CLIMATIC-GEOMORPHOLOGIC INTERPRETATION OF PLEISTOCENE SEDIMENTS IN THE EURAFRICAN SUBTROPICS

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INTRODUCTION

EFFECTIVE UNDERSTANDING of Pleistocene stratigraphy in terms of palaeoclimatic units is dependent upon systematic interpretation of geomorphic features. Most existing literature however has emphasized cycles and denudation chronologies while the corresponding sediments are frequently ignored. The core of the problem of "pluvial" paleoclimates, viz. whether an increase of precipitation or a decrease in evaporation is involved, can only be reached by sedimentological investigation. Sedimentology cannot provide absolute answers and indeed small variations in rainfall intensity, amount, or variability within a single climatic province may render absolute or numerical generalizations inadequate. The size, slope, and relative elevation of a catchment area may also determine the details of sedimentation by fluviatile processes. Nevertheless, wherever tectonic factors can be discounted it is the sediment rather than the erosional form that is more elucidating—providing of course that the former is preserved.

Although some observed deposits or phenomena are more or less fossil, many can still be interpreted indirectly when compared to modern analogies. Transport capacity of the fluviatile agents which are responsible for the different specific classes of sediments can be compared by quantitative or semiquantitative evaluations of modern and Pleistocene constituents. Similarly, Pleistocene deposits of differing stratigraphical age can be comparatively analyzed and can on occasion be subjected to micro-stratigraphic analysis. The intensity of soil development at different periods may often be assessed by field observation alone. A knowledge of the vegetation type and vegetative mat associated with different degrees or types of denudation and deposition is also useful in process interpretation.

Comparative interpretation can be successfully applied to most Pleistocene sediments and the following discussion of sediments commonly found in the subtropical zone is based upon personal study in two distinct climatic provinces:

(1) the modern Mediterranean littoral climate (*Csa*) studied in a subhumid and semiarid variety (Catalonia and the Balearic Islands, respectively), and (2) the modern winter-rain desert climate (*BWhs*) studied in the arid zone of Egypt. Comparative observations in other parts of Spain and in Italy and Palestine have also been included although the writer does not claim general validity for the conclusions reached outside of the specific areas studied. Reference is specifically made to lowland areas which have a limited altitudinal variation in their catchment basins, and thus exclude sedimentation which may have been caused by cold climate agents of the Pleistocene. Tectonic activity was also absent or insignificant in the areas of detailed investigation during post-Villafranchian time.

The various gradational agents and related sediments will be outlined and briefly discussed.

I. AEOLIAN PROCESSES

Regressional Dunes (Aeolianites)

The shores of many subtropical and tropical lands, characterized by arid or semiarid climate today, have widespread calcareous littoral dunes. In areas of limestone bedrock these dunes are over 90% soluble in HCl and contain large quantities of organic materials such as molluscan debris and Foraminifera. In more humid climatic zones littoral dunes are composed of much greater proportions of quartz sands since calcareous materials have been extensively removed by solution. Such littoral dunes alone are not indicative of local aridity, but the calcareous facies is almost exclusively developed in semiarid landscapes where solution and leaching have been moderate if not ineffective. In these areas the greater part of such littoral dunes are consolidated and immobile, and consequently fossil. Such massive deposits are due to accelerated deposition following deflation of epicontinental lime sands and marine rubble during glacio-eustatic regressions. In a pioneer study on Bermuda, R. W. Sayles (1931) defined these fossil littoral or *regressional dunes* as *aeolianites*. They are frequent on rocky or cliff coasts where beach sands are no longer available for deflation today. [Synonyms: "*grès*" *dunaire* (French North Africa), *ramleh* (Lebanon), *kurkar* (Palestine-Israel).]

Morphology. Aeolianites developed in typical aeolian facies may be found either as (1) steeply inclined, foreset-bedded dunes embanked against coastal cliffs with typical seaward dip values of 40–60%, and landward values of 60–80%; (2) free longitudinal dunes of subdued morphology on coastal plains, where they often form littoral cordons. The local relief of one dunal generation may be in the order of 5–25m, while slopes are gentle, and seldom exceed 25%. Barkhan and transverse forms are also known in such deposits, particularly in desert areas with little or no vegetation; (3) undulating sand sheets with longitudinal affinities of subdued dunal topography, concentrated in 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.

Sedimentology. 1.) It is difficult to give quantitative data on *grain size* distributions as many different gradations between fluviatile-colluvial and aeolian bedding may occur. Water-borne admixture can be invariably recognized by discoloration from the normal white or very pale brown (10 YR 7–8/2–4 according to the *Munsell Soil Color Charts*) due to addition of weathered materials. Aeolianites without such admixture were analyzed from Mallorcan samples and it was found necessary to subdivide them into a coastal (coarse-grained) and an interior (finer-grained) facies (Table 1). The typical coastal facies has an average composition 70% in the coarse sand (200–2000 microns) fraction, and 90% in the sand (20–2000 microns) fraction. The respective proportions of interior aeolianites may be reduced to 40% and 70%. Predominantly aeolian but highly mixed deposits will still retain a 75% sand fraction but the coarse sand component is reduced to 25–30%.

TABLE 1

GRAIN SIZES OF AEOLIANITE SAMPLES FROM MALLORCA (in percent)

(A: typical Pleistocene coastal aeolianite; B: modern coastal dune; C: typical Pleistocene interior aeolianite; D: mixed Pleistocene coastal aeolianite; E: semicolluvial Pleistocene coastal aeolianite)

Sample	*200–2000μ*	*60–200μ*	*20–60μ*	*20–2000μ*	*6–20μ*	*2–6μ*	*<2μ*
A	66.6	22.6	3.6	92.8	2.2	1.3	3.7
B	80.7	5.5	0.2	86.4	3.1	1.9	8.6
C	42.7	22.9	6.8	72.4	8.9	6.2	12.5
D	59.1	28.5	3.4	91.0	1.1	1.4	6.5
E	28.3	41.6	6.1	76.0	9.9	4.3	9.8

2.) Aeolianites are composed of disintegrated molluscan rubble and clastic inorganic materials derived directly from coastal bedrock. They are then essentially a terrestrial form of calcarenite. Along the Miocene limestone coasts of Mallorca, unweathered littoral dunes, whether modern or fossil aeolianites, contain calcareous components as high as 95%. The second major component is quartz which averages 0.5–4.5%, whereas Fe_2O_3, Al_2O_3, MnO, etc., amount to as much as 1%. Mixed and particularly semicolluvial beds contain higher values of noncalcareous materials and quartz proportions rise to 30% or more in some beds.

3.) Analyses of *quartz-grain micromorphology* have disclosed that the percentage of rounded glossy water-worn, or frosted wind-worn grains are matched by a large percentage of angular unworn grains (Table 2). Furthermore, waterworn grains frequently out-number the wind-worn specimens but without an obvious explanation. This can be attributed to the fact that aeolian transport is over such small distances in many or most instances that quartz grains are only partly modified by aeolian agencies—unlike the continental dunes of desert regions where transport, which is often repeated after renewed deflation, involves great distances. Analysis of 300–1500 micron quartz components were of little more significance than those of 60–200 micron quartz for interpretative purposes, despite the reduction in the number of unworn grains. Wind-worn, smooth ellipsoidal calcite grains are in fact a more significant feature under the microscope.

TABLE 2
MICROMORPHOLOGIC ANALYSIS OF QUARTZ GRAINS
(of medium-sand fraction, in percent. Referring to Table 1)

Sample	*Waterworn*	*Windworn*	*Unworn*
A	7%	66%	27%
B	15	45	40
C	38	24	38
E	30	31	29

4.) Bedding features of many aeolianites are marked stratification surfaces occurring at certain intervals. These often show increased consolidation indicating temporary erosion and prolonged exposure to subaerial agents. Foreset bedding is common, crossbedding rare. Embanked aeolianites at the base of cliffs always exhibit marked stratification, whereas many coastal plain or interior deposits lack bedding. Poor or no stratification is usually associated with frequent root drip or with the root casts and calcified roots of halophile shrubs or conifers such as *Juniperus*. The writer attributes this class of aeolianites to deposition under vegetation, such as intermingling with the needle *førna* under coniferous woodland. Unbedded littoral dunes form in this fashion today. On the other hand, well-bedded coastal plain or interior aeolianites without root drip are certainly indicative of sparse vegetation and prevailing aridity.

Further palaeoclimatic information can be derived from bedding directions (directions of dip), which can be used to compare mean storm wind deviations of various stratigraphic units with modern conditions (cf. Butzer 1961, Butzer & Cuerda 1962).

Stratigraphic Significance. Well-developed aeolianites which occur along sandy or shallow-water coasts, or any form of aeolianite along rocky or cliff coasts without sandy beaches, may be regarded as evidence of marine regressions. Only under regressive conditions can sufficient unconsolidated shelf sediments be subjected to deflation by storm winds. In particular, as H. E. Wright (1962) has argued, such aeolianites are indicative of a marine regression actually in

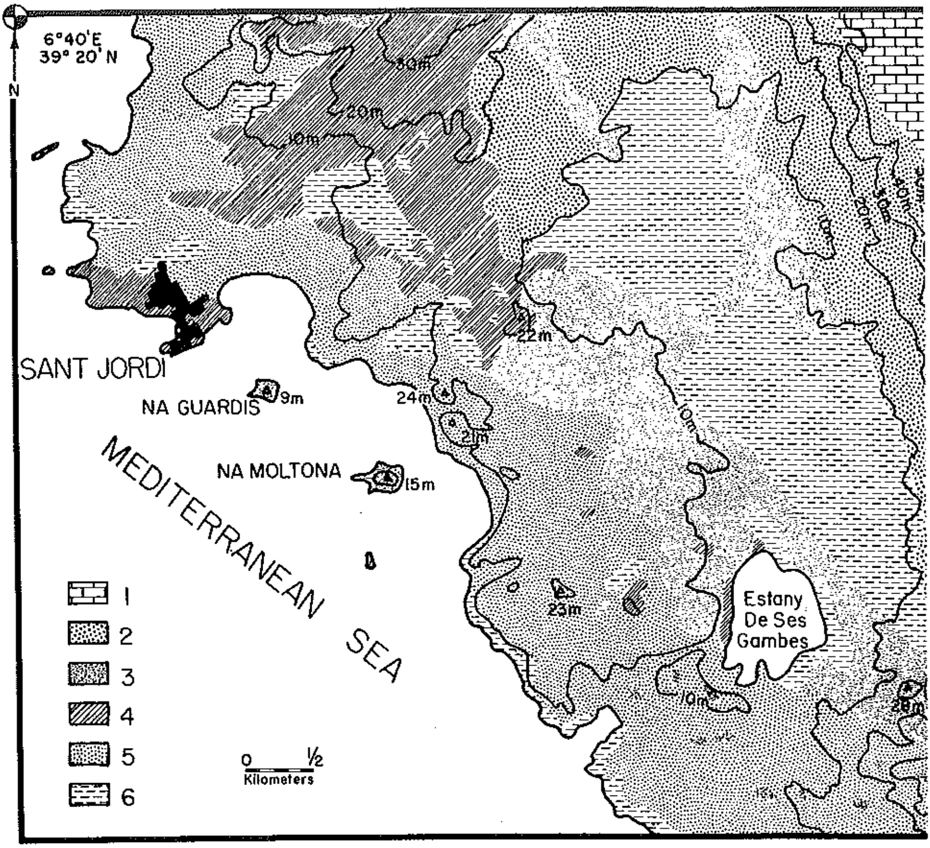

FIGURE 1

Littoral cordon of three generations of Pleistocene Aeolianites on the southern coast of Mallorca. 10 m. contour interval. 1: horizontal Miocene limestones; 2: cemented and weathered aeolianite of antepenultimate major regression; 3: consolidated and weathered aeolianite of penultimate major regression; 4: semiconsolidated aeolianite of last major regression; 5: unconsolidated littoral dunes (subrecent) or loose aeolian mantle; 6: unconsolidated and cemented colluvial silts of various ages. From 1:50,000 geological map by the writer.

progress. For once regression ceases or a renewed rise in sea level occurs, no new sands are exposed to deflation and consequently sedimentation stops. Conformable stratigraphic sequences are present on Mallorca (Butzer and Cuerda 1962) where final interglacial transgressive beds with thermophile faunas are succeeded by colluvial beds to approximately modern sea level. Such colluvial silts grade over into aeolianites which extend to well below modern sea level. Many typical aeolianites also contain small wind-worn mollusca which are often

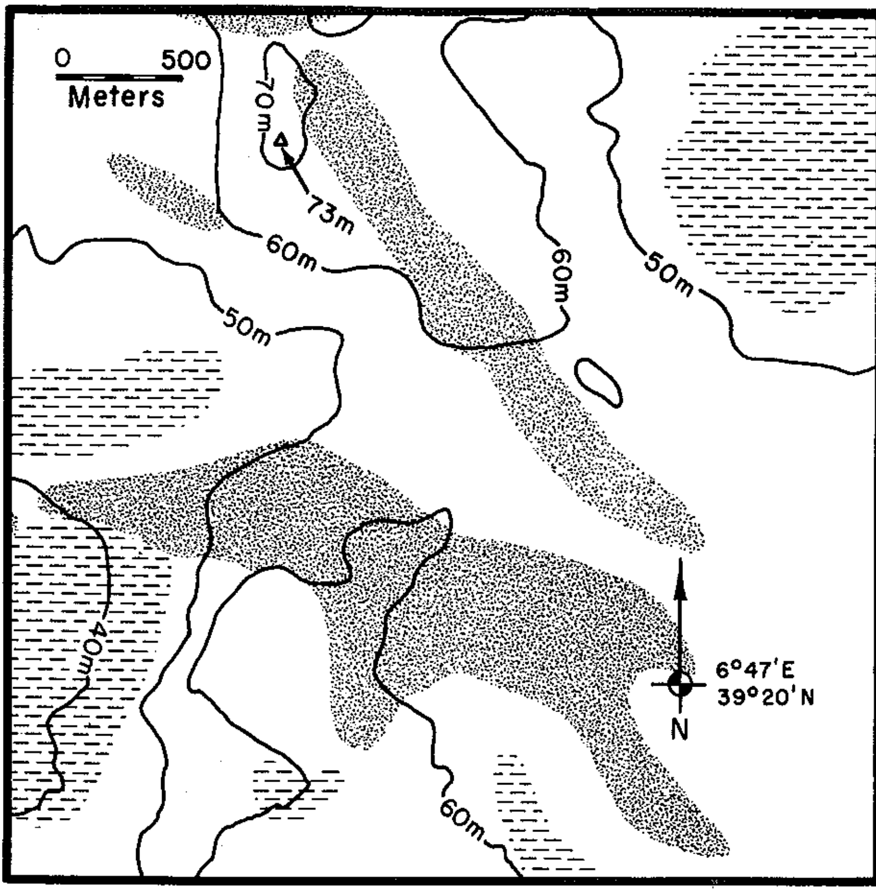

FIGURE 2
Interior aeolianites of subdued topography (from southern Mallorca). Dot pattern indicates shallow aeolianites of the penultimate regression, shaded pattern unconsolidated colluvial silts largely of last regressional date.

quite intact. Such coarse components are not present in later beds nor in those with interior situations. There can be absolutely no question of the regressive character of the aeolianites studied by the writer in Spain, or of those described by various French authors (e.g., J. Hilly 1957) for North Africa and by R. W. Hey (McBurney & Hey 1955) for Cyrenaica. Recent unfounded suggestions by K. H. Kaiser (1960) to the effect that Lebanese aeolianites are transgressive sediments must be discounted.

As interpreted here aeolianites are invaluable as an indirect means of correlation with higher latitude glaciation through the glacio-eustatic chronology. Interruptions of aeolianite deposition may indicate world-wide halts or oscillations of the continental glacier advances. Similarly aeolianite deposition must more or less cease when the maximum of a glacial regression has been attained (Wright, 1962). True aeolianite therefore is stratigraphically indicative of the earlier phases of continental glacial advances until the period of maximum ice extent.

The widespread occurrence of aeolianites provides a most valuable paleoclimatic and stratigraphic guide along subhumid to arid subtropical and tropical coasts.

Continental Dunes

Although continental dunes do adjoin coastal aeolianite fields in some areas, the former are generally a quite distinct feature in arid zones. Certainly dunes form under a wide range of thermal and precipitation conditions if a ready source of loose, unstabilized material is available. The extensive fields of parabolic or blow-out dunes of the Würm-Wisconsin tundras of Central Europe and the United States were deposited under a considerable herbaceous vegetation. Small active dune fields are not unknown along the sandy beds of seasonally overloaded streams in semiarid climatic zones. Continental dunes of the barchan, transverse and longitudinal type are however essentially a characteristic of the world's deserts. Within these deserts their distribution is determined by the presence of suitable materials for deflation. The majority of *ergs* moreover are not a product of present conditions.

Morphology. The dunal forms of the continental arid zone include free dunes of the well-known longitudinal, barchan, and transverse type, as well as tied dunes of the lee type. Sand or loess mantles of subdued or incoherent morphology are also not unknown within the same physiographic zone.

Sedimentology. The typical *grain size* distribution of continental dunes (Shepard and Young 1961, Bagnold 1954; J. Meckelein 1959, p. 176) differs appreciably from that of aeolianites. Medium-grained sands (60–200 microns) provide 20–90%, i.e., twice or more the medium sand components of aeolianites. Very coarse sands are less frequent since transport is over much greater distances than that involved in the formation of regressional littoral dunes. The most striking characteristic of these dunes is the almost complete absence of any component under 30 microns. Granulometric spectra are thus necessary to help to determine the mode of origin of fossil sands and particularly that of sands found in coastal proximity.

Fossil desert loess is reported from northern Tripolitania (C. Rathjens 1929) but no grain size analyses are available, and the proximity of the Mediterranean Sea is disturbing.

The material composition of continental dunes is characterized by a dominance of quartz although very appreciable calcite components may be present if the local bedrock is calcareous.

Quartz grain morphology of such aeolian sands has been adequately described by A. Cailleux (1952). Wind-worn frosted grains are quite dominant and well developed.

Paleoclimatic Significance. Fossil dune fields dominate the Saharan subcontinent today. Successive authors have described crusts, paleosols, and stabilizing oxidation horizons of incipient (B)-type from the great Algerian ergs and Fezzan *edeyens.* In fact several dune generations are obviously represented in these. The *goz* of the Sahel belt, which is a broad zone of apparently rather complex genesis, provides an example of fossil dunes that are now located well within semiarid or even subhumid climates. On the other hand the dune fields of the Libyan Desert are apparently mobile and this also applies to innumerable smaller fields in various parts of the Sahara.

In view of the occurrence of both fossil and mobile dunes in full desert country which is quite devoid of vegetation today, the climatic geomorphology of widespread aeolian deposition seems a little perplexing. In fact, J. Meckelein (1959, pp. 63 ff.) suggests that dunes are representative of marginal rather than full desert conditions, and that the Fezzan *edeyens* are really relics of a moister climate. This interpretation is open to question, but it seems certain that Meckelein's conclusion that former moist phases presumably provided large expanses of wadi sands and lacustrine sand plains, which were then available for subsequent deflation under quite arid conditions, is more convincing. Other authors have suggested that the Libyan Desert sands were originally derived from regressional dunes during various phases of the Pleistocene (G. Knetsch, personal communication).

The only solution to reliable paleoclimatic interpretation lies in comparative analysis (eg., Butzer 1959a, c). Local aeolian processes must be studied from the contemporary viewpoint and past and present source areas of deflation must be located and compared with fossil dune orientations. The possibilities of mechanical dune field migration and hence "accidental" sedimentation must be explored. But whatever the situation, provided that sedimentological characteristics are sufficiently distinctive or that the particular dunal morphology corresponds to barchan, transverse or longitudinal forms, the presence of little or no vegetation may be assumed.

II. FLUVIATILE PROCESSES

Alluvial Beds

Pleistocene sediments transported and laid down by more or less channelled watercourses are frequent throughout the subtropical arid and semiarid zones. They represent the effect of regular or irregular stream removal, transport and deposition of clays, silts, gravels or cobbles during waterflow of variable intensity or duration.

Morphology. Water-laid deposits of linear, channelled type are generally preserved in two major forms: undissected or dissected alluvial valley fill (fluviatile *terraces*), and radially deposited *fans* of alluvium at the mouths of steep-sided channels abutting on to open plains or broader valleys.

So-called non-cyclic or non-paired alluvial terraces are not known to the writer in the Mediterranean area or northern Africa. Tectonically controlled terraces are locally present. The overwhelming majority of alluvial terraces are however the result of local climatic change within the catchment area or are an indirect response to climatic change elsewhere expressed by changes in base level of the ocean or of major river valleys. An example of the latter is the relationship between the Nile River and its tributary wadis. Broader stream valleys of the river, arroyo, torrent, wadi, khor, etc., type very often display several terrace levels indicating several phases of climatic change, often susceptible to stratigraphic differentiation.

Alluvial fans are found in numerous situations where steep-sided streams emerge onto broad flat surfaces leading to radial spread of waters, loss of stream volume with distribution and braiding, and hence loss of velocity and carrying capacity. Reductions of stream gradient intensify the localized deposition of alluvium on the margins of the flat terrain. Such alluvial fans of varying size and development are to be found at the piedmont of various mountain ranges (e.g., Morocco, Mallorca) or at the mouths of various wadi channels emerging from dissected country onto open plains or into such large valleys as that of the Nile. Semiarid countrysides today, particularly in the vicinity of the Mediterranean Basin, often have complex alluviated valley systems with irregular valley gradients due to fan deposition at tributary confluences.

Sedimentology. On account of the tremendous range of intensity and duration of transporting capacity by running waters, granulometry, quartz grain morphometry, stratification, and sorting vary within an almost undefined range. According to the geology of the drainage basin in question the mineralogy of sediments will vary from place to place. Except for a basic characteristic of fluviatile wear (some rounding of coarser components) and stratification (crude horizontal bedding of either horizons or individual size components), which is necessary to determine the possible fluviatile nature of deposits, no diagnostic sedimentological characteristics can be cited. This does not render sedimentological study either ineffective or unnecessary but makes such analysis essential.

Morphometric quartz grain analysis is capable of determining the degree of rounding as well as percentage of water-worn glossy grains (Cailleux 1952). Gravel size and morphometric gravel analyses are moreover essential to the characterization and eventual genetic interpretation of alluvial beds.

Gravel size studies are particularly useful in attempting an over-all interpretation of stream deposits. The standard units employed in size analysis are fine gravel (2–6 mm. diameter), medium gravel (6–20 mm. major axis), coarse gravel (20–60 mm. major axis), and cobbles (over 60 mm.). Completely angular materials such as grit (2–20 mm.) are also distinguished from detritus (over 20 mm. diameter).

Morphometric gravel analysis can only be briefly referred to in this paper but general references to the various indices, applications, and geomorphic significance can be obtained from M. Blenk (1960). After particular application of various indices to largely angular gravel samples of the Mediterranean area it seems that several indices can be most effectively employed. They are (1) the Szadeczky-Kordoss index of rounding (G. Lüttig 1956), which refers to the percentage of smoothed, convex circumference of the individual pebble. The following classes of mean values per sample are suggested by Butzer & Cuerda (1962):

0–10%	angular
11–20%	subangular
21–40%	subrounded
41–60%	rounded
over 60%	well rounded

Such divisions are quite useful for effective characterization of deposits. The Cailleux (1952) index of 2r/L, where *r* is the smallest radius of curvature and *L* the length of the major axis, was not considered satisfactory for analysis of the morphometry of arid zone samples. Further information on genetic homogeneity can be obtained by counting the pebbles of a sample (100 pebbles) with $\rho \leq 8\%$ as well as by the use of the coefficient of variability within a sample. (2) the index of flattening, whereby the ratios E/L and e/l (*E* breadth, *l* minor axis, *L* major axis) are simplest and most effective as comparative indices of dominant sliding (low ratios) or rolling (high ratios) motions (e.g., Blenk 1960). Pebble flattening is an index of mechanical action rather than climatic regime. The ratios indicated above can be more simply and accurately determined by such techniques as Lüttig's (1956), than by the more lengthy procedure involved in the evaluation of Cailleux's (l+L)/2E index.

The significance of morphometric gravel analyses is, however, not absolute.

Nevertheless, such analysis does enable (a) accurate, quantitative description of sediments; (b) comparative analysis of differences in precipitation effectiveness (this can be obtained by the study of fossil gravels of various ages as opposed to the modern bed materials of one catchment basin locality); and (c) differentiation of fluviatile, colluvial, or slope components within heterogeneous beds, or the identification of the dominant transport agent responsible for questionable sediments. Morphometric gravel analysis should always be used in comparison with modern samples from the same local area.

Paleoclimatic Significance. Climatic-geomorphologic interpretation of alluvial beds is only possible when the climatic or base-level stimuli to aggradation can be isolated. If these stimuli can be isolated, what kind of genetic interpretation can be made of "climatic" alluviation?

Local watercourses of the dry belts may be divided into three hydrological types: (1) perennial streams with considerable seasonal fluctuations in volume ("rivers"); (2) seasonal streams with protracted waterflow for a part or all of the rainy season, drying out for several weeks or months during the dry season (arroyos); and (3) episodic streams which experience irregular floods after major rains, often at intervals of many years, but which are otherwise permanently dry (torrents, wadis, or khors). On the basis of sediment study it is certainly possible to determine whether transporting capacity was greater or smaller than that of today, and very often possible to suggest whether a contemporary stream belongs to the same hydrological class as it did in the past. Greater rounding of gravel samples indicates greater transport distance and consequently not only either greater or longer waterflow or both, but also more runoff and a greater availability of moisture (see Table 5). Greater pebble size indicates greater erosive or transport capacity. Better stratification and sorting of the beds may indicate perennial or seasonal rather than episodic flow.

This comparative and partially quantitative approach renders the application of theoretical arguments to the problems of paleoclimates unnecessary. The familiar polemic as to whether alluviation or vertical incision indicates greater aridity or greater humidity, or whether alluviation upstream and downcutting downstream are representative of semiaridity as opposed to aridity, or vice versa, is both futile and unnecessary. The deposits themselves reflect the conditions of deposition and tell their own story. On the basis of sedimentary analysis it seems that climatically induced alluviation in the Eurafrican subtropics—in so far that it was solely determined by local moisture changes—can be largely associated with progressive increases of precipitation. Changes between the different forms of geomorphic equilibrium produce disruptions of the delicate balance of erosion and deposition in a stream system. Soils, residual mantles, and detritus provided by one climatic balance may be available for large scale areal denudation and subsequent alluviation of the entire stream channel during a climatic change to more intense or greater rainfall. Various forms of Pleistocene geomorphic equilibrium in the Mediterranean area have been outlined previously by the author (1961).

It is symptomatic of stream deposits of northern Africa and of the Mediterranean area that terraces usually accompany most or the whole length of rivers, so allowing no differentiation of "erosion upstream, deposition downstream" or vice versa. Instead, the differentiation of areal from linear erosion and deposition is more significant. The fact that many coastal streams aggraded their beds even during falling sea levels suggests that absolute loads are more significant than the longitudinal distribution of complementary agencies in the interpretation of the significance of alluvial beds.

Stratigraphic Significance. It is a well-known fact that alluvial terraces are quite useful as a means to establish relative stratigraphies in given localities especially when found in association with prehistoric assemblages, faunas, or floras. Of greater significance are alluvial deposits whose stratigraphic association to high or low sea levels can be determined, so that local continental chronologies can be related to glacio-eustatic fluctuations of sea level. Thus the complex problem of Nile and wadi terraces in Egypt (Butzer 1959b) is directly or indirectly associated with the Mediterranean chronology of sea level fluctuations. Hence the Pleistocene terraces of many smaller rivers draining to the sea may be of great stratigraphic importance.

Colluvial Beds (*Limons Rouges*)

A curious sediment, which has been described only from the Mediterranean area, western and southern Australia, is what French authors have called *limons rouges* or "red silts." There are predominantly fine beds with a varying admixture of gravel and detritus, and not infrequently, interbedded tufaceous crusts (cf. below). Their location as thin areal spreads on hillsides, in hollows, or on smooth surfaces with gentle gradients indicates that surface washing and colluvial deposition are the agencies responsible. Eroded soils of *terra rossa* type form the major constituent, along with a variable quantity of angular to subrounded local detritus. Aeolian components may also be present. Such sediments were first interpreted by G. Choubert (1948a, b) in Morocco, who showed that they were due to pluvial washing and sheet-flooding. C. Arambourg (1952) has also outlined analogous cave silts and surficial silts in North Africa and the Levant, where they were associated with a Levalloiso-Mousterian-type industry and an Upper Pleistocene fauna of warm affinities. A pedological study in Algeria by J. H. Durand (1959) represents the most recent analysis of more general interest. A synthetic analysis of the colluvial silts is still lacking while not one of the recent geomorphological texts (including French efforts) mentions such deposits.

Morphology. These deposits usually occur as relatively thin areal sheets, which seldom attain a meter in thickness. Thicknesses of 5 m. may be attained at the bottom of moderate or steep slopes or in original topographic depressions. Surface slopes seldom exceed 15% and characteristic examples can be cited from Mallorca where the general bedrock topography has slopes of 1-3%. In drainage channels the silts can often be observed to grade laterally into fluviatile conglomerates with an identical silt matrix. Clearly then the sediment morphology is nondescript, and consists of essentially shallow, irregular detrital mantles. It is not surprising that closely analogous alluvial and cave features should have been recognized first since the greater part of the typical spreads were simply considered as "soils."

Sedimentology. Corresponding to the colluvial character of these silts the sedimentology is *par force* highly variable from one instance to another. In general stratification of individual beds rather than of individual coarse components is characteristic while sorting is less common.

In the silt mantles on gentle or moderate slopes the coarse component of over 2 mm. diameter is largely confined to coarse angular to subrounded detritus or gravels embedded in finer sediments. The granulometry of the fines shows a spectrum in which the clay, silt, and sand (fine, medium, and coarse) fractions are approximately equal (Table 3). Frequently a moderate maximum may be

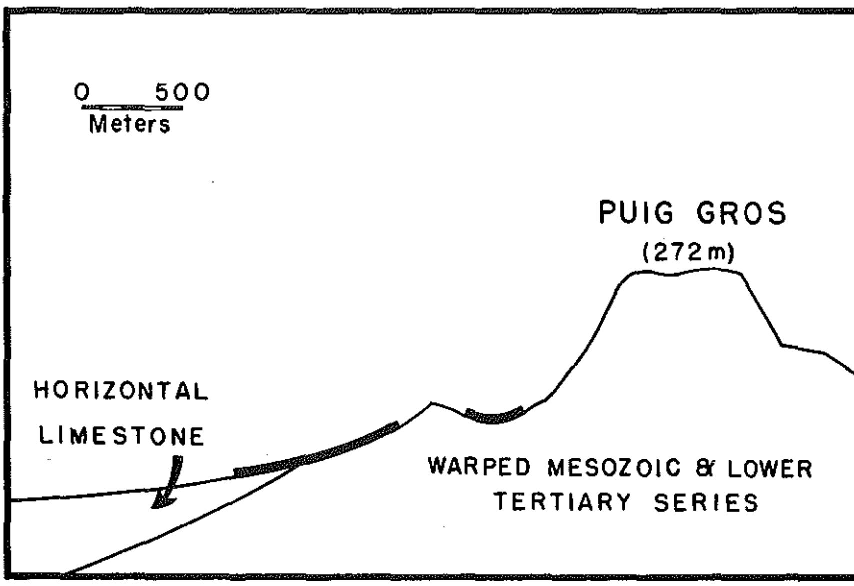

FIGURE 3
Topographic Situation of typical Colluvial Silts (from southern Mallorca). Heavy black line indicates silt deposits 50–200 cm. thick. Vertical exaggeration 5:1.

TABLE 3
GRAIN SIZES OF COLLUVIAL SILT SAMPLES FROM MALLORCA AND CABRERA
(in percent of fraction under 2 mm.)

(A–D: typical range of typical *limons rouges* samples derived mainly from ancient soils with a little aeolian admixture, primary or derived; E, F: semi-aeolian *limons rouges;* G: *limons rouges* derived from slightly weathered aeolianite; H: semi-aeolian silt resembling loess in appearance.)

Sample	*200–2000μ*	*60–200μ*	*20–60μ*	*6–20μ*	*2–6μ*	*2–60μ*	*<2μ*
A	7.8	20.1	4.1	21.6	5.6	31.3	40.8
B	6.9	4.4	21.7	18.1	14.7	54.5	34.2
C	18.7	17.9	12.8	14.4	12.7	39.9	23.5
D	25.0	16.7	7.9	22.7	12.3	42.9	15.4
E	42.2	25.4	9.5	7.8	6.9	24.2	8.2
F	13.0	37.2	13.6	11.2	11.0	35.8	14.0
G	50.9	25.1	12.4	1.3	3.5	17.2	6.8
H	13.7	20.7	19.5	32.6	8.9	61.0	4.6

found in the coarse silt and finer sand fraction, but the writer knows of no granulometric spectra in which over 70% of the sample occurs in the 2–60 micron range and consequently typical loess deposits are not known.[1] Semiaeolian beds are however not uncommon in association with regressional dunes, or specifically aeolian materials bedded by water action. More frequently however the grain-size spectrum is related to that of the source materials for surface washing, namely, soils and weathered older aeolian beds.[2] Particularly conclusive evidence of the dominance of water bedding in all but a very few coastal deposits is provided by the axial orientation of gravels, conformable tufaceous calcareous crust beds, and submicroscopic bedding of the fines. Such criteria are important when grain sizes are almost identical with those of aeolianites (e.g., Table 3 E, and Table 1 C).

Micromorphologic study of quartz grains (Table 4) does not provide any very significant information.

With the exception of unstratified breccia-like sediments, which are caused

1. C. Virgili & I. Zamarreño (1957), and L. Solé Sabarís (1960, personal communication) consider that true loess deposits occur at Sant Andriá near Barcelona. The writer visited the site together with Dr. Solé but does not consider them distinct from analogous beds on Mallorca whose granulometry is not truly "loessic" (Table 3, H). Grain size analyses of the Sant Andriá "loess" have been made, but the writer has not been able to obtain any details. In our opinion these beds are semi-aeolian silts and in fact innumerable water-laid sand, grit, or pebble bands interrupt the profile.

2. Another variety of red silt has been suggested by R. W. Hey (1962) from interior Tripolitania, which on the basis of unpublished laboratory analysis are thought to be "aeolian silts." Just how unequivocally "aeolian" the grain size spectrum may be remains to be seen, however.

TABLE 4
MICROMORPHOLOGIC ANALYSIS OF QUARTZ GRAINS
(of medium sand fraction, in percent. Refers to Table 3)

Sample	*Waterworn*	*Wind-worn*	*Unworn*
A	26	18	56
C	36	51	13
D	36	6	58
F	50	32	18
G	18	49	23
H	24	28	48

by the combined gravity and fluviatile activity of very steep slopes, *limons rouges* contain an interesting assortment of slightly rolled gravel wherever detritus (excluding aeolianite rubble) is locally available. A knowledge of the modifications of this gravel is essential to a determination of the conditions of transport and deposition.[3] Table 5 shows that the degree of rounding of gravel contained in colluvial beds is similar to that of gravel found in modern torrent beds, although it is usually somewhat better. Occasional bands of subrounded stream gravels (such as Sample I in Table 5) occur within the silt beds and emphasize the importance and duration of water flow in comparison to that of the present. The E/L ratio indicates that rolling in contrast to sliding motions were dominant during transport. The large number of gravel samples of colluvial silts analyzed from Mallorca and Soria indicate that both overall transport capacity and duration of effective water flow was equal or greater than that of the episodic and seasonal streams of today. The spectrum of homogeneity as expressed by the coefficient of variation is identical to that of modern torrents. Consequently violent, torrential sheetflooding as opposed to the gentler forms of surface washing (*ruissellement*) may be considered as the geomorphic agency responsible, aided by gravity action in areas of accentuated relief.

Paleoclimatic Significance. As indicated, colluviation of *limons rouges* is essentially a fossil process in subtropical latitudes, in spite of the atypical counterpart in southern Morocco and such analogous features as soil stripping induced by anthropogenic action in the Mediterranean world today. Modern analogies of greater pertinence may well exist in parts of the savanna belt today, but they are incompletely understood or have not yet been described. It therefore seems necessary to present an independent interpretation of the fossil features. Prolonged

3. Prof. R. Négre informed the writer that silt colluviation by surface washing is known to occur at very slow rates today, namely in southern Morocco in a zone with only 300 mm. precipitation. These are fine sediments, and cannot be considered genetically identical with Pleistocene *limons rouges*, for the gravel contained in Pleistocene beds of this type indicates greater water transport than today (in areas with 400–700 mm. precipitation at present).

TABLE 5

MORPHOMETRIC ANALYSES OF ALLUVIAL AND COLLUVIAL GRAVELS

(Samples A, D, F–I, and K from Mallorca; C, E from Gerona; B, J from Soria. C and E as well as G–I are from single stratigraphic sequences. K consists of colluvial silts of semi-alluvial type.)

	Sample Description	*Sample Size*	*Mean ρ in %*	*Percent ρ ≤ 8%*	*Coefficient of Variability of ρ (in %)*	*E/L (in %)*	*Lithology*
A	Episodic stream (recent)	100	12.1	57	111.3	52.1	Limestone
B	Episodic stream (Pleistocene)	100	10.9	55	95.3	58.3	Limestone
C	Seasonal stream (recent)	50	37.7	16	63.7	......	Granite
D	Seasonal stream (Pleistocene)	50	36.3	4	47.0	51.7	Limestone
E	Perennial stream (Pleistocene)	50	45.8	0	34.0	......	Granite
F	Perennial stream (Pleistocene)	100	57.6	0	36.5	55.2	Limestone
G	Episodic stream (recent)	100	8.4	68	106.2	55.4	Limestone
H	Pleistocene colluvium	100	14.0	52	104.7	53.0	Limestone
I	Pleistocene colluvium	100	23.0	38	78.3	58.9	Limestone
J	Pleistocene colluvium	100	12.9	43	83.7	58.3	Limestone
K	Mixed colluvium (Pleistocene)	100	26.6	10	55.0	......	Limestone

torrential rains, of some duration and not inconsiderable frequency, imply that annual rainfall amounts must have been at least as great as they are now. The possibilities of violent sheetflooding to strip soil and transport detritus would be unlimited under the vegetation type which exists in Mallorca, Catalonia, or Soria today. The garrigue has no sod grasses and little or no bunch grass or other soil-protecting herbs, while much bare soil is exposed. Even in the light oak or mixed oak-pine woodlands, dispersed coarse tuft grasses and the little or non-existant sod vegetation also provide only incomplete soil protection. Similar sod conditions also prevail under woodlands with 500 mm. or even with 1000 mm. precipitation today. Similarly, an increase in aridity would not significantly change the area of bare soil. Consequently no change in vegetation physiognomy or association is necessary to permit colluviation of the *limons rouges* type. The present seasonality of rainfall must therefore have been characteristic.

An explanation of more "fluvial" rather than absolutely moister conditions is untenable as present rainfall is rarely sufficient for coherent runoff today. (Butzer 1961). Morphologically effective sheetflooding under Mediterranean climates can only be understood as a consequence of pluvial erosion and transport. Only prolonged, intensive rainfalls will saturate the dominantly coarser textured *terra rossa* type soils to the point that they become impermeable. Accelerated runoff and soil stripping will then follow. These are the characteristic

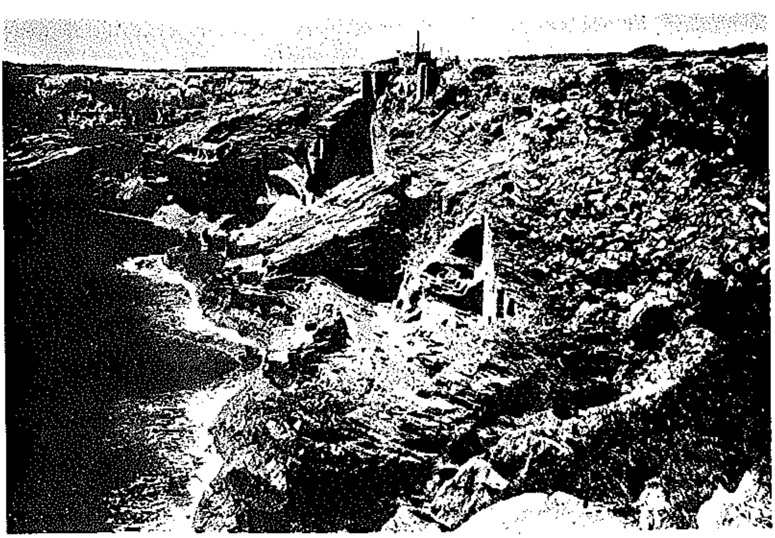

FIGURE 4
Upper Pleistocene aeolianite embanked against Miocene limestone cliffs. Crude breccia in colluvial silts overlying aeolianite at right. Southern Mallorca, S'Estret d'es Temps.

deposits of the geomorphologically significant pluvials of the Mediterranean zone although they do not represent the wettest Pleistocene climates of this area, which seem to have occurred during phases of red soil development (Butzer 1961).

Stratigraphic Significance. Stratigraphic aspects of the colluvial silts are analogous to those of alluvial beds. The widespread occurrence of *limons rouges* particularly along coastlines enhances their stratigraphic value. Abundant snail faunas when studied statistically may be used not only to indicate ecological conditions but can be stratigraphically employed. Similarly, Munsell colours are often useful in the field since a relationship frequently exists between clay content and intensity of red colouration. Thus certain *limons rouges* are sufficiently distinctively coloured to be of some limited stratigraphic value in local correlations. Consequently, in spite of their nondescript morphology colluvial beds are of prime significance for total interpretation of past environments. It is interesting that major silt deposition of this type can be associated with the very beginning of the major glacial regressions.

Tufaceous and Travertine Crusts (*Croûtes zonaires*).

A widespread phenomenon of many subtropical and tropical lands are calcareous crusts or "caliche," which are mainly of Pleistocene, but also partly of Recent date. Interpretations of such crusts vary to an unbelievable degree and indicate that genetically distinct phenomena are too often grouped under the one misleading term "calcareous crust." In fact almost every author using this term implies something quite different from that described by another. The only comprehensive study for part of the Mediterranean area has been made by J. H. Durand (1959, pp. 75–136), who outlined several distinct types of "crusts" as follows: [4]

1. Powdery sediments (*formations pulvérulentes*). Powdery lime, gypsum, or salt inorganically precipitated at the bottom of lakes, lagoons, or playas.
2. Zonal crusts (*croûtes zonaires*). Calcareous surface deposits left by intermittent sheetflooding of highly calcareous waters. Each film of sediment is consolidated between successive water flows. Durand incorrectly assigns a Lower Pleistocene age to these crusts.
3. Chalky nodules (*nodules farineux*). Nodules formed at the same time as the deposition of a particular sediment by the almost instantaneous segregation of the carbonates within contraction fissures or hollows.
4. Concretions (*nodules concretionnés*). Nodules formed by—allegedly only modern—pedogenesis which involves calcareous precipitation at greater depth.

4. A lengthy lithological but unfortunately not pedologic or stratigraphic study by E. Rutte (1958) treats calcareous crusts in Spain. Both Durand's and the writer's interpretations disagree with Rutte's. Rutte considers the various genetic types of calcareous crust as genetically analogous.

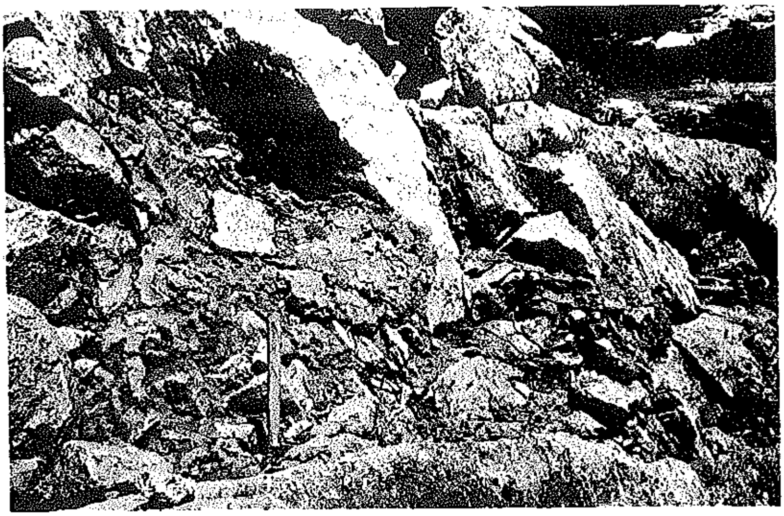

FIGURE 5
Upper Pleistocene colluvial silt-breccia. Southern Mallorca, S'Estret d'es Temps.

This is a somewhat poor characterization of the typical Ca (calcium) or Sa (salt) horizons, due largely to carbonate (or salt) leaching of upper soil horizons. Such pedogenetic Ca horizons (as they should be called) form both nodules, irregular horizontal bands which often grade into massive honeycomb structures, as well as dense chalky horizons and chalky precipitation along contraction fissures. These deposits may occur in the (B) or C horizons. Nodules may also be chalky, and the genetic class of chalky nodules identified by Durand is therefore a little dubious and certainly difficult to identify.

5. Calcrete cementation (*encroûtements calcaires*). Precipitates or evaporites of calcium carbonate or salts found in shallow zones of aeration above a ground water table which is situated near the surface. These calcrete crusts are formed by the upward movement of capillary water with dissolved materials during periods of desiccation. Similar processes may also be involved in the formation of pedogenetic Ca horizons.

The most widespread and indicative of the various "calcareous crusts" are the so-called *croûtes zonaires* or tufaceous (and sometimes travertine-like) varieties. These will be considered in some detail here on the basis of Spanish samples studied.

Morphology. These deposits are widely found in association with colluvial silts, where they are either interbedded or cap horizons of a few millimeters to several tens of centimeters thick. Consequently they generally have no morphology whatever, except where independent areal spreads in hollows or shallow depressions occasionally attain 50–100 cm. These durable crusts have geomorphological significance when they form land surfaces.

Sedimentology. Sediments are composed of 75% or more of crypto-crystalline calcite with some detritus which varies from microscopic to pebble size. This detritus includes calcite crystals, often weathered; quartz grains, largely waterworn; manganese particles; feldspar crystals, if present in local bedrock; clay aggregates from microscopic to pebble size, representing stripped soil particles or lumps; and finally silicified root particles. Iron oxides are distributed within the free calcite and their presence leads to discoloration of the sediment in fine, wavy bands. A high colloidal SiO_2 content is present.

The macrosedimentology can be summarized under three headings.

1. Laminated, former surface crusts. These shallow, well-cemented crusts are most frequently if not almost invariably found in association with colluvial beds. The lamina can be easily recognized on the basis of the fine oxide bands. Although typically a pure white, these crusts have many rather discolored bands of pink, reddish yellow, or yellow color, which reflect the considerable silt content in the form of oxidized calcite crystals or of minute soil particles (clay aggregates). The discolored crusts have a transitional position between silts and tufaceous crusts, and the white laminated tufas indicate clear sedimentation with a reduction of mechanical erosion and a cessation of alluviation. As C. Virgili (1957) has already shown in the Barcelona area, concretionary zones are most frequently found below a capping of calcareous crusts. These are often but not necessarily conformable with the tufaceous crust, and are mainly of the calcrete cementation type caused by upward movement of capillary waters. They are however also formed by downward percolation of lime-charge waters but in many instances both movements are involved. It is difficult to decide whether an upward or a downward movement is dominant in this type of process.[5]

2. Massive, inconspicuously bedded calcite beds. These comparatively rare alluvial-type crusts which often possibly attain a meter or more in depth also contain coarse detritus in the form of crude, subangular chunks of former dehydrated soils of *terra rossa* or *terra fusca* type. Subsequent calcification imparts to such inclusions a resemblance to rock pebbles within a consolidated although less resistant calcite mass. Such massive beds may also occur in association with spring tufas of the soft, rather porous type which have frequent plant impressions.

3. Travertine beds. Massive tufaceous calcite sediments may grade locally into true travertines of a vertical, columnar structure.

Paleoclimatic Significance. Considerations of the genesis of the tufaceous or travertine-like calcareous crusts (*croûtes zonaires*) suggest that they are un-

5. The writer gratefully acknowledges stimulating discussion with L. Solé Sabarís on genetic differentiation of crusts. Solé outlined a rather significant and appealing sequence of calcareous segregation, concentration, and deposition during and after sedimentation of the sediment concerned. The writer looks forward to publication of the results and conclusions.

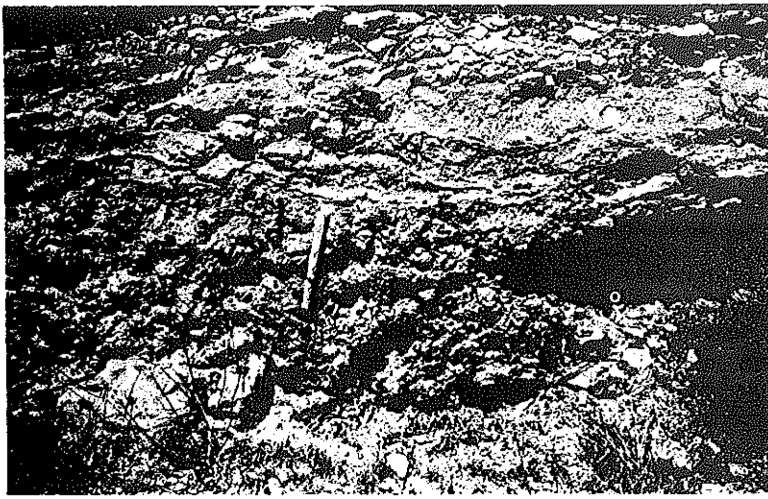

FIGURE 6
Colluvial silt grading into laminated, calcareous crusts. Middle Pleistocene age. Southern Mallorca, KM 5 of local route to Cap Salines.

doubtedly formed by the surface washing of lime-charged waters (Durand 1959, Butzer 1961). Durand believes that such slow calcareous precipitation is only feasible with warm waters. Certainly the lack of numerous coarse components such as sands and gravel presumably indicates that there is little loose detritus other than cracked, desiccated *terra rossa* soils which may have been available for stripping. The presence of the latter soils may suggest that these crusts were largely deposited after the first, severe late summer rains after the dry season. Also if parched *terra rossa* chunks were available in September, for example, then grain by grain soil stripping should have been possible later on during the rainy season. Many of the interbedded tufaceous crusts in colluvial silts may well be explained in this way.

The capping tufaceous crusts on silt deposits as well as the massive calcite or travertine beds must however be interpreted as representing a change in vegetation-soil-rainfall equilibrium. A rather complete mat of herbaceous vegetation must have sprung up after the first rains so that pluvial soil erosion was limited to removal and transport of odd fragments of dehydrated soil in late summer. The subsequent development of a sodgrass type vegetation, as is found today near seasonal or perennial sources of underground or spring waters, then effectively inhibited any further erosion. Such sodgrass along with the absence of much loose detritus suggests that there was a rather dense vegetative mat and very possibly incipient pedogenesis of the *terra rossa* or *terra fusca* type. The stripped soil fragments indicate that the dry season persisted, but over-all precipitation must have been greater than during the colluvial silt phases. For the Balearic Islands area—with 400–600 mm rainfall and with limestone bedrock—these fossil crusts represent wet phases with a precipitation several hundred millimeters greater than today. Rainfall reliability was probably greater, rainfall distribution more equitable, and over-all intensity of rainfall less or at least no greater than that of today. In other regions of the Mediterranean or the savanna belt analogous features may however be indicative of drier conditions. So for example, the limited carbonates present in areas with silicate bedrock are rapidly lost through solution under moist conditions. It is thus absolutely essential to specify the particular type of calcareous deposit concerned and to study its local significance. Generalizations over wide areas are dangerous and such frequent stereotype statements that "caliche deposits" are indicative of "aridity" without close investigation or specification are irresponsible.

Other than in local association with springs, tufaceous crusts no longer develop in the Mediterranean area (Durand 1959, cf. Rutte 1958). This raises a last outstanding problem of the original carbonate solution in water. This could of course be performed by the surface solution of humic acids which are derived from the biochemical activity of vegetation and soil fauna. Very little calcite however, would be released at the surface after a late summer rain. Strongly increased spring activity—seasonal or perennial—over larger areas must also have been involved. General surface washing (rather than violent sheetflooding) by activated, lime-charged underground waters after protracted rains seems the most probable source of these tufaceous and travertine-like crusts. The *terra rossa* fragments embedded in calcite may not even be related to these lime charged waters, but may well have been removed by earlier rain storms and then subsequently buried by lime precipitates. Innumerable fissures which show evidence of former spring activity can be observed on the cliff coasts of the Balearic Islands today and certainly support this interpretation. A climatically significant increase in spring activity must be unquestionably linked with travertines and thus stratigraphically associated with the tufaceous crust formation on the Balearic Islands.

In conclusion it is suggested (1) that tufaceous and travertine-like crusts or beds of the Mediterranean area are largely formed by precipitation from slowly moving, lime-charged waters of limited or moderate underground trajectory in soil or bedrock and also in part from sheetflooding rain waters; (2) that they are deposited under a dense vegetation mat with considerable spring activity and sufficient rainfall, with temperatures certainly no lower than those of today; (3) that their coarse clastic components were probably embedded *in situ* by such precipitates after their original transport by the first late summer downpours, before the grass mat had developed again after the intense dry season.

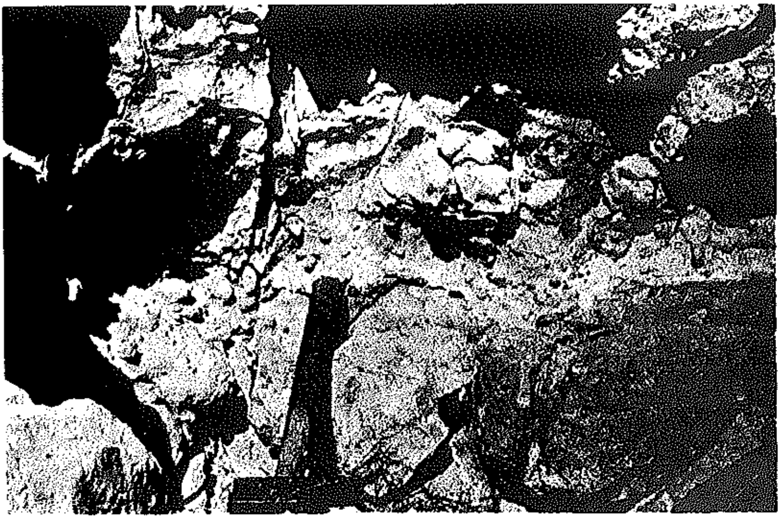

FIGURE 7
Massive, inconspicuously bedded calcite beds of Upper Pleistocene age, with embanked "pebbles" of *terra fusca* soil. Overlying semicemented aeolianite. Southern Mallorca, Cala Pi.

Stratigraphic Significance. Tufaceous crusts have only a limited stratigraphic significance, with exception of the massive calcite beds of late interglacial date sometimes found disconformably under regressional sequences (Butzer 1961; Butzer & Cuerda 1962). In their relationship to colluvial silts the *croûtes zonaires* proper occur too frequently and variably to be of anything but local paleoclimatic value.

III. LACUSTRINE AGENCIES

Subaqueous deposits of the arid and semiarid subtropics comprise a great number of genetic types:

A. Coastal-Lagoonal
   1. Salt water (marine)
   2. Brackish water (estuarine and semilacustrine)
   3. Fresh water (lacustrine)
B. Interior-Lacustrine
   1. Fresh and brackish water (swamps and lakes)
   2. Salt water (lakes and pans)

A wide variety of facies is also present:

1. evaporites, usually gypsum or halite;
2. calcareous beds, including chalky;
3. marls;
4. silts and clays;
5. sands;
6. organic deposits.

The following remarks are intended to describe no more than some of the typical aspects of these facies, since it is impossible to generalize about a multitude of local possibilities.

Evaporites, mainly gypsum (calcium sulfate) and other salts such as sodium, magnesium, and potassium chloride, which are frequently indicative of desiccation. Such desiccation may refer to periodic seasonal shrinkage during the dry season, or long term reduction of a larger lake to a lagoon or pan. So for example the Middle or Upper Pleistocene Jordan Sea, which was the ancestor of the Dead Sea, deposited some 50,000 varvelike alternations of silts (rainy season influx) and carbonates, sulfates, or chlorides (dry season evaporites) (cf. Butzer 1958, p. 78). Evaporites with the exception of open coastal lagoons are indicative of some degree of aridity.

Calcareous beds, usually *lacustrine chalks*, are not infrequent in French North Africa (Durand 1959, pp. 75–90) and in other parts of the Sahara, such as in

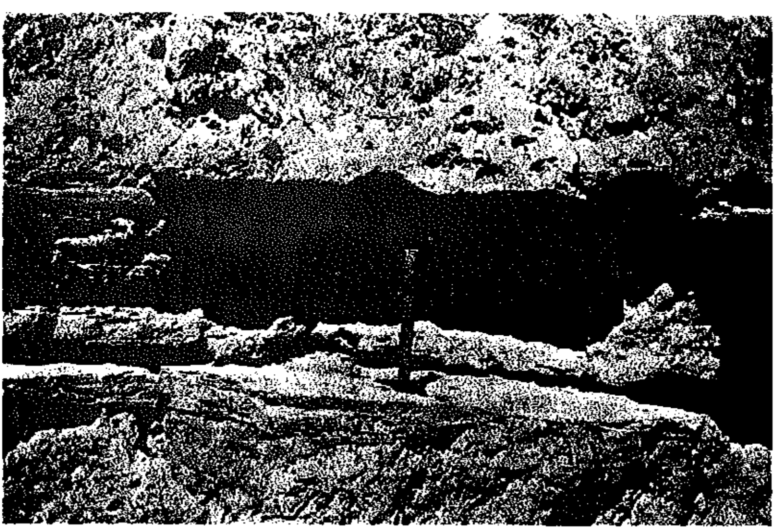

FIGURE 8
Travertines with intercalated massive calcite bed, consolidated aeolianites at base and top. Southern Mallorca, Cala Pi.

the depressions of the Kordofan *goz*. These chalks may or may not be fossiliferous. Such chalks usually indicate perennial lakes which were not subject to very great seasonal fluctuations of oxygen content.

Marls, or highly calcareous silts, may be deposited in both lakes and swamps. They are more frequent in the semiarid than in the arid zone where lateral streams are able to carry soil products into comparatively small water bodies.

Silts and *clays* are generally carried into standing waters in suspension by local streams. They may however also be at least partly aeolian in origin, as is the "lacustrine loess" of the Namakzar Kavir of the Persian Lut Desert (cf. Hückriede, 1962). Lacustrine silts and clays are again less typical of the Pleistocene deposits of the arid zone, and are generally limited to local situations such as spring-fed lakes in some of the Saharan oases.

Sands of lacustrine deposition are a comparatively widespread Pleistocene facies in the Saharan region. They are largely derived from sandy wadi deposits, and to a lesser extent also from wave action on local bedrock. The prehistoric Fayum and Chad lakes are striking examples.

Organic deposits, although comparatively rare in the subtropics are however not unknown, particularly in the temperate mountain areas of the Mediterranean zone. These may be gyttyas, peats or humic sands, silts, and clays. Few such deposits of Pleistocene date are known, however; their major significance is the possibility they provide for palynology (e.g., Menéndez-Amor & Florschütz 1961).

Some of these deposits are susceptible to different methods of interpretative study, but since local conditions will necessarily determine such methods, it does not seem warranted to discuss lacustrine deposits any further here.

IV. CONCLUSIONS

It is hoped that this outline of characteristic Pleistocene sediments and their paleoclimatic and stratigraphic significance may possibly serve towards a tentative sketch of Pleistocene sedimentary processes in the Old World sub-tropics. General textbooks and many specialized studies attempt to interpret lower latitude geomorphology summarily by analogy to higher latitude processes. Almost half of the existing literature on the lower middle latitude Pleistocene is devoted to glacial or "periglacial" features. No comprehensive study of Pleistocene processes equatorward of the former cold climate morphogenetic system exists.

Because of this lack of appreciation of the individuality of lower latitude processes, many a higher latitude specialist has erroneously ascribed glacial or "periglacial" attributes to features such as colluvial breccias. It is insufficient to have theoretical acquaintance with arid zone morphology and yet be unaware of the range of sedimentary processes present in semiarid and arid regions. Pleistocene geology in lower latitudes is as specialized as glacial geology or "periglacial" geomorphology.

A thorough investigation of contemporary and Pleistocene processes of the lower latitudes must be the object of many qualified specialists in different areas. Such process investigation should emphasize weathering, pedogenesis, and sedimentation. Above all, study of sites or regions should aim at comprehensive interpretation. Only in this way can the paleoecology of archaeological sites, which is so crucial to our understanding of prehistoric time, be effectively reconstructed.

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