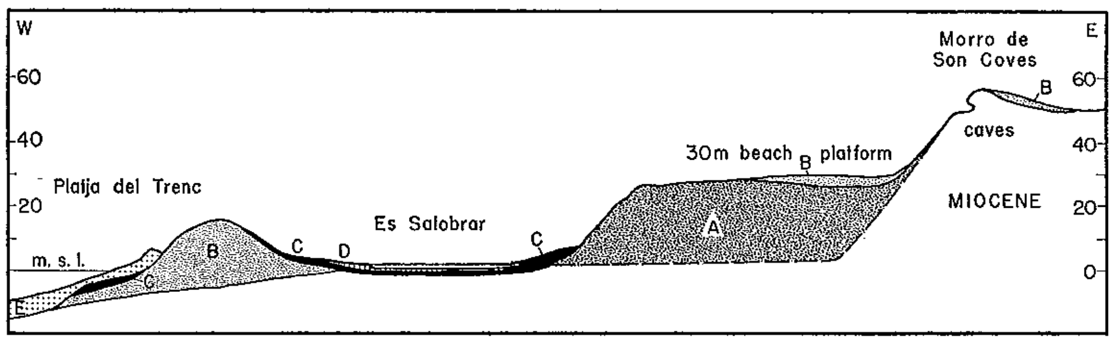

FIG. 16. Generalized profile from Son Coves to Platja del Trenc. A = pre-Tyrrhenian aeolianite, B = aeolianite of penultimate regression, C = silts of Würm regression, D = Recent colluvium, E = modern beach deposits. Vertical exaggeration 20×.

grain size (at least 75 per cent are larger than 0.2 mm.), which precludes the possibility of transport over considerable distances. The peripheral aeolianite ridge (possibly about 20 m. thick) northwest of Campos is horizontally bedded between N 85° E and N 115° E. This permits a sole conclusion that the source area of deflated marine lime sands was north or landward of Campos. The highest flat Miocene shelf in the basin is at about 45 m. above the sea level and presumably corresponds to the 48–50 m. shoreline. The lack of notable cliff development on the northwestern flanks of the Campos Basin is readily explained by wind directions: only westerly winds could develop stormy seas in the former bay of Campos, and these would undercut the easterly and southerly flanks, where the aeolianites are also found.

Marine excavation is also responsible for the excavation of the lowland plains of Palma and Alcudia, although small synclines may be present at the foot of the Sierra Norte.[33]

Tyrrhenian Beaches

Numerous Pleistocene littoral forms are found in the immediate proximity of the modern coasts. In fact, such "fossil" features often form an integral part of contemporary littoral landforms. All of the coastal types outlined above seem to be present in the array of Middle and Upper Pleistocene shorelines, except possibly the bar-and-lagoon type. In areas of significant sedimentation, depositional forms are preserved. These have been surveyed for all of the undeformed coasts of the island.[34] Along the more rocky coasts, a wide variety of cliff, notch, and platform features testify to an interesting sea-level sequence. These erosional phenomena were studied in detail on the southeastern coast.

Wherever conditions of preservation are favorable, the elevated shoreline features indicated better development than the modern shoreline. Shoreline preservation is good within and at the entrance to drowned valleys and relatively poor on straight, steep-cliffed coasts. Where the cliffs of Miocene bedrock stand less than 20 m. above the sea, northeast of Porto Petro, only the lower and younger strand lines are preserved at the coast. In the areas of Pleistocene bedrock near Cap Salines, shorelines are poorly preserved but recognizable. The reason for poorer preservation is that subsequent erosion was much more effective in these softer sediments.

The sequence of high Tyrrhenian shorelines generally recognizable along the southeastern coast is as follows:

TABLE 1.—MARINE CHRONOLOGY OF THE TYRRHENIAN STAGES OF SOUTHERN MAJORCA[1]

Antepenultimate Regression (2 phases) ("Mindel")	
33–34 m.	Tyrrhenian I Complex
29–30 m.	
23–25 m.	
15.5–19 m.	
4– 5 m.	
Penultimate Regression (4 phases) ("Riss")	
10.5–12.5 m.	Tyrrhenian IIa
8– 9 m.	Tyrrhenian IIb
6– 7.5 m.	
2– 4 m.	
Minor Regression (Late "Eem" or very early Würm)	
0.5– 2.8 m.	Tyrrhenian III
Last Regression (3 phases) (Würm)	

[1] The detailed local evidence on which this table is based (i.e., marine erosional and depositional features, marine faunas, and sedimentological analysis of complex stratigraphic sections) can not be described at length in a general paper. For further discussion see K. W. Butzer and J. Cuerda, "Nota preliminar sobre la estratigrafia y la paleontologia del cuaternario marino del Sur y SE de la Isla de Mallorca," *Boletin*, Sociedad de Historia natural de Baleares, 6 (1961), pp. 9–29; *idem*, "Coastal Stratigraphy of Southern Mallorca and Its Implications for the Pleistocene Chronology of the Mediterranean Sea, *Journal of Geology*, Vol. 70 (1962), in press; and *idem*, "Nuevos yacimientos marinos cuaternarios de las Baleares," *Notas y Communicaciones*, Instituto Geológico y Minero de España, 1962, in press.

The values were obtained by measurement (± 10 cm.) of median notch altitudes (or where absent, of cliff bases) at over 50 localities. Much of the data is confirmed by palaeontological study of marine sediments.[35] Chronological order is ascertained from com-

[33] Unpublished information collected and evaluated by Sr. Muntaner Darder from a large number of deep bore-profiles. However, Muntaner does not assume downwarping in the central and southern parts of the *llanos* of Palma and Alcudia, as does Solé (*op. cit.*). This does not discredit a primary marine origin for the larger morphological entities.

[34] Butzer and Cuerda, *op. cit.* (1962b).

[35] See K. W. Butzer and J. Cuerda, "Nota preliminar sobre la estratigrafia y la paleontologia del cuaternario marino del Sur y SE de la Isla de Mallorca," *Boletin*, Sociedad de Historia natural de Baleares, Vol. 6 (1961), pp. 9–29; and Butzer and Cuerda, *op. cit.* (1962a, b).

plex sedimentary sequences of intercalated littoral-continental and marine sediments, together with corresponding marine erosional features. Shingle beaches, shorelines cut into Pleistocene sediments without horizontal bedding or into homogeneous Miocene calcarenites, and fossiliferous beds with distinctly littoral faunas on limestone benches are quite frequent. They make it possible to eliminate the dangers involved in interpretations of limestone beach platforms formed upon horizontal strata of differing resistance, e.g., algal limestones of high, calcarenite of moderate, and chalk or chalky-marl strata of low resistance. Generally, this convergence of the incipient notch with bedrock structure was found to be only a minor source of error. Throughout the study, the norms proposed by the Subcommission on Mediterranean Shorelines of the International Quaternary Association (INQUA) were adhered to.[36]

A student of glacio-eustasy might raise objections that this number of shoreline levels seems incredible, since a comparable number of levels are unknown elsewhere, or that there is no evidence for so many climatic oscillations. The Tyrrhenian II–III complex may be presumed to represent the Last Interglacial, and possibly the incipient stages of the Last Glaciation. The fact that the Tyrrhenian II levels ("Monastirian" in the obsolete terminology) all lie in the lower part of the 5–20 m. elevation range generally adopted for that stage,[37] indicate that epeirogenic movements are insignificant if present at all. An explanation for the multitude of levels is that no attempt at simplification is made: distinct stages present at any one locality are considered separately and not collectively, as is all too often done. Again, intimate acquaintance with local topography permits greater detail than sweeping coastal surveys carried out on the basis of topographic maps and control checks.[38] The complex nature of local climatic fluctuations[39] illustrates the oversimplification usually applied to palaeo-climatological analysis.

Nevertheless, brief reference may be made to high post-Pleistocene sea levels. These can be identified at +4 and at +2 m. Both can be found in excellent post-Pleistocene stratigraphic context, incised into regressional dunes of the last glacial age.[40] Neither of these two levels was of sufficiently great duration to be recorded in resistant Miocene bedrock other than at the mouths of some inlets. The younger, +2 m. stage was repeated, once in prehistoric times and again during the post-Roman period. Fauna collected from associated deposits is extremely poor and contains no thermophile species, as do the Tyrrhenian associations.

The Coastal Lagoons

Reference has already been made to lagoons or coastal swamps lying inland of the beach-ridge coasts. The three largest swamp areas of this kind are located in the three lowland plains: the *Prat*[41] of the Palma plain (Fig. 1), the Salobrar lagoon of the Campos Basin (Fig. 15), and the Albufera swamp of the plain of Alcudia (Fig. 1). Small ponds or *estanys*[42] are also found at and a little southeast of Sant Jordi (Fig. 15), at Magaluf, west of Palma, and adjacent to the bay of Pollensa. In each case, the waters are largely derived from the sea by seepage via subterranean ducts of spring dimensions.

Investigation of these areas is hampered by a lack of accessible data—bore profiles are not available and cisterns or wells are lined with rock or cement. Ditch or canal sections

[36] F. E. Zeuner, "Criteria for the determination of mean sea-level for Pleistocene shore-line features" mimeographed notes for the INQUA Subcommission on Mediterranean shorelines.

[37] Zeuner, *op. cit.* (1952); Butzer, *op. cit.* (1958, 1960); E. Bonifay and P. Mars, "Le tyrrhénien dans le cadre de la chronologie quaternaire méditerranéenne," *Bulletin*, Société géologique de France (1959), pp. 62–78; G. Castany and F. Ottmann, "Le Quaternaire marin de la Méditerranée occidentale," *Révue de Géographie physique et Géologie dynamique*, Vol. 2 (1957), pp. 46–55.

[38] As an example, see the detailed critique of existing work on the Arabs' Gulf sequence of Egypt in Butzer, *op. cit.* (1960).

[39] Butzer and Cuerda, *op. cit.* (1962a).

[40] Butzer and Cuerda, *op. cit.* (1962b).

[41] The *Prat* (Mallorquin for the Castilian *pradera* = meadow) still had some 9 sq. km. of open water during the 12th century A.D. according to a 1:135,000 surficial geology map of A. Muntaner, *op. cit.* The area was systematically drained by private and organized enterprise during the period 1815–1850. See V. Rosselló, La huerta de Levante en Palma de Mallorca," *Estudios geográficos*, Vol. 20 (1959), pp. 523–578. Open waters are now present only in a few small salines.

[42] Mallorquin for *estanque*.

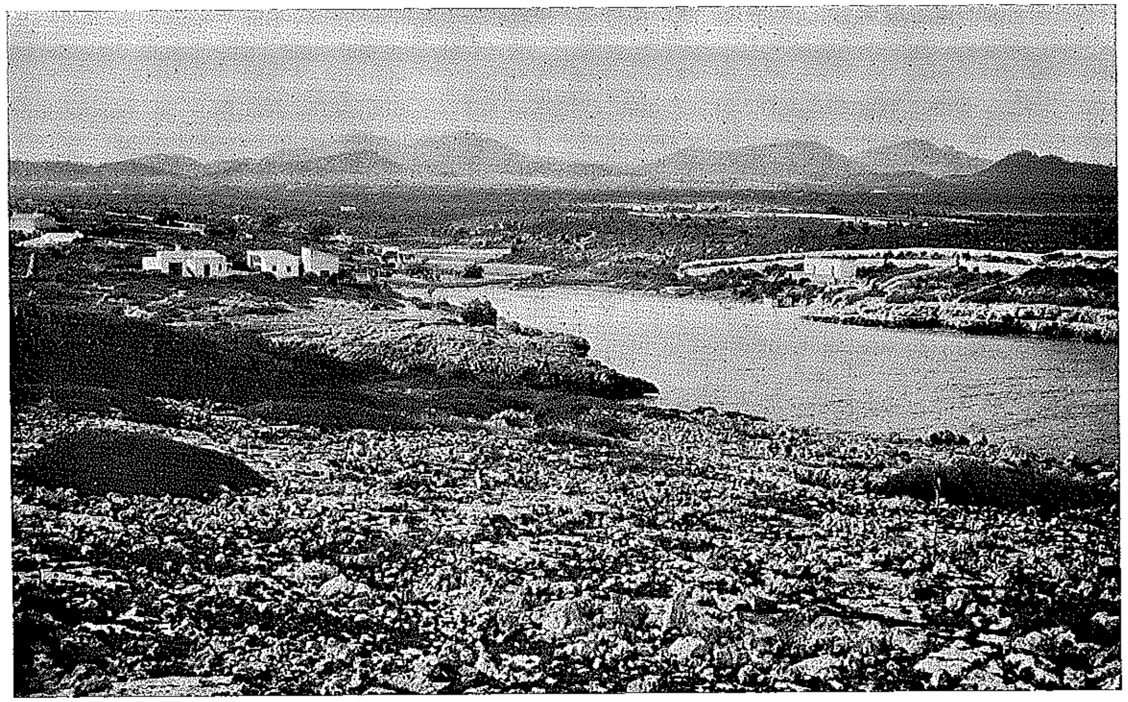

FIG. 17. A shallow cala (Cala Marsal) immediately south of Pto. Colom. The marine sculptured Miocene strata extend to the foot of the Sierra de Levante.

do, however, expose instructive sections in many of these lagoons. In the *Prat* of Palma rendzina-type soils, developed in about 30 cm. of mixed silts, overlie fossiliferous Tyrrhenian II/III beach deposits. In the Magaluf area, about 30 cm. of wash (silty sands) overlies a Tyrrhenian beach conglomerate. In the Salobrar lagoon about 50 cm. of Recent lime sands (with small, lagoonal forms of *Cardium edule*) or wash derived from aeolian deposition overlie marine Tyrrhenian III or continental silts of the last Glacial period. Such silts also form the floor of the Estany de Ses Gambes near Sant Jordi. Lastly, sterile lime sands overlie fossiliferous calcarenite of Tyrrhenian age in the Albufera of Alcudia.

These data show that in each case the coastal lagoons represent former bays of the Mediterranean Sea, which are not of Recent but of Last Interglacial age. Separated from the sea by Pleistocene or Recent dune cordons or coastal sand ridges, they were apparently not flooded in postglacial times, since marine beds of Recent date have not been found so far. The waters present are the result of indirect penetration of sea water into low-lying coastal flats, and lack of drainage of surface runoff and underground waters derived from precipitation on the land surface.

The evolution of the sandy beach-ridge and lagoon coasts of Majorca can be summarized as follows: (1) marine excavation of the lowland plains during Lower and Middle Pleistocene times; (2) marine deposition in lower parts of the lowland plains during the Tyrrhenian transgression of Last Interglacial date; (3) emergence of the lowland plains during the regression accompanying the Last Glacial; subaerial deposition; and (4) postglacial rise of sea level and creation of modern shoreline; the lower parts of the lowland plains are reduced to swamps or lagoons but remain separated from the open sea by Pleistocene and Recent littoral dunes as well as by the active beach ridge.

The Classic Cala Coastline

Fluvial modifications of coastlines have been neglected thus far. Yet certain coastal sectors, in particular the eastern-southeastern coast, offer fine examples of river action. Such examples are provided by the drowned dry-stream valleys or *calas* (Fig. 17). All but a few of the streams originating in the higher sierras, are of the episodic or torrent type.[43] Torrent dissection of the upland plain or of the shallow-water coastlines is almost negligible. But the cliff coasts adjacent to the eastern Sierras have been incised by innumerable short, narrow, and steep-sided valleys. The visual impression of single or complex *calas*, interrupting limestone cliffs and "fossil" coastal forms, and the topographic expression of large-scale maps or air-photos are vivid.

Despite a complete lack of field study or adequate maps, A. Penck defined a *cala* coastal type and used the Majorcan east coast as his example as long ago as 1894.[44] H. Louis[45] distinguishes a *cala* coast characterized by flat-bottomed valleys (*Muldentalküste*) from a ria coast with V-shaped valleys. His distinction is, however, different from that of Penck, who emphasized the degree of dissection or spacing of the inlets as a major distinction between *ria* and *cala* coasts. Another characteristic of *cala* coasts as such is the fact that the valleys are not occupied by watercourses, i.e., the *calas* are typical drowned *torrent valleys* of the semiarid zone.

Many of the Majorcan *torrents* originate on quite flat terrain of the limestone plains, while others are indirectly associated with drainage lines incised in the ancient folded hill country. In only a few exceptional instances do such torrents form a clearly defined drainage system from the rough country to the sea. Most torrents are separated from their technical headwater segments by at least a kilometer of flat limestone terrain, where the broad, smooth channel may have a total relief of less than 2 m. and hence be almost unrecognizable (Figs. 18, 19).

Fluvial processes are quite negligible today. Mechanical weathering is inconspicuous, and chemical weathering has been sufficient only to develop xerorendzina soils on Upper Pleistocene sediments or in those places where the relict *terra rossa* soils have been denuded.[46] Chemical weathering has consequently been limited to moderate solution of carbonates. Fluvial transport is minimal because of the lack of coherent flow. Silts and sands are occasionally transported by rare floods in the more steeply channeled coastal torrents, but gravel and coarser debris is merely moved downslope. Morphometric indices based upon $2r/L$ values for 100 specimen samples obtained from Recent gravels are in the range of 0–100, which indicates that transport has been minimal.[47] In fact, there is no record that rain waters of the Sierra de Levante torrents have reached the sea within memory, despite annual precipitation of 600–750 mm. in the higher country, compared with 350–600 mm. on the plains. The porous nature of the limestones leads to rapid percolation of waters in the piedmont area. On the upland plains, the aeolian admixture of silts and sands to the relict *terra rossas*, together with a coarse block structure, renders these semi-plastic soils quite permeable.

Judged by modern processes, the fluvial forms of the littoral zone are "fossil." This is borne out fully by the stratigraphy. Many smaller coastal torrents have partially exhumed old incisions by re-excavating Upper and Middle Pleistocene regressional deposits (silts and dunes) and early Recent unconsolidated fill. The original incision of the valleys in limestone bedrock must therefore be of Basal and Lower Pleistocene age. Similarly, the lower torrent valleys show modifications related to the Tyrrhenian I and II transgressions, i.e., erosional platforms, sea caves, and fluvial, bedrock terraces graded to the various levels. This indicates that the *calas* had more or less achieved their modern dimensions prior to the Middle Pleistocene. The situation is analogous in the sierran torrents,

[43] The Mallorquin term *torrent* is used for both the dry stream valley, in the American sense of *arroyo*, as well as for the flash floods occasionally present therein. In Spanish usage *arroyo* is most widely used to describe watercourses with seasonal rather than episodic flow.

[44] Penck, *op. cit.* The term has persisted in use among French and German geographers; it is used locally on the Balearic Islands, the Catalonian Costa Brava, and on Malta. The Provençal equivalent, *calanca* or *calanque*, is used in southern France.

[45] H. Louis, *op. cit.*, p. 247.

[46] H. Klinge and A. Mella, "Los suelos de la islas Baleares," *Annales de Edafológia y Fisiológia vegetal*, Vol. 17 (1958), pp. 57–92; K. W. Butzer, "Palaeoclimatic implications of Pleistocene stratigraphy in the Mediterranean area," *Annals*, New York Academy of Sciences, Vol. 95 (1961), pp. 449–456.

[47] For detailed discussion of the Cailleux indices see J. Tricart and R. Schaeffer, "L'indice d'émoussé des galets," *Révue de Géomorphologie dynamique*, Vol. 1 (1950), pp. 151–179; for limitations of their applicability in the arid zone see Butzer, *op. cit.* (1962).

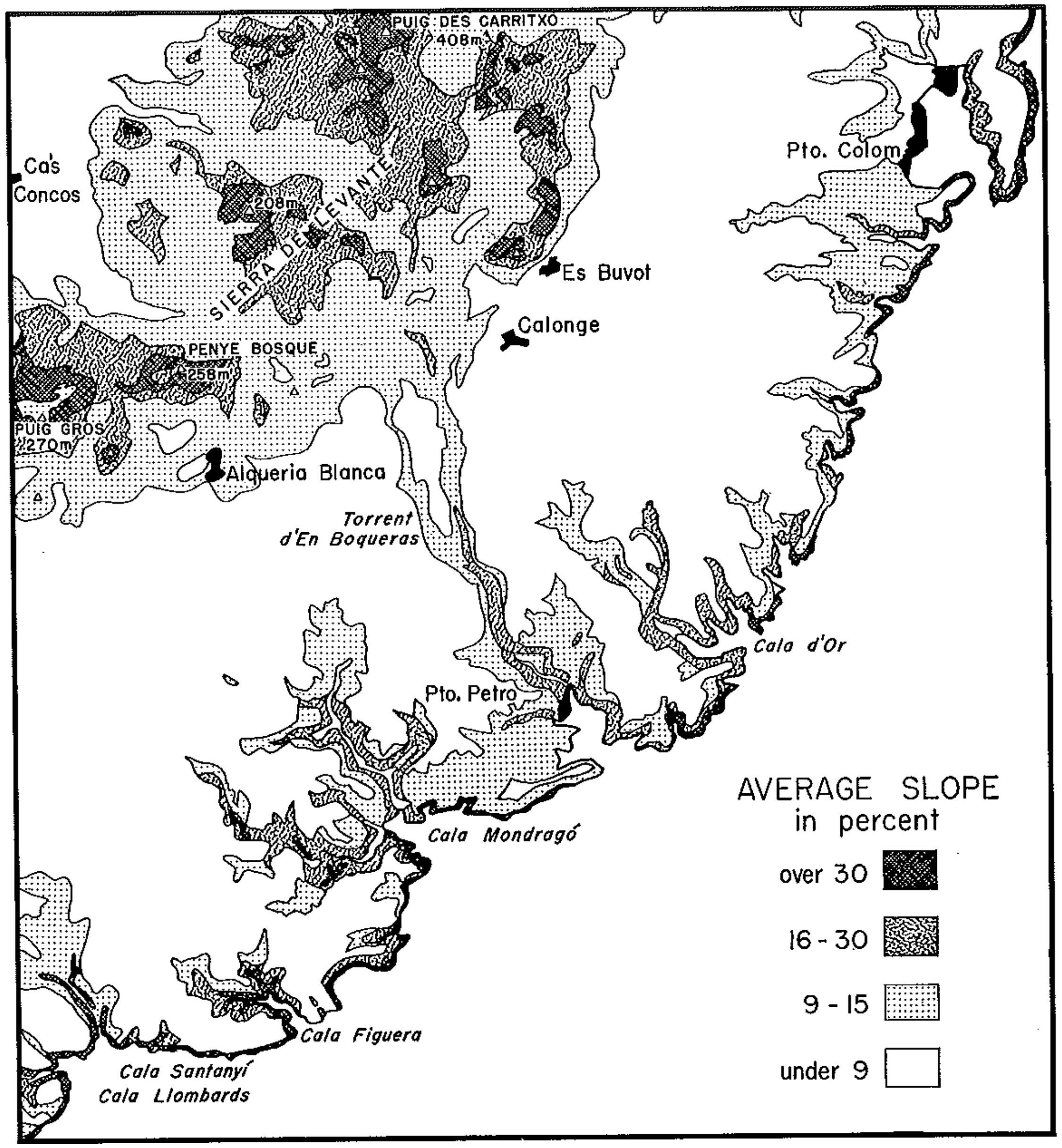

FIG. 18. Average slope (in per cent) of the dissected Sierra de Levante and the adjacent cala coastline (southeastern coast). Note the negligible dissection of the upland plain of horizontal Miocene strata. Data derived from 1:30,000 air photos and 1:25,000 topographic maps.

where the remnants of ancient alluvial fans or tufaceous deposits are embanked against the slopes. These well-rolled gravels or sandy beds have been subjected to subsequent *braunlehm* development, which can be demonstrated to be contemporary with the later Tyrrhenian stages.[48] The *calas* are of considerable age and their development complex, and it may be assumed that their origins go back to the Lower Pleistocene or Upper Tertiary. In short, the *calas* were not simply formed by drowning during the postglacial rise of sea level. Preservation in their present form may be attributed to the almost defunct character of the torrents.

[48] Butzer and Cuerda, *op. cit.* (1962a).

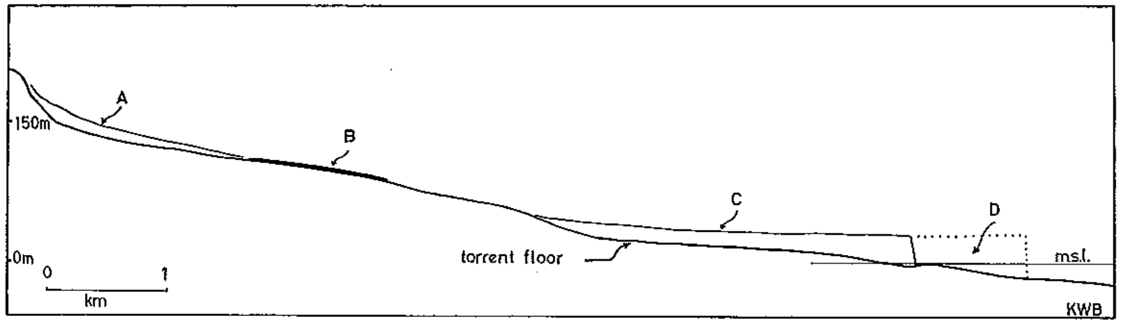

FIG. 19. Longitudinal profile of an east coast torrent at Cala Mondragó. A = bedrock shoulder of valley caused by pluvial dissection of uplands, B = dissected Pleistocene alluvial fans, C = marine terrace forming bedrock shoulder of valley and produced by downcutting at coast, D = Cala Mondragó. Vertical exaggeration 7.5×.

The actual location of the torrent systems themselves reflects a rectilinear pattern of minor structural lines in the Miocene limestone. These are observable joint systems running parallel and normal to the axis of Lower Miocene folding of the pre-Cenozoic basement. On southern Majorca, these linear structures[49] are oriented N 50° E and N 40° W, and it can also be shown that several, almost parallel coastal segments of the southeastern littoral follow these lines of weakness. There is little likelihood that more than a few smaller torrents originated through collapse of coastal caverns of karstic origin, contrary to the opinion of Carandell.[50]

The evolution of the *cala* coasts can be summarized as follows: (1) fluviatile dissection of the edge of the upland plain during one or more phases of low sea level during the Tertiary and the Basal or Lower Pleistocene; (2) marine sculpture of the coastal cliffs and *cala* inlets during both the Tyrrhenian I and II intervals; (3) moderate or insignificant aggradation of the torrents during the last Pleistocene regression; and (4) ultimate drowning of the *calas* during the Recent.

Such coasts are of widespread occurrence in the western Mediterranean area, particularly in areas of low relief with small drainage basins adjacent to the shore. *Cala* coasts can be considered as a zonal feature of the semiarid zone.

[49] Theoretical aspects of minor linear structures are considered by H. J. Pincus, "Statistical methods applied to the study of rock fractures," *Bulletin,* Geological Society of America, Vol. 62 (1951), pp. 81–130. An outstanding application has been made to the horizontal Tertiary beds of Egypt by M. Yallouze and G. Knetsch, "Linear structures in and around the Nile Basin," *Bulletin,* Société de Géographie d'Egypte, Vol. 27 (1953), pp. 168–207.

[50] Carandell, *op. cit.*

CULTURAL SIGNIFICANCE OF COASTAL LANDFORMS

Widespread shortage of water and a limited area of productive soils have motivated the Majorcan population to adjust land use to the physical landscape. With a minimum of mechanization, agricultural methods are nevertheless effective and adapted to the existing conditions of soil, climate, and water resources. Thanks to prudent land use, Majorca shows none of the scars of over-utilization and historical soil erosion that are common in other parts of the Mediterranean realm.[51] Coastal geomorphology, as pertaining to modern or Pleistocene features, finds noticeable expression in the cultural panorama of the island.

The shallow-water coasts of the nip, shingle-beach, or beach-ridge type do not generally provide suitable, natural harbors. Fishing settlements in the Bay of Palma, apart from the artificial harbor of Palma, are limited to the site of Es Arenal, where a torrent mouth provides some shelter. The same conditions occurred originally in the entire Bay of Alcudia, except for the harbor of that name. On the southern coast, Sant Jordi, making use of a sheltered bay, was the only harbor until the 19th century. The uniqueness of the site of Sant Jordi is emphasized by its apparent importance in Roman times.

The cliff coasts provide a somewhat differ-

[51] K. W. Butzer, "Remarks on Soil erosion in Spain (Abstract)," *Annals,* Association of American Geographers, Vol. 51 (1961), p. 405.

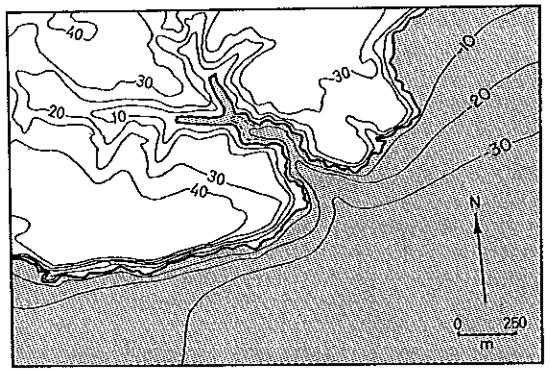

FIG. 20. Relief and submarine topography of Cala Figuera. Bathymetry from personal observations and the 1:31,250 series of J. Mascaró Pasarius.

ent picture. The deep-water *calas,* not encumbered by bar-and-lagoon features, provide outstanding harbors. This is so in the case of narrow *calas,* such as Cala Figuera (Fig. 20) or in the inner harbor of Porto Christo, or bottleneck *calas,* such as Porto Petro and Porto Colom. In both types, wave action is very limited and marine bars do not develop. These particular *calas* are significant fishing centers, and submarine pottery finds substantiate their use in Roman times. During the 13th–16th centuries A.D., Miocene limestone quarried at Santanyí was shipped to Catalonia, Roussillon, Valencia, and Naples via Cala Figuera.[52]

The Recent littoral dunes and aeolian mantles, widespread along the southern coast (Cap Salines to Rapitá) and the Bay of Alcudia, are a major obstacle to agriculture. Even where mature rendzina soils are developed, their structure is too loose for ploughing, so that livestock grazing or pine plantations are the only economic uses. Clearing and farming attempted at one large estate near Sant Jordi have resulted in wind erosion and destruction of the organic structure of the soil.

Pleistocene aeolianites have a more variable significance. Fully cemented aeolianites such as those of pre-Tyrrhenian age have practically no soil on top and are invariably left to woodland or garrigue. The consolidated, well-weathered aeolianites of "Riss" age provide *terra fusca* soils of moderate productivity, whereas the xerorendzinas on Würm aeolianites, although generally under furrow, are little better than those on Recent dunes. The latter soils are midway between a granular and block structure and have a *mulliform* humus type. However, the arid soil environment and low water table are not assets, and many square kilometers of the island are either unarable or of limited productivity. A sole positive aspect to the aeolianites is their value for quarrying. Würm and "Riss" aeolianites can be cut easily with steel saws and are widely used for cheap building stone; however, high porosity makes them undesirable for house construction.

The great marine-cut platforms and shelves are quite noticeable in the agricultural landscape. The lowland plains of Palma, Campos, and Alcudia form the highly productive *huertas* or market gardens of Palma, Campos, and La Puebla. Being near sea level, the water table is located close to the surface, and a considerable depth of alluvial and colluvial soil products was derived from the higher country in Pleistocene times. Consequently, pump irrigation enables as many as four crops to be obtained each year. However, because of excessive ground water use in the last 40 years, salinization of the ground water, caused by the penetration inland of the sea, beneath the lowland plains, has taken place.

The marine sculptured surfaces of the upland plains suffer from the same water shortage and low ground-water tables as does most of the Miocene meseta. But the *camps* referred to above are favored zones within this area because of the unconsolidated, fertile *terra rossa* sediments that accumulated in them during the Pleistocene. The great depth of soil here is probably a major reason for the desire of large landowners to retain these plots, although they have often sold or leased the intermediate ridges with thinner soils to small independent farmers. At any rate, the *camps* are operated as units by a few large estates.

Another interrelationship of coastal geomorphology with the cultural landscape is found in the lagoonal zones. Drainage, land-reclamation, and irrigation of the *Prat* of the Palma

[52] Permanent settlements at the east coast *calas* were, at the latest, abandoned by the early 16th century on account of the serious pirate menace. Pirate attacks began in 1386 and led to widespread devastation after 1525. See the articles by B. Vidal y Tomás in the newspaper *Santanyí,* Vol. 1, Nos. 7, 9, 10, 12–14, 17, 19, 21–22 (1958). Only during the reign of Carlos III (1759–1788) were the Majorcan coasts systematically recolonized.

area has been one major factor in the great population expansion of Majorca during the last century.[53] In other coastal lagoons, salt farming has been significant for centuries, and both Majorca and Ibiza export considerable salt to the Spanish mainland.[54]

A last point of interest is the abundant cockle (*Cardium edule*) populations of the Estany de Ses Gambes and some of the *cala* lagoons (formerly also of the Salobrar), which are widely used for human consumption.

CONCLUSIONS

During the course of the Pleistocene, the Miocene strata of Majorca were effectively, although at first glance not always conspicuously, modeled by gradational processes. This tectonically undeformed structural unit has the morphology of an emerged shelf, subsequently modified by littoral agencies and to a lesser degree by running water. Relative aridity and remarkably low gradients have been responsible for the preservation of the marine-littoral features.

Coasts of the cliff type are characteristic of the southeastern littoral. Here plunging cliffs with notches, but only poorly developed platforms, are frequently interrupted by drowned torrent valleys or *calas*. This coastline runs parallel to the anticlinal axis of the nearby Sierras, and its location is related to linear structures or joint lines reflecting deformation features of the folded basement. However, the actual evolution of the southeastern coastal segment is a product of Pleistocene fluctuations of sea level and moderate dissection. The modern sea level appears to be just a temporary phase among a series of well-developed marine-cut terraces from many meters below to 30 and more meters above sea level. Older and higher abrasional features of marine origin extend beyond the 100 meter-contour and to the foot of the Sierras. Orographic intensification of precipitation in the same areas has, together with steeper gradients, allowed greater fluvial activity than on the northeastern and southwestern coastal sectors, and has caused the dissection of the coastal fringes by torrents.

The more irregular coastlines facing northeast and southwest are more frequently of the shallow water type. Cliffs, although present, are rare. Instead nip or shingle coasts alternate with sandy beaches accompanied by large zones of "fossil" littoral dunes. Aeolian processes, responsible for the deposition of several generations of regressional dunes, replace fluvial activity as auxiliary agency here. Corresponding to weak gradients, the coastal environment is necessarily extensive, ranging from a broad shelf and platform offshore to aeolian beds located well inshore. Pleistocene beaches dominate the limestone mesetas or upland plains. Similarly, marine erosion has excavated the lowland plains, parts of which have been reduced to lagoons by the Recent transgression of sea level.

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[53] The cultural significance of physical contrasts between the hinterlands of the rocky nip coasts and beach ridge coasts of Palma Bay, as well as the economic development of the *Prat*, are vividly described in the outstanding study by Rosselló, *op. cit.* Quite analogous features in the Bay of Ibiza are described from a cultural viewpoint by G. M. Foster, "The *feixes* of Ibiza," *Geographical Review*, Vol. 42 (1952), pp. 227–237.

[54] Both the pond at Sant Jordi and the Salobrar have been used for salt-production since the 13th century, if not since Roman times (B. Vidal y Tomás, personal communication). A commercial saline has operated the latter at least since the 17th century, and one of the largest Spanish salines was established in the Salobrar in the early 1950's.