COASTAL STRATIGRAPHY OF SOUTHERN MALLORCA AND ITS IMPLICATIONS FOR THE PLEISTOCENE CHRONOLOGY OF THE MEDITERRANEAN SEA[1]

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ABSTRACT

Detailed geomorphologic, stratigraphic, and paleontologic investigations on the southern littorals of Mallorca indicate the existence of at least three complex glacio-eustatic regressional intervals, belonging to the last three glacial complexes of the Pleistocene. The incipient regressive oscillations were initiated by climatically induced colluviation and followed by deposition of regressional aeolianites. Deflation of freshly exposed marine deposits necessarily ceases soon after the negative fluctuation stops. A complete stratigraphy of the actual regressional parts of each major glacial low-water stage is locally preserved and discussed in detail for several sites. Three major dunes characterize the last regression, four the penultimate regression and at least two the antepenultimate regression. The transgressive intervals with thermophile marine faunas presumably corresponded to interglacial intervals. They comprise several oscillations, the youngest of which, in the case of the last and penultimate interglacials, was preceded by a negative fluctuation to below modern sea level. These phases were significant for major *Rotlehm* development, but typical regressional aeolianites are lacking. Consequently the Tyrrhenian III, a final oscillation of this type, is considered as last interglacial. Similarly, a final Tyrrhenian I level of +4–5 m., with *faune banale*, here recognized and studied for the first time, is considered as the final stage of the penultimate transgressive complex. Weathering is also indicated during the "interstadial" interruptions of the various regressions.

INTRODUCTION

Studies of coastal deposits pertaining to various eustatic transgressions and regressions of the Mediterranean Sea cover a time span of two generations since the fundamental work of C. Depéret, M. Gignoux, and A. Issel. Yet despite the multitude of outstanding regional studies, there is no general agreement beyond the basic stratigraphic framework. Such features as the Tyrrhenian III (Néotyrrhénien) are variously allotted to the Last Interglacial or to the Last Glacial. The relation of the high-level stage designated as Milazzian, to the early or Tyrrhenian I (Paléotyrrhénien) stage, is also unclear (Butzer, 1961*a*). The major difficulty arises from the variable number of phases represented in any complex of sediments related to a regression or transgression. In many cases these are simply grouped and ignored, in others they are assigned to quite distinct fluctuations of sea level. In order to solve some of the inherent problems it is necessary to study sites with exceptional detail and continuity and to apply to them all modern techniques of investigation. Interpretation should proceed by logical deduction and argumentation rather than by premature or assumed correlation with the disputed details of higher-latitude stratigraphy.

During the past years attention has been drawn to the numerous and instructive Pleistocene sedimentary series on the Spanish coasts (Gigout *et al.*, 1956; Cuerda, 1957; Muntaner Darder, 1957; Virgili and Zamarreño, 1957; Mercadal, 1959; Solé Sabarís, 1961; among others). Possibly most rewarding although often difficult to interpret are the marine and littoral deposits of the Balearic Islands east of Spain. In the course of a 5-month field study in Mallorca (Majorca) during 1959 and 1960 by Butzer, a number of comparatively complete stratigraphic sections covering the time span of the post-Villafranchian were discovered and investigated, and later in part revisited in conjunction with Cuerda, who studied the paleontologic material collected by both authors. The investigation was based on systematic microstratigraphic analysis of sec-

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tions and a 1:50,000 scale mapping of surficial deposits and of soils. Materials of all strata in pertinent sections were analyzed in the laboratory. Some of these representative sections have been described, partly in full detail, and their significance to the Pleistocene chronology of the Mediterranean discussed. A terminology avoiding correlative implications has been employed, and although this procedure involves the use of some awkward phraseology it is the authors' aim to base their conclusions on independent evidence.

The area studied in detail is situated between Porto Colom on the southeast coast and Cala Pí on the south coast, including the Cabrera island group. Apart from the latter, the bedrock consists of horizontal Miocene limestones, which are wholly undeformed except for sections adjacent to ancient collapsed grottoes. The stratification and contact of the Miocene with the folded Mesozoic and Lower Tertiary beds in the interior leaves no doubt that the area has had tectonic stability throughout the Pleistocene. Such features as the Es Verger escarpment (fig. 1) or the Campos basin are clearly the result of exogenic forces (Butzer, 1962*b*). The two coastal sections in question are morphologically distinct. The southeastern littoral is characterized by a moderately high, steep cliff, which is incised by numerous arroyos (torrents) and drowned valleys (calas). Here the Pleistocene deposits are situated on marine abrasional platforms or embanked against the cliffs in massive fashion. The southern coast, however, is formed by Recent and Pleistocene dunes and alluvial valleys of gentle or moderate slope, and a cliff coast only reappears west of Punta Plana. With the exception of the latter section, the Pleistocene record of the flat, shallow-water coast between the southern tip of the island, Cap Salines, and Punta Plana is rather incomplete. The present paper is consequently concerned primarily with the southeastern coast and the section from Punta Plana to S'Estalella.

MARINE BASE OF UPPER PLEISTOCENE STRATIGRAPHY

Numerous sites record a complex stratigraphic succession for what may be described as the last regression. The fundamental difficulty here is to determine the base of the series. In some cases the base is provided by marine abrasional platforms which indicate that the various high-water stages of the later Tyrrhenian transgressions were generally present in the area (Butzer and Cuerda, 1961; Butzer, 1962*b*). In others the regressional deposits grade conformably into the earlier marine sediments and therefore leave no doubt as to their relationships.

To clarify this problem, the guide horizons provided by the Tyrrhenian II and III stages may be briefly outlined and surveyed as they occur on the Mallorcan coasts.

Possibly the most definite Pleistocene transgression of the Mediterranean Sea is the Tyrrhenian II level generally found at about 5–10 m. on stable coasts. It is associated with a varied thermophile fauna of Senegalese species now extinct in the Mediterranean. The most noted fossils of this association are *Strombus bubonius* Lmk., *Natica lactea* Guilding, *Mytilus senegalensis* Reeve, *Arca plicata* Chemn. and *Cardita senegalensis* Reeve, *Conus testudinarius* Martini, *Tritonidea viverrata* Kien. According to Bonifay and Mars (1959) some of these species are also occasionally encountered in beds of both the older (Tyrrhenian I, "standard" altitude 15–25 m.) and the youngest (Tyrrhenian III, standard altitude 2–5 m.). But the total association, which is often a fauna containing a greater frequency of gastropods, is fairly distinctive, particularly when deposits of the older or younger stages can be recognized in the same area. Where the Senegalese fauna is not represented in these Tyrrhenian II beds, coastal geomorphology must provide lateral correlations.

On Mallorca the Senegalese fauna of the Tyrrhenian II has been studied in great detail by Cuerda (1957, with references to earlier work) and found to be associated with

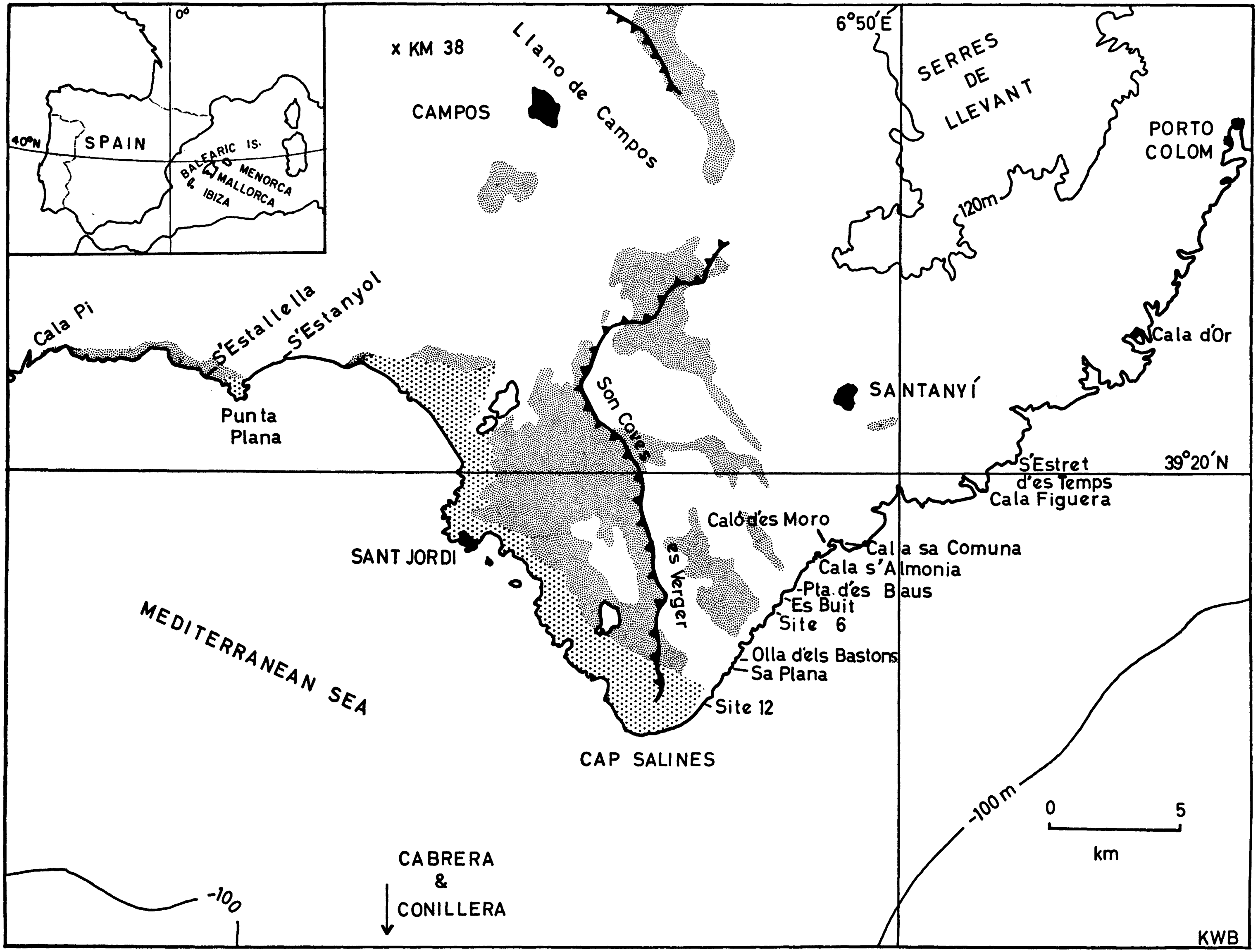


FIG. 1.—Outline map of southern Mallorca. Heavy dotted pattern indicates immobile dunes or Recent age, light pattern Pleis'ocene aeolianites (unclassified and simplified). Inset map indicates location of Balearic Islands.

several altitudinal levels in the range of 2–11 m. These sites in the Bay of Palma have not experienced differential earth movements, for the sediments between Arenal and Cap Orenol are undisturbed. The Tyrrhenian III at 1.5 to 2.5 m. is disconformably embanked against these beds, and lacks *Strombus bubonius*, while most of the other Senegalese forms among the 150 species recognized in the Tyrrhenian III association are not rare. Subsequent study of the southern littorals revealed that identical levels could be identified, although the fauna is somewhat sparser. Geomorphologic study of these Pleistocene shore lines was integrated with sedimentary associations of marine faunas. The sequence of major independent levels is 10.5–12 m., 6–7.5 m., and 2–4 m., with a briefer stand at 8–9 m. Only the older, 10–12-m. stage is characterized by the Senegalese faunal association, although one site (Cala Santanyí) belonging to the final 2-m. level contains *Conus testudinarius*, *Tritonidea viverrata*, and *Triton costatus* Born (in littoral association) (Butzer and Cuerda, 1961). The authors therefore believe that, on the basis of comparative study of the southern coast and the Bay of Palma, correlation between the corresponding stages of both areas is justified.

Transgressive beds of the Tyrrhenian III in southern Mallorca have a "common" (i.e., non-thermophile) fauna, except for a distinctive, more globular subvariety of *Purpura* (*Thais*) *haemastoma* L. var. aff. *laevis* Monterosato which is also found in corresponding beds in the Bay of Palma (Butzer and Cuerda, 1961). The local absence of the other minor Senegalese forms is considered accidental. The stage can be associated with an abrasional feature in range of 2.6–2.8 m. or a little more.

The Tyrrhenian II and III are invariably separated by a regression of unknown but presumably moderate magnitude. On faunal grounds (Cuerda, 1957) this must have been of considerable duration, as is confirmed by pedological evidence at Cala S'Almonia.

The inlets of Cala S'Almonia are dominated by Tyrrehenian II abrasional platforms at +4.7, +5.7, and +9 m. cut into the Miocene deposits, and which also extend along the lower torrent courses as fluviatile terraces. At the base of the little settlement, the following sequence (fig. 2) is exposed on bedrock with a base at sea level:

i) 60–90 cm. Coarse, angular, crudely stratified and well-cemented limestone rubble, representing collapsed materials of a cave whose base was originally at about modern sea level. The limestone is intensely weathered, and the cavities are filled with a semi-cemented, red to dark reddish brown clay (2.5 YR 5/8 or 3/4). This material is identical in physical appearance

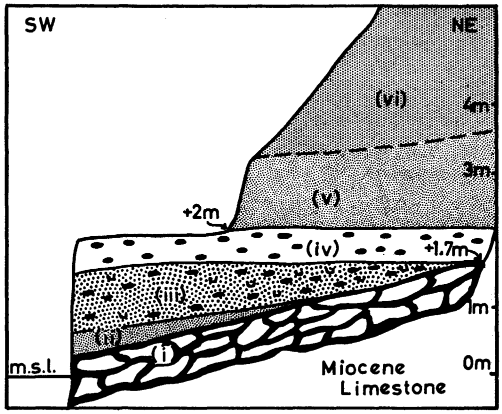


FIG. 2.—Composite section of Upper Pleistocene deposits at Cala S'Almonia. (*i*) Limestone debris and fossil soil; (*ii*), (*v*) colluvial silts; (*iii*), (*iv*) marine and semi-marine conglomerates; (*vi*) aeolianite. Approximately to scale. Nip in 2 m. is Recent.

and color to that in a nearby grotto at +12 m., and obviously represents a cave sediment.[4] The weathered limestone, however, leaves no doubt of a *terra rossa*-type weathering *in situ*, necessarily at a time of lower sea level than today, prior to the next disconformable horizon.

ii) 0–70 cm. Cemented reddish yellow (5 YR 7/6) silt with crudely stratified angular detritus, the upper part going over conformably into beach rock and

iii) 100–105 cm. Horizontally stratified ma-

[4] O. Fränzle kindly re-examined samples microscopically, adding that a veneer of small calcite crystals along fissures, or calcite aggregates and secretions in the hollows, indicate redeposition and secondary calcification. Veneers or concretions of manganese are also derived from redeposition.

rine sand, cemented along bedding planes, with root drip and fine to medium angular detritus and marine rubble (reddish yellow 7.5 YR 7/8). Laterally the bed goes over into stratified beach cobbles in red (2.5–5 YR 5/6) silts. The deposits attain at least +1.7 m. above sea level and contain a Tyrrhenian III fauna of *Purpura haemastoma* L., *P. haemastoma* L. var. aff. *laevis* Monterosato, *Patella lusitanica* Gmel., *Spondylus gaederopus* L., *Arca noae* L., *Cardium edule* L., *Pectunculus violacescens* Lamarck, and *Lucina reticulata* Poli. Particularly the extinct *Purpura* variety with little ornamentation recalls the Tyrrhenian beaches of the Palma area (Cuerda, 1957).

iv) 50 cm. Marine rolled and well-stratified gravel (see table 6 below) with (2.5 YR 5/6) sandy silt and a terrestrial fauna (fifteen specimens) of *Tudorella ferruginea* L. (85 per cent) and *Eobania vermiculata* O. F. Müller (15 per cent). A few *Cardium* shells at the base indicate the mixed marine-colluvial character of the bed, which attains +2.1-m. elevation.

v) 100 cm. Reddish yellow (5 YR 6/6–7/8) silt with occasional slightly rounded, crudely stratified medium gravel. Goes over conformably into several meters of regressional aeolianite, which forms an integral part of the last regressional sequence.[5]

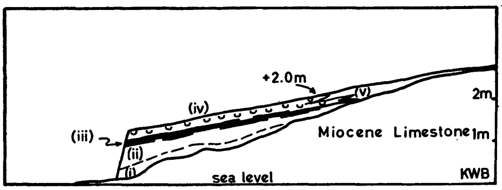


FIG. 3.—Tyrrhenian III deposits at Punta de Son Bieló, S'Estanyol. (*i*), (*ii*) colluvial silts; (*iii*) beach rock; (*iv*) fossiliferous marine sand intercalated with (*v*) terrestrial silts. Vertical exaggeration 3×.

The conclusions derived from analysis of Cala S'Almonia are that a lower sea level than today was contemporary with a *terra rossa*-type soil development in local caves—after a sea level of 5–9 m., and prior to a new transgression to at least +2 m. This latter Tyrrhenian III stage was followed by the continental series of the last regression. There is also an analogous site at S'Estanyol (fig. 3), whose fauna is described in detail by Butzer and Cuerda (1961).

[5] Colors given refer to the *Munsell Soil Color Charts* (Baltimore, 1954) and are designated for dry sediments. Statistical sampling of land snails refers to counts of one hundred individuals, unless otherwise stated. Grain-size analyses were carried out by the Köhn method, and invariably refer to the fine soil component. The pH values listed have been electrometrically determined in H_2O. As an indication of weathering the grains of the medium sand component, after dissociation from the other fractions, were statistically studied under the microscope (samples of one hundred), whether or not they were directly weathered or coated with iron oxides. Cross-sampling by various techniques of preparation indicated that the errors were small. The method presents a quantitative estimation of the oxidized grains with due qualifications. Morphoscopic sand-grain analyses (cf. Cailleux, 1952) were made of the medium grain size in order to analyze the aeolian component of the silts as well. This procedure is more difficult although it is as significant as study of the 300 to 1,500 μ components.

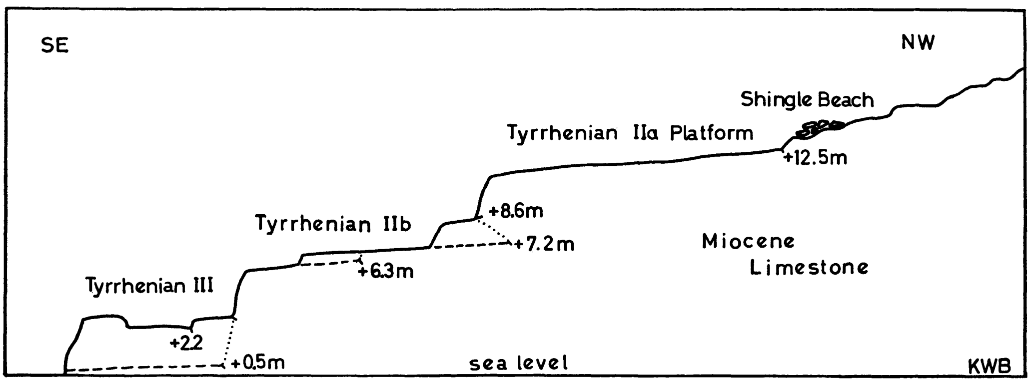


FIG. 4.—Composite section of Tyrrhenian II–III marine platforms near Cala d'Or (Punta Grossa-Cala Esmeralda). Vertical exaggeration 3×.

The internal chronology of the older, typical Tyrrhenian (II) can be derived from a sequence of independent marine abrasional platforms found between Punta Grossa and Cala Esmeralda (Cala d'Or). The earliest Tyrrhenian II*a* stage evidenced is represented by a broad platform up to 40 m. wide, with a shingle or boulder beach but little or no cliff. The maximum level ranges from +10.5 to 12.5 m. (fig. 4). Beyond this level there is a marked change in topography and the smooth bare platform with a veneer of cemented silty light red (2.5 YR 6/8) sands and marine microfauna is replaced by an undulating rocky surface with soil and vegetation that is noticeably affected by chemical weathering.

The later Tyrrhenian II*b* lies at the back of a small cliff, and it is best developed at a level of +7.2 m. It is characterized by notable notches and a 25-m. wide abrasional platform with up to 80 cm. of cemented red (2.5 YR 3–4/6) silts intercalated with beach rock, which traces of microfauna and rubble of marine mollusks. The level apparently oscillated, for there are immature platforms and notches at +8.6 and +6.3 m.

A third Tyrrhenian stage is represented at Cala d'Or by small platforms and notches at +3.3, +2.6, and +0.5 m. Their origin is undoubtedly due to sculpturing during both the final Tyrrhenian II and the Tyrrhenian III. Each of the three general Tyrrhenian II and III levels can be observed over long stretches of the coast line, although the relationships are nowhere as clear.

Similar interrelationships of erosional and depositional phenomena illustrating the internal chronology of the Tyrrhenian II and III can be observed in the cave excavated into the semi-conformable sequence of three regressions at Sa Plana (fig. 5).

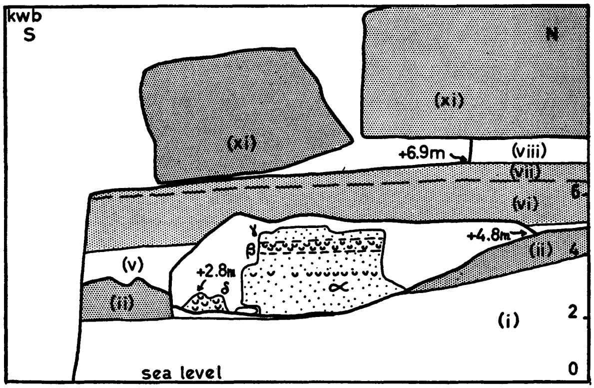


FIG. 5.—Intrusive Tyrrhenian II–III deposits and their relation to the regressional series in cave at Sa Plana. Approximately to scale. α and γ, beach sandstone; β, fossiliferous Tyrrhenian II; δ, transgressive Tyrrhenian III beds; (*ii*), (*vi*), (*vii*), and (*xi*) aeolianites; (*i*), (*v*), and (*viii*) silts and colluvium. Note older notches at 4.8 and 6.9 m. Units at margin in meters.

The stratigraphy of the marine Upper Pleistocene can then be summarized as follows:

Tyrrhenian II*a*. Thermophile *Strombus* fauna. Maximum +10.5–12.5 m. (cf. figs. 4 and 9).

Oscillation to about modern sea level. Colluviation of terrestrial silts and *terra rossa* soils. Implies previous soil development.

Tyrrhenian II*b*. Some thermophile fauna. Falling levels +9 m. to +2 m. with major stands at 6–9 m. and 2–4 m., interrupted by a negative oscillation. Adjustment of torrent gradients to the 6–9-m. level implies considerable water flow.

Protracted regression to modern sea level, then to at least −5 m., with *terra rossa*-type soil development at sea level. Collapse of grottoes and recementation of rubble under moist conditions.

Tyrrhenian III. Some thermophile faunal elements (not locally). Maximum at least +2.8

m. (possibly +3.3 m.) was preceded, accompanied, and followed by terrestrial colluviation.

STRATIGRAPHY OF THE LAST REGRESSION

During each of the eustatic marine regressions a peculiar sequence of widespread sheetflooding and areal denudation occurred. The later regressions were periods of increased aridity during which aeolianites were deposited. This is evidenced by beds of colluvial silts or coarse, massive scree breccias under coarse-grained dune sands. The stratification of the latter is more pronounced toward the top and is marked by topset or foreset beds. The earliest dune record is often poorly represented but commences with mixed silt-aeolianite beds, overlain by weakly bedded sands. It is inferred from modern analogies that such unbedded sands may be deposited in open-stocked pine woodland or maquis scrub, but the conspicuously well-bedded facies of aeolianite could not conceivably have been deposited on a continuous vegetative mat, and certainly not in woodland (for details see Butzer, 1962*b*, *c*).

The sequence of silt–aeolian sand is repeated several times during each regressional complex. The individual sequences are separated by periods of unknown duration when there was no deposition. Such interruptions are most probably a result of static or even positive trends of sea level; these interruptions were, however, almost generally contemporaneous with soil development under somewhat moister conditions than today. The silt phase corresponds to a widespread, little studied phenomenon in the western Mediterranean, the *limons rouges* of the French authors (e.g., Durand, 1959). These deposits are definitely climatic (i.e., zonal as opposed to azonal phenomena), and geomorphological studies by one of the authors suggests they are due to sheetflooding and colluviation in a moist climate with pronounced rainfall seasonality (Butzer, 1962*c*).

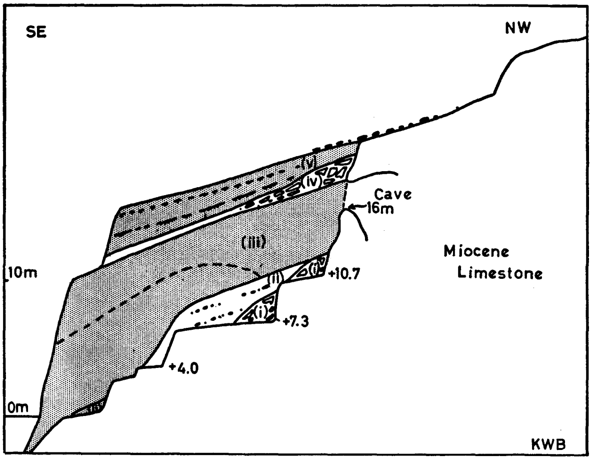
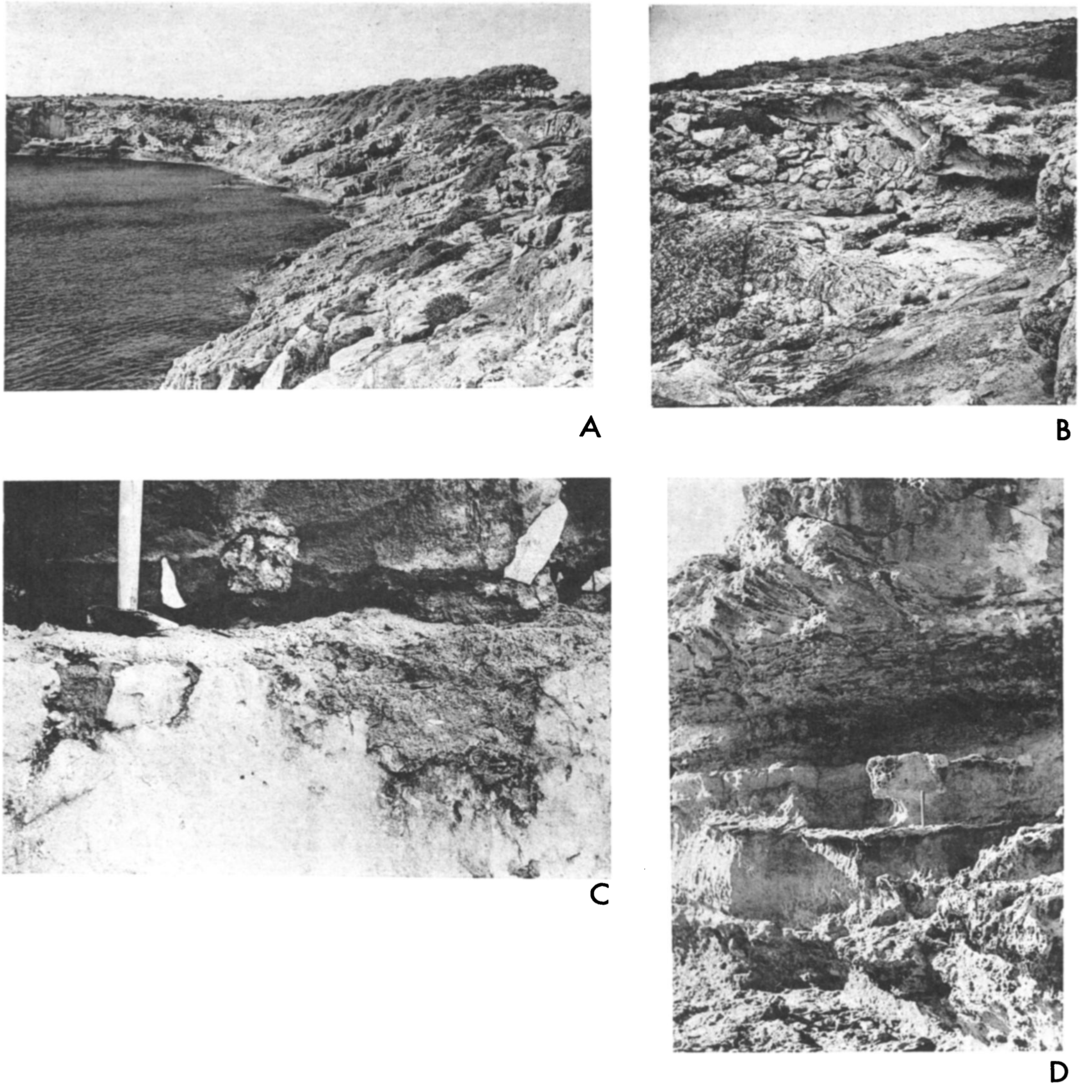


FIG. 6.—Composite section of the last regressional deposits in S'Estret d'es Temps. (*i*), (*ii*), and (*iv*) silts, colluvium, and breccias; (*iii*) and (*v*) aeolianites. Approximately to scale.

One of the many sequences of the last regression is illustrated at S'Estret d'es Temps. Above abrasional platforms at +3.3, +4.0, +7.3, and +10.7 m., which presumably represent Tyrrhenian II and III, this broad shallow bay has a succession of Würm regressional deposits as follows (fig. 6 and pl. 1, *A*):

i) 0–200 cm. Limestone blocks, corroded and later cemented by crystalline calcite, formed by the collapse of large grottoes on or above the 7-m. platform. The rubble had been strongly weathered red (10 R −2.5 YR 4–6/8) before



Pleistocene coastal sections of southern Mallorca (and partly during) cementation. Disconformity.

ii) 20–200 cm. Red (2.5 YR 4–5/8) to reddish yellow (5 YR 7/8) consolidated silts (table 1) with medium to coarse angular talus, bedded at 10°–12° downslope. Abundant fauna (two hundred specimens sampled) of *Tudorella ferruginea* (97.5 per cent) and *Eobania vermiculata* or *Helicella prietoi* Hidalgo (2.5 per cent). The deposit originally extended to or below modern sea level.

iii) Over 8 m. Coarse-grained, semi-cemented, unweathered (10 YR 7/3) dune sand dip to 30° seaward, foreset dip to 40° landward, with at least one general bedding disconformity. Isolated *Helix* shells occur at the base; root drip and root casts are common. The uppermost portions frequently have fine, tufaceous calcareous crusts (10 YR 7/4) indicating passage of calcareous surface waters. Such a pink (7.5 YR 7/4) crust 2–3 mm. thick terminates the major aeolian deposition.

iv) 60–200 cm. Yellowish red (5 YR 5/8) colluvium of weathered and redeposited sand, partly intercalated with aeolian beds at base, going over into true colluvium with root remains and stratified slabs of aeolianite at 10°–15° angles. Locally grades laterally into limestone talus. Fauna (three hundred specimens) *Tudorella ferruginea* (78 per cent), *Mastus pupa* Bruguière (1 per cent), various Helicidae (*Eobania vermiculata*, *Helicella frater* Dohrn & Heynemann, *Helicella prietoi*) (21 per cent).

v) 170–350 cm. Consolidated, unweathered (10 YR 7–8/3) dune sand, with some fauna in basal 40 cm. of sixty specimens *Eobania vermiculata* (60 per cent), *Tudorella ferruginea* (40 per cent). About a third of the way from the base there is a disconformity with a 1-cm. pinkish tufaceous calcareous crust (10 YR 7–8/3–4; 7.5 YR 7/4), indicating water washing and limited weathering. The final dune indicates a rapid veer of wind direction from N. 15° W. toward N. 5° E. (direction of dip). It is capped by similar (7.5 YR 7–8/4, 6/6) crust.

The increase of the clay component, the quantity of weathered grains, and the percentage quartz by weight (table 2) indicate that the colluvium (*iv*) was preceded by a period of noticeable weathering. Corresponding to a cessation of aeolian deposition, this period must represent a positive oscillation of sea level of considerable duration. This implies an interstadial of the continental glaciers, which appears logical in association with local weathering, under moist conditions. No absolute dating of the sequence is yet possible. However, the deposition of the regressional dunes must theoretically stop with the maximum regression and maximum extent of the glaciers, as no further marine sediments are exposed for deflation (cf. H. E. Wright, 1961). Presumably, therefore, the two dunes at S'Estret represent the last regression from its initiation to the maximum lowering of sea level. The oscillation present toward the end of the sequence may represent one of the major higher latitude interstadials. Local contemporary sea level was below that of the present. The first post-Tyrrhenian (Würm-Wisconsin, it is supposed) red bed of silt, with 85–100 per cent *Tudorella* fauna, is a conspicuous guide horizon on the eastern coast (for convenience designated as W-Red 1). The second red bed, with 70–78 per cent

PLATE 1

A, *S'Estret d'es Temps*. Aeolianite W-Dune I*b* and II (distinguishable as incomplete lobes not quite extending to sea level in center) embanked against Miocene cliffs (far right and center background). (Photos by K.W.B.)

B, *Sa Plana* (*Torrent*). Part of the last regressional series consisting of massive gravels and silts underlying aeolianite, resting on +9-m. abrasional (fluviatile-marine) terrace in Miocene limestone (cf. text). The continuous sequence begins in the immediate foreground.

C, *Sa Plana*. Pipes of buried *terra rossa* soil developed on aeolianite of antepenultimate regression (whitish), and underlying marine beds of final Tyrrhenian I (under hammer). Upper beds represent basal colluvial silts (*v*) of penultimate regression.

D, *Sa Plana*. Standard Würm series: bed (*xvi*) at base over major erosional disconformity under scree; bed (*xvii*) capped by tufaceous crust under hammer; bed (*xix*) in level of hammer; bed (*xx*) in "notch"; aeolianite bed (*xxii*) overlying well-stratified semi-aeolian bed (*xxi*).

Tudorella and occasional *Mastus pupa*, is equally striking (W-Red 3). The early dune is designated as W-Dune I, the second as W-Dune II. The general disconformity present in the latter represents a minor glacio-eustatic oscillation coupled with very moderate weathering. The disconformity in W-Dune I at Cala Sa Comuna and S'Estret becomes more noticeable toward Cap Salines, where the dune is generally subdivided and separated by another red bed (W-Red 2).

The early red bed (W-Red 2) is discussed in detail below for another site (Sa Plana) and is magnificently developed at Es Buit and Punta Llarga near Punta des Baus. The earlier W-Dune I*a* is coarse-grained and contains much coarse marine rubble, whereas the second (W-Dune II*b*) is finer and encloses few marine faunal remains, illustrating the recession of the coast line. Bedding inclinations and directions above and below the disconformity remain identical, yet some 10 cm. of reddish yellow (5 YR 7/8) silts and 2 cm. of tufaceous pink (5 YR 8/4) crust separate the two. W-Red 2 is invariably sterile.

The stratigraphy of the last regressional complex following the Tyrrhenian III transgression can be synthesized as follows:

W-Red 1. Colluvial *Tudorella* silts. Sea level falling in stages from +2.8 m.

W-Dune I*a*. Coarse-grained aeolianite with marine rubble. Full-scale regression.

W-Red 2. Sterile colluvial silts (local). Positive sea-level oscillation (below modern sea level).

W-Dune I*b*. Regular aeolianite. Full-scale regression. Admixture of terrestrial silts implies greater local moisture.

W-Red 3. Colluvial *Tudorella-Mastus-Helix* silts. Protracted positive sea-level oscillation (below modern sea level) accompanied by soil development, weathering, and subsequently intense sheetflooding and colluviation.

W-Dune II. Regular aeolianite. Full-scale regression separated by sea-level oscillation and moderate weathering.

The average sedimentation duration of W-Dunes I*a*, I*b*, II*a*, and II*b* is in the ratio of 5:5:1:1, that of the pre-Tyrrhenian III, W-Red 1, 2, 3, and intra W-Dune II silts, etc., in the ratio of 20:70:10:70:1. This

TABLE 1

S'ESTRET GRANULOMETRIC ANALYSES

(Per Cent)

	200–2,000 μ	60–200 μ	20–60 μ	6–20 μ	2–6 μ	<2 μ	pH
Dune (*v*)	69.0	13.4	2.7	4.7	4.4	5.2	8.08
Colluvium (*iv*)	50.9	25.1	12.4	1.3	3.5	6.8	7.66
Dune (*iii*)	66.6	22.6	3.6	2.2	1.3	3.7	8.14
Silt (*ii*)	25.0	16.7	7.9	22.7	12.3	15.4	9.82

TABLE 2

S'ESTRET MEDIUM SAND FRACTION ANALYSES*

(Per Cent)

	Weathered Grains	Percentage Quartz	Waterworn Quartz	Windworn Quartz	Unworn Quartz Grains
Dune (*v*)	0	0.5	19	19	62
Colluvium (*iv*)	45	2.7	18	*49*	23
Dune (*iii*)	4	1.6	7	*66*	27
Silt (*ii*)	91	6.1	*36*	6	58

* Well-defined maxima are italicized.

gives a very gross approximation of the possible time intervals involved.

STANDARD MIDDLE AND UPPER PLEISTOCENE SEQUENCE AT SA PLANA

The most important and complete stratigraphic sequence yet found on the Spanish coasts was discovered in June, 1960, on an almost inaccessible section of the southeastern coast at a place locally known as Sa Plana, situated a little southwest of the cave Olla dels Bastons. The stratigraphic and paleoclimatic portent of the semi-conformable sequence are almost unrivaled in the western Mediterranean. The details are so fundamental to understanding the chronology and interpretation suggested here that the site is described at great length. A composite of four profiles studied in the field and the laboratory is given below (see figs. 7 and 8, tables 3–6, and pl. 1, *B*, *C*, and *D*).

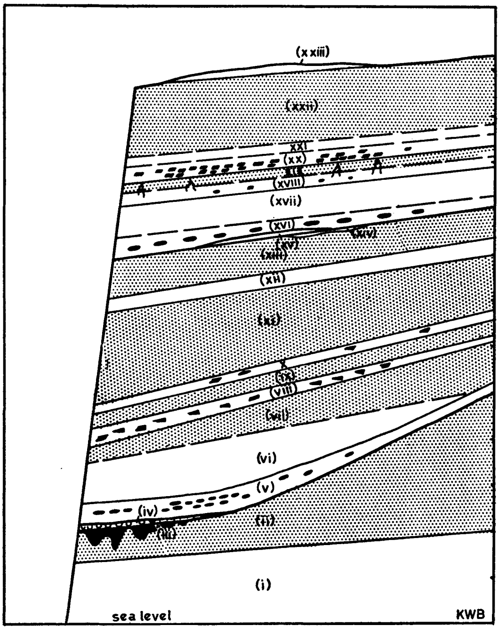


FIG. 7.—Generalized profile of Pleistocene series at Sa Plana. Roman numerals refer to description in text. Scale intervals at margin indicate 2-m. units.

i) Over 4 m. Cemented light red and reddish yellow (2.5 YR 6/6, 5 YR 7/6) silts and coarse breccia with silt matrix, extending to well below modern sea level. Ancient fauna (sixty-six specimens) with a very large form of *Rumina decollata* (60 per cent) and Helicidae (40 per cent) including *Iberellus minoricensis companyoi* Aler. and *Helix* aff. *punctata* Müll. Foregoing pedogenetic conditions can be estimated from the presence of almost 30 per cent colloidal

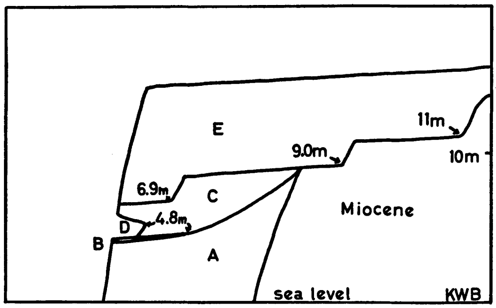


FIG. 8.—Composite profile of various beaches at Sa Plana in relation to the three regressional series, *A*, *C*, and *E*. The Tyrrhenian II–III deposits are disconformably located in *D*. *B* refers to bed (*iv*).

TABLE 3

SA PLANA GRANULOMETRIC ANALYSES

(Per Cent)

	200–2,000 μ	60–200 μ	20–60 μ	6–20 μ	2–6 μ	<2 μ	pH
Dune (*xxiii*)	28.4	38.4	11.8	8.9	2.8	9.7	8.52
Silts (*xx*)	35.9	21.7	10.8	14.9	8.3	8.4	8.43
Dune (*xix*)	28.3	41.6	6.1	9.9	4.3	9.8	....
Silts (*xvi*)	7.8	20.1	4.1	21.6	5.6	40.8	8.32
Silts (*xii*)	22.8	24.0	13.4	12.6	13.2	14.0	8.63
Dune (*vi*)	40.3	25.0	10.1	7.1	6.9	10.5	8.81
Silts (*iv*)	13.0	37.2	13.6	11.2	11.0	14.0	8.74
Soil (*iii*)	11.8	20.1	12.2	20.1	6.9	28.9	8.83

SiO_2, thus accounting for the high pH value of 8.97 (table 3). The presence of abundant foraminifera in thin section and silicified marine organisms in the non-carbonate fraction leaves the possibility open that the original alkaline soil environment was provided by marine sediments. Disconformity.

ii) 125–550 cm. Cemented, moderately weathered, pink (7.5 YR 8/4–6) aeolianite, with 1-cm. wide vertical fissures filled out with secondary calcite. *Helix* aff. *punctata* present. The aeolian character is emphasized by the extremely fine quartz grains present, the advanced stage of regression by a dominance of windworn quartz. The aeolianite surface is obviously planed by marine abrasion, an inclined platform extending to at very least +10 m. Although marine fauna has not been found here as yet, the responsible transgression probably is identical with one or more of the levels of +29–30, +23–25, and +15.5–19 m. represented by cliffs and notches throughout the area studied, where not obscured by younger sediments as at Sa Plana. N. 75° W. (direction of dip).

iii) 0–50 cm. Mature 2.5 YR 4–5/8 *Rotlehm*, preserved in pockets and stone pipes of the previous regressive dune. The surface has been largely eroded and the pocket fillings mixed with marine sand and lenses of fine conglomerate with occasional mollusks. Concentrations of innumerable foraminifera are visible in thin section. The clay fraction (29 per cent) has been partly washed out, the coarser sand is partly foreign as suggested also by quartz percentages: 16.2 per cent of middle sand fraction, only 6.8 per cent of coarse sand fraction. This soil was developed *in situ* from the dune (*ii*). The upper part has been removed and the semi-marine facies goes over into

iv) 10–30 cm. Calcareous marine sand with lenses or crusts of beach rock, fine marine conglomerate and a fauna of *Columbella rustica* L., *Spondylus gaederopus* L., *Lima squamosa* Lmk. (?), *Clamys varia* L., *Arca noae* L., *Pectunculus* (*Glycimeris*) *violacescens* Lmk., *Cardium edule* L., and *Lucina lactea* L. This fauna attaining +4 m. is littoral in character, with a bathymetric range of 0 to 5 m., which does not, how-

TABLE 4

SA PLANA TOTAL SEDIMENT ANALYSES*

(Per Cent)

	Quartz	Waterworn Quartz	Windworn Quartz	Unworn Quartz	Carbonates	pH (H_2O)
Calcite (*xv*)	2.3	*39*	20	41	84	8.66
Dune (*xi*)	1	*54*	20	26	97	8.78
Silts (*xiv*)	5	*60*	24	16	93.5	8.92
Dune (*ii*)	1	30	*49*	21	98	8.80
Silts (*i*)	1.5	*58*	25	17	60	8.97

* Well-defined maxima are italicized.

TABLE 5

SA PLANA MEDIUM SAND FRACTION ANALYSES*

(Per Cent)

	Weathered Grains	Quartz	Waterworn Quartz	Windworn Quartz	Unworn Quartz Grains
Dune (*xxiii*)	15	7.8	21	*41*	38
Silts (*xx*)	77	17.2	18	*40*	42
Dune (*xix*)	81	32.9	30	31	29
Silts (*xvi*)	27	73.7	26	18	56
Silts (*xii*)	88	23.8	24	25	51
Dune (*vi*)	61	4.9	*56*	33	11
Silts (*v*)	79	6.3	*50*	32	18
Soil (*iii*)	82	16.2	*53*	12	35

* Well-defined maxima are italicized.

ever, solve the problem of exact sea level due to lack of a marine notch. Possibly this short transgression left no distinctive abrasional forms. The fauna is not characteristic, although *Spondylus* may suggest a climate similar to that of the present.

v) 50–100 cm. Consolidated to cemented red (2.5 YR 5–6/6–8) colluvial silts with beds of moderately stratified, medium to coarse subrounded gravels (table 6). Some basal sections are clayey in character and have a polyhedral structure, suggesting colluviation of *terra rossa* materials. The gravels leave no doubt as to a moister climate. Aeolian materials increase rapidly toward the top, suggesting an incipient regression. Disconformity.

vi) 170 cm. Cemented light red (2.5 YR 6/6) sands, of dominantly aeolian character but without noticeable bedding other than occasional bands of weakly stratified, angular pebbles. All but the upper 20 cm. of this dune are punctuated by calcareous concretions implying leaching of the surface and Ca-precipitation in a pedogenetic horizon. Disconformity.

vii) 50–230 cm. Cemented (2.5–5 light red 6–7/6) fine aeolianite, bedded N. 70° W. The surface is capped by a 1-cm. tufaceous calcareous crust. The limited fauna consists of *Tudorella ferruginea*, *Iberellus minoricensis companyoii*, and a large *Helix*. Disconformity.

viii) 0–40 cm. Semi-cemented reddish yellow (5 YR 6/6) silts, with occasional medium, subangular pebbles (table 6). Disconformity.

ix) 0–120 cm. Cemented pink (5 YR 8/4) aeolianite with silt admixture.

x) 25–75 cm. Consolidated red (2.5–5 YR 5–6/6–8) plastic silts with moderately stratified bands of angular medium gravel. Disconformity.

xi) 0–4 m. Cemented reddish yellow (5 YR 7/8) weathered aeolianite, with innumerable manganese concretions. Where not overlain by upper beds (*xii*–*xiv*), 1-cm. root or burrow casts filled with crystalline calcite are vertically developed in bifurcating systems to 2 m. below the original surface. N. 50° W. Disconformity.

xii) 0–75 m. Cemented alternating series of colluvial reddish yellow (5 YR 7/8) silts and tufaceous calcareous crusts.

xiii) 0–190 cm. Cemented pink (5 YR 8/4) weathered aeolianite alternating with tufaceous calcareous crusts in upper 40 cm. N. 65° W.

xiv) 0–15 cm. Cemented reddish yellow (5 YR 6/6) silts alternating with tufaceous calcareous crust.

Major erosional disconformity initiated by development of an abrasional platform at +11

TABLE 6

MORPHOMETRIC GRAVEL ANALYSES*

VALUES OF ρ (LÜTTIG'S INDEX OF ROUNDING), $2r/L$ (CAILLEUX'S INDEX OF ROUNDING), AND $(l + L)/2E$ (CAILLEUX'S INDEX OF FLATTENING)

	Sample Size	Mean ρ (Per Cent)	Per Cent ($\rho \leq 8$ Per Cent)	Coefficient of Variation ρ (Per Cent)	Mean $2r/L$	Mean $(l+L)/2E$
Cala S'Almonia (*iv*)	50	54.9	4	44.5	....	....
Modern beach marine gravel	100	80.4	0	99.2	....	1.40
Sa Plana:						
Recent fill	100	8.4	68	106.2	59.6	1.55
(*xx*)	50	9.3	52	129.0	....	....
(*xvi*)	100	14.0	52	104.7	79.3	1.65
(*x*)	25	11.0	52	72.3	81.8	1.58
(*v*)	100	23.0	38	78.3	88.3	1.64

* The index of rounding (ρ) by Lüttig (1956) is obtained by estimating the percentage of a pebble's circumference that is smoothened and convex. It proved to be capable of greatest differentiation in samples of angular or subangular gravels. The writers suggest the following ranges of mean ρ's to define classes as follows: 0–10, angular; 11–20, subangular; 21–40, subrounded; 41–60, rounded; 61–100, well rounded. Lüttig's ρ index is also subject to less possible error, particularly in the angular-subangular range where the Cailleux (1952) index of rounding ($2r/L$) is prone to considerable error. The pebble's major axis L poses no difficulty, but the smallest radius of curvature (r) becomes a matter of arbitrary selection on an angular pebble. Cailleux's index of flattening (l indicating minor axis, E, width of pebble) indicates greater rounding with increased values in a possible range of 1 to 9. This index does not vary significantly in these Mallorcan samples. The writers, however, attach some importance to the coefficient of variation of the rounding index introduced here. Although the coefficient of variation (100 [standard deviation]/mean) varies inversely with the mean value of ρ, it expresses the homogeneity of the gravel samples quite effectively. It is lowest with river or beach gravels sculptured by a single process, rising rapidly with torrential and colluvial samples containing greater quantities of scree and local detritus. Consequently it is quite useful for genetic interpretation of gravels.

m. over the series, very probably a beach. Subsequently the local torrent was adjusted to a marine platform of +9.0 m., followed by a later marine notch at +6.9 m. and an even later excavation of the cave (notch +4.8 m.) indicated in fig. 5, with the ensuing sequence of later Tyrrhenian II*b* and Tyrrhenian III deposits. This disconformity probably represents the Last Interglacial.

xv) 0–10 cm. Calcite-cemented aggregate of very fine manganese particles, groups of quartz crystals and interspersed calcite crystals, together with crumbs or fragments of calcite-saturated (*terra fusca*) *Braunlehm.* The yellow color (10 YR 7/6) is chiefly due to derived weathered calcite particles as well as some primary limonitic oxidation. The immense quantities of free calcite imply deposition by highly calcareous water derived from sheet floods (Butzer, 1962*c*). Probably late Tyrrhenian as the surface was intensely washed prior to deposition of

xvi) 30–70 cm. Consolidated to cemented red (2.5–5 YR 4–5/6–8) clays and silts, derived from colluviation of a *terra rossa.* The high quartz content (over 70 per cent) indicates that this was originally a decalcified residual soil. Calcareous aeolian sand admixture becomes evident toward top, while calcareous concretions gradually go over into a tufaceous silt crust. Crudely to moderately stratified subangular (table 6) gravels are common, going over laterally into 2 m. of red conglomerate at the torrent mouth.

xvii) 75–120 cm. Consolidated to cemented reddish yellow (5 YR 5–6/6–8) fine silts of mixed colluvial-aeolian origin, laterally going over into wind-bedded sections. Capped by 5–6 cm. tufaceous silt crust of reddish-brown (2.5 YR 5/4) color. (Beds *xvi* and *xvii* represent W-Red 1.)

xviii) 40–65 cm. Semi-cemented pink to reddish yellow (5 YR 6–8/4–6) silts, predominantly aeolian with root casts and also occasional pebbles and a capping tufaceous calcareous crust.

xix) 35–55 cm. Semi-cemented pink (7.5 YR 8/3) to reddish yellow (5 YR 7/6–8) aeolianite with root drip (extending downward into *xviii*). N. 50° W. There is a considerable admixture of aeolian or colluvial silts, predominantly weathered materials noted by a high quartz content (over 30 per cent). This is typical W-Dune I*a*. Disconformity.

xx) 40–70 cm. Semi-cemented yellowish red (5 YR 5–7/6–8) silts with some aeolian material and gravel bands of stratified, angular pebbles (table 6). The latter are superficially rubefied and in one bed were largely (44 per cent) mechanically fractured after original rolling, that is, during or immediately after sedimentation. This phenomenon is not conspicuously repeated in the contemporary 1-m. bed of conglomerate in the local torrent but may well be an indicator of more frequent frosts.[6] No torrent transport during W-Red 2. Gravel deposition in the local torrent ceases hereafter until Postglacial times.

xxi) 50–60 cm. Consolidated to semi-cemented reddish yellow (5 YR 6–7/6–8) silts of alternating colluvial (with coarse, angular gravel) and aeolian (bedded sands) character and secondary calcareous concretions due to illuviation from

xxii) 70–500 cm. Consolidated (5 YR 7/6–8) medium-grained aeolianite conspicuously bedded N. 50° W. (against the cliffs, S. 80° W. on the plateau) at a moderately steep inclination. Major bedding planes are semi-cemented and root drip is not infrequent. W-Dune *Ib*. Disconformity.

xxiii) 0–55 cm. Cemented breccia with reddish yellow (5 YR 7/6–8) silts representing a strongly eroded colluvial deposit. W-Red 3.

INTERPRETATION

The twenty-three visible horizons of the semi-conformable series extending from well below sea level to +19 m. give one of the most complete and detailed Middle and Upper Pleistocene sequences of the western Mediterranean area. Only the last W-dune and deposits of the earlier Tyrrhenian I in-

[6] Obviously such a feature does not in any way qualify a description as "cryoclastic beds" with the implication that such mechanical weathering was very significant, e.g., as "periglacial." No typical cryoclastic phenomena were observed on the southern or southeastern coasts. Solé Sabarís (1961) emphasizes the occurrence of a limestone breccia at Cala Pí, which he suggests may be "cryoclastic." Butzer studied the Cala Pí sections in detail in October, 1960. The deposits in question are large crumbs or fragments of calcified *Braunlehm* embedded in a 90-cm. *croûte zonaire* (cf. Durand, 1959; Butzer, 1962*a*) laterally conformable with true travertines. Microscopic and chemical study of a dozen such "pebbles" is conclusive to this effect. On the basis of wind directions of three aeolianites in the Cala Pí sequence the questionable horizon immediately preceded W-Red 3.

terval are lacking. At some other exposures the lower part of the antepenultimate or pre-Tyrrhenian I regressive deposits is visible in a little more detail, which indicates the presence of at least two antepenultimate regressional dunes.

The penultimate regressional series is represented by four clear-cut dunes, which were separated by periods of weathering and subsequent colluviation. The plasticity of sediment (*viii*) indicates that the soil development between R-Dunes II and III was notable. The local torrent has little access to residual *terra rossa* soils of earlier date and has xerorendzinas developed on limestone bedrock or rubefied Middle or Upper Pleistocene sands. Consequently colluvial sediments of weathered materials in most cases mainly indicate soil development on immediately preceding aeolian deposits. The stratigraphic system of the exposure is given in table 7.

The information provided by these outstanding exposures of the coastal cliffs at Sa Plana is corroborated at numerous sites several kilometers up or down the coast, as at Site 6, a defunct torrent at Punta Llarga entirely choked with an excellent semi-conformable series with three last, four penultimate, and at least two antepenultimate regression dunes.

GENERAL CONSIDERATIONS OF PRE-TYRRHENIAN II MARINE STAGES

Whereas the later Tyrrhenian transgressions and the subsequent aeolianites only affected the immediate coastal areas, those of earlier stages left deposits and erosional features right across the upland plains. The transgressions will be considered first.

The Cenozoic strata of Mallorca have been notably modified by high Pleistocene sea levels (for details see Butzer, 1962*b*). Well-developed cliffs, notches, and extensive marine abrasional platforms or shelves are commonplace. Most of the interior aeolianites are associated with retreats from these elevated shorelines. Former relative sea levels of 100 m., 72–75 m., 62–65 m., 48–50 m., 33–34 m., 29–30 m., 23–25 m., and 15.5–19 m. are represented over wide areas, and all these levels are older than the Tyrrhenian II. On the basis of the soil stratigraphy and the bedding directions (table 8) of the associated aeolianites all but the four highest levels postdate the antepenultimate regression. For example, dunes of the penultimate regression can be traced inland by characteristics of lithology, bedding, and weathering to northeast of Campos. Beyond Campos their bedding suggests that they were deflated from marine beds inland from that town—at the 40–50-m. contour. Similarly intensely weathered, fully cemented aeolianites of the antepenultimate regression can be traced from Sant Jordi to northeast of Campos, where they underlie the younger series. The older dunes near Ses Salines and elsewhere in the Balearic Islands clearly postdate the 48–50-m. transgression. This still leaves four major transgressive stages between 15.5 and 36 m., between the antepenultimate and penultimate regressions, in what may be called the Tyrrhenian I Complex. To this range must still be appended the late transgressive phase of 4 m., first recognized at Sa Plana.

Another site illustrating the final Tyrrhenian I oscillation is found at S'Estalella

TABLE 7

Antepenultimate Regression. At least 10 m. (*i*) (*ii*)
Tyrrhenian I Interval. 0–80 cm. (*iii*) (*iv*)
Penultimate Regression. 8.5–11 m. (*v–xiv*).

	Average
R-Red 1 (*v*)	90 cm.
R-Dune I (*vi*) (*vii*)	310 cm.
R-Red 2 (*viii*)	50 cm.
R-Dune II (*ix*)	60 cm.
R-Red 3 (*x*)	20 cm.
R-Dune III (*xi*)	200 cm.
R-Red 4(*xii*)	40 cm.
R-Dune IV (*xiii*)	95 cm.
R-Red 5 ? (*xiv*)	5 cm.

Tyrrhenian II–III Interval. 0–145 cm. (*α-δ*) (*xv*)
Last Regression. 6.5–10 m. (*xvi–xxiii*).

W-Red 1 (*xvi*) (*xvii*)	150 cm.
W-Dune I*a* (*xviii*) (*xix*)	95 cm.
W-Red 2 (*xx*) (*xxi*)	110 cm.
W-Dune I*b* (*xxii*)	300 cm.
W-Red 3 (*xxiii*)	25 cm.

(fig. 9), at the medieval tower of that name, some 650 m. W.N.W. of Punta Plana. The top of this sequence is formed by a Tyrrhenian II beach at 10.2 m. The rich Senegalese fauna of this beach has been discussed in Butzer and Cuerda (1961). The continental series of the penultimate regression occurs just below the 10-m. beach, overlying a fossiliferous sandy silt. The silt is 15 cm. thick and contains a primary fauna of *Trochocochlea* (*Monodonta*) sp., *Patella caerulea* L., *Hydrobia* sp., and probably *Cardium edule* L. The greatest part of the *C. edule* and a larger *Cardium* sp. is, however, derived from the basal Miocene calcarenite. The deposit attains at least +4.2 m., and on the evidence of these littoral or marine-lagoonal species did not exceed +5 m. The bed overlies a *terra rossa* developed *in situ* on the basal calcarenite. This soil occupies an analogous position to that at Sa Plana, and the stratigraphic parallels are more than coincidental, for the calcarenite surface was planed off by marine abrasion by an earlier Tyrrhenian I sea. This *terra rossa* is almost equivalent to a guide horizon of the Tyrrhenian I in context with aeolianites.

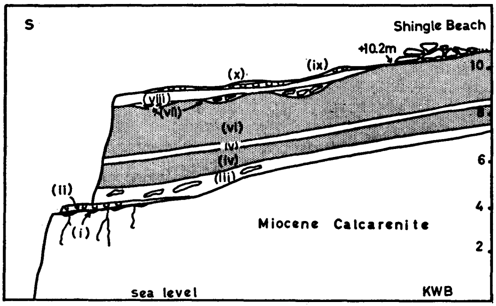


FIG. 9.—Profile of Tyrrhenian I–II deposits at S'Estalella. The fossiliferous Tyrrhenian I bed (*ii*) is overlain by penultimate regression silts and colluvium (*iii*), (*v*), (*vii*) and aeolianites (*iv*), (*vi*), and (*viii*). The marine beds of the Tyrrhenian II (*ix*) contain Strombus as well as several other thermophile species and are locally veneered by terrestrial silts (*x*). Vertical exaggeration 2×. Units at margin in meters.

The widespread distribution of the older aeolianites results from several factors. Some occurrences may be explained by the deflation of marine sediments well inland. Another explanation is climatic: the last regression aeolianites are conspicuously bedded only where banked against the coastal cliffs. On the surface of the Miocene strata their bedding is remarkably poor, in contrast to the aeolianites of the penulti-

TABLE 8*

DEVIATION OF MEAN AEOLIANITE BEDDING IN SOUTH MALLORCAN DEPOSITS FROM MODERN STORM-WIND DIRECTIONS

Stratigraphy	Direction of Dip	Deviation	No. of Observations
East coast:			
W-Dune II (late)	N. 4° W.	48° E.	6
W-Dune II (early)	N. 27° W.	25° E.	5
W-Dune I*b*	N. 25° W.	27° E.	18
W-Dune I*a*	N. 43° W.	9° E.	14
R-Dune III	N. 9° W.	41° E.	7
R-Dune I	N. 14° W.	38° E.	5
"Antepenultimate" Dunes	N. 30° W.	22° E.	2
West coast:			
W-Dune II (early)	N. 30° E.	50° W.	2
W-Dune I*b*	N. 42° E.	38° W.	5
W-Dune I*a*	N. 50° E.	30° W.	10
R-Dune IV	S. 77° E.	23° E.	9

* Isolated observations and stratigraphically uncertain or unfixed aeolianites were systematically excluded. East-coast deviations are based on two modern averages, the strong winds of the plateau surface, and the topographically modified "local" directions at the base of the cliffs. Both are internally quite consistent, as indicated by coefficients of variation and can be determined by brush and tree deformation.

mate regression. This may imply that local climate was considerably drier at the height of the penultimate regression than during the last. A second climatic explanation may be indicated from the storm-wind directions themselves, which were quite different during the various stages (table 8). During the last regression, most important winter gales blew from the east and thus limited aeolianites on the west coast to localized areas sheltered from easterly winds. During the penultimate regression the most important storms came from the Gulf of Valencia (Butzer, 1961*b*)—the *Llebeig*—and they were able to sweep sand right across the Mallorcan uplands. Due to the more limited eastern storms contemporary east-coast dunes are confined to the lee of the cliffs.

Although few sections expose a complete stratigraphy of the antepenultimate regression, the general sequence is one of two major dunes interrupted by a period of weathering. The base is visible at only one section at 85-m. mean sea level which is located in a railroad entrenchment west of Campos at KM 38. The beds lie upon Miocene calcarenite locally reduced to wide marine platforms of the 62–65-m. and 72–75-m. transgressions. The section is as follows:

i) 0–120 cm. Cemented pink (7.5 YR 7–8/4) coarse-grained aeolianite with abundant foraminifera. On Miocene.

ii) 0–70 cm. Semi-cemented, weathered reddish yellow (5 YR 7/6) aeolianite with concretions and secondary cementation. Disconformity.

iii) 20 cm. Consolidated light red (2.5 YR 6/8) colluvial soil and derived aeolian silts and stratified detritus.

iv) 100 cm. Cemented reddish yellow (5–7.5 YR 7–8/6) fine-grained aeolianite with two colluvial horizons (20–25 cm.) of consolidated loess-like materials.

v) 140–170 cm. Consolidated pink (7.5 YR 8/4) mixed colluvial loess with root drip and calcareous concretions. The upper 130 cm. alternate with massive tufaceous calcareous crusts.

Above this are up to 50 cm. of light red (2.5 YR 6/8) clayey loam (*vi*) representing a slightly redeposited B-horizon of a *terra rossa* developed *in situ* from (*v*). At a somewhat later date *terra rossa* sediments were locally redeposited with tufaceous beds and again subsequently weathered. The original *terra rossa* conforms to the physical and chemical properties associated with Tyrrhenian I weathering. The section appears then to postdate the 60–70-m. transgressions and antedate the Tyrrhenian I. The granulometry of beds (*i*) and (*ii*) is so coarse-grained that the deflated marine sediments must have been nearby, which suggests that beds (*i*) and (*ii*) represent the first aeolianite actually deposited, so that this was only a two-phased regression. Later beds (*v*) are moderately loess-like, indicating long distance transport, and implying a regression of considerable depth.

The weathering during the positive oscillation of sea level (tables 9 and 10) was expressed by oxidation and weathering of bed (*ii*) which probably indicates a truncated BC or B horizon, and by the high quartz concentration in the colluvial bed (*iii*), which indicates extensive leaching of carbonates in the intervening interval.

CONCLUSIONS AND SYNTHESIS

The stratigraphic results of these investigations can be most effectively summarized in the form of a eustatic graph (fig. 10). The time scale is entirely relative and the criteria employed are heterogeneous. These criteria include not only exact sea-level positions and indirect evidence of regressions but also evidence of their comparative amplitudes as expressed by the thickness of respective aeolianites. The evidence of some three dozen major sites has been incorporated so that the curve is fairly reliable—in a relative, not an absolute, sense—from the later Tyrrhenian I onward. Obviously the type of evidence used does not permit quantification of the amplitude of regressions, while the incomplete sedimentary record of the regressions in particular makes chronological estimates next to impossible.

Earlier data are not quite complete. It is not known whether the earlier Tyrrhenian I levels are really successive. Also the amplitude, duration, or intensity of the regressive oscillations between the Tyrrhenian I levels is not known. With such a multitude of apparently progressively falling beach levels and oscillations, the Tyrrhenian I was truly a very extensive and perhaps heterogeneous complex. The steplike sequence of beaches reflects the progressive lowering of Quaternary sea level. The large number of such levels indicates that correlation of Lower Pleistocene beaches around the Mediterranean will be most difficult. The authors offer no qualifications for this multitude of levels, which are based on independent criteria and do not reflect regional differences of one and the same shore line.

That part of the curve which is continu-

TABLE 9

KM 38 GRANULOMETRIC ANALYSES

(Per Cent)

	200–2,000 μ	60–200 μ	20–60 μ	6–20 μ	2–6 μ	<2 μ	pH (H_2O)
Soil (*vi*)	26.4	32.8	4.5	12.8	11.7	15.8	8.62
Silt (*v*)	13.7	20.7	19.5	32.6	8.9	4.6	8.69
Dune (*iv*)	....	....	....	....	....	....	8.30
Silt (*iii*)	10.5	41.5	9.8	6.4	10.7	21.1	7.09
Dune (*ii*)	38.4	26.1	9.2	5.2	9.3	11.8	8.25
Dune (*i*)	42.7	22.9	6.8	8.9	6.2	12.5	8.42

TABLE 10

KM 38 MEDIUM SAND FRACTION ANALYSES

(Per Cent)

	Weathered Grains	Quartz	Waterworn Quartz	Windworn Quartz	Unworn Quartz Grains
Soil (*vi*)	23	1.9	29	19	52
Silt (*v*)	8	4.0	24	28	48
Silt (*iii*)	3	19.5	30	37	33
Dune (*ii*)	62	3.9	35	24	41
Dune (*i*)	3	1.1	38	24	38

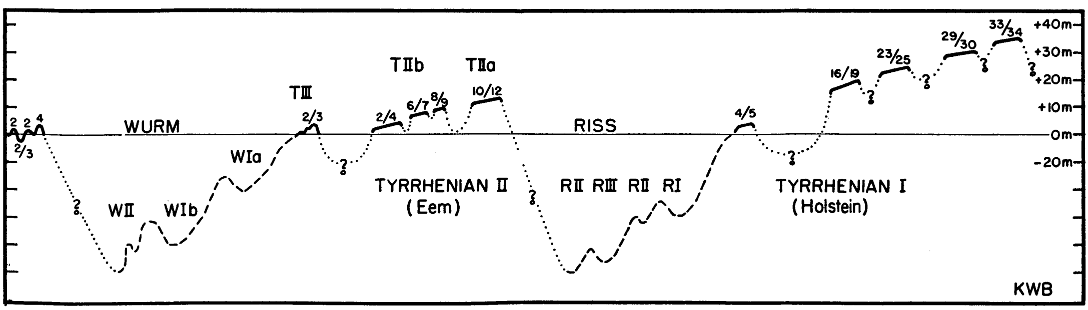


FIG. 10.—Generalized curve of relative sea level deduced from Pelistocene deposits of southern Mallorca. Time scale is relative. Solid line indicates recognizable transgressive beaches; dashed line indicates relative extent of regressions attested by aeolianites; dotted line indicates presumed transgressive oscillations. Scale below modern sea level is only relative.

ously, even if only schematically, drawn does in the authors' opinion indicate a reliable estimate of Mediterranean sea-level fluctuations of the Middle and Upper Pleistocene. The question of appropriate terminologies can thus be raised. The last major regressive interval may be correlated with the Würm or Wisconsin glaciation, without specifying details of middle latitude stratigraphy. Similarly the classical Tyrrhenian II recalls the last interglacial in many ways. The term *Riss*, however suggestive, might add unnecessary connotations to the penultimate regression. Whether the Tyrrhenian I complex should be correlated with the Great or Holstein (Mindel-Riss) interglacial is impossible to decide at the present state of stratigraphic controversy. It would seem preferable on existing evidence to delineate the chronology as shown in table 11.

The chronological context of the "final" transgressive oscillations remains to be clarified. These final oscillations could be either "late interglacial" or "early glacial" in the glacio-eustatic curve. Both in the late Tyrrhenian I, recognized and studied for the first time in this paper, and also in the controversial Tyrrhenian III, true regressional dunes first appear after and not before the transgressive oscillation. This, we believe, warrants the intra-Tyrrhenian I and intra-Tyrrhenian II–III intervals to be considered as minor oscillations, each within a dominantly transgressive interval. The characteristic *Rotlehm* or *Braunlehm* development of both periods is also incompatible with a glacial-age climate for these are subtropical or semitropical soils, according to such authors as Reiffenberg (1947), Albareda (1950), Kubiëna (1955), Klinge and Mella (1957), Durand (1959), Fränzle (1959), and others. The impoverishment of the marine fauna, on the other hand, is logical since such late interglacial intervals apparently had a climate not much warmer than the present, long after the respective thermal maxima.

TABLE 11

PLEISTOCENE CHRONOLOGY OF SOUTHERN MALLORCA

Lower Pleistocene	*ca.* 110 m.	Transgression	Early Sicilian
	ca. 72 m.	Transgression	Later Sicilian
	ca. 62 m.	Transgression	
	ca. 50 m.	Transgression	
	Antepenultimate regression (2 phases)		
Middle Pleistocene	33 –34 m.	Tyrrhenian I complex	
	29 –30 m.		
	23 –25 m.		
	15.5–19 m.		
	4 –5 m.		
	Penultimate regression (4 phases)		
Upper Pleistocene	10.5–12.5 m.	Tyrrhenian II*a*	
	8–9 m.	Tyrrhenian II*b*	
	6–7.5 m.		
	2 m.		
	3.3 m.(?)	Tyrrhenian III	
	2.6–2.8 m.		
	0.5 m.		
	Last regression (3 phases)		
Recent	4 m.	Flandrian transgression*	
	2 m.		

* These features of post-Pleistocene date are described in Butzer and Cuerda (1961) and Butzer (1962*b*). They can be easily distinguished from the Tyrrhenian shore lines on the basis of few species of fauna originally studied in good stratigraphic sections where Flandrian beaches were excavated into last regressional series. Such Recent beaches are very poorly developed and only locally present.

In terms of the glacio-eustatic curve, world glaciation during the Tyrrhenian III Transgression cannot have exceeded that of the present day. It would seem more logical to consider it as an interglacial rather than as an interstadial situation. The preceding negative pulsation was moderate, so that it seems preferable to include this transitional period in the Last Interglacial and commence the classical Würm Regression with W-Red 1.

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