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Pleistocene Geomorphology and Stratigraphy of the Costa Brava Region (Catalonia)

von

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Deutsche Zusammenfassung. (Pleistozäne Stratigraphie und Geomorphologie Mittelkataloniens). Auf Grund von Geländeuntersuchungen 1960–61 konnten weitverbreitete Strandplattformen in 100 m und 60 m festgestellt werden. Jüngere, schwach entwickelte Abrasionsformen in 30–35 m, 22–27 m, 16–19 m, 12–13 m und 4–8 m gehören wahrscheinlich den verschiedenen mittel- und jungquartären Stadien an. Gründe für die wenig markanten Strandterrassen und das Fehlen zugehöriger Ablagerungen werden angeführt.

Eine ziemlich vollständige stratigraphische Folge, freilich ohne direkte pollenanalytische oder paläontologische Anhaltspunkte, konnte auf Grund sedimentologischer, bodenkundlicher und morphologischer Detailbearbeitungen für das gesamte Quartär aufgestellt werden. Hierzu dienten die plio-pleistozänen Ablagerungen der Selva-Senke, die altquartären Terrassen des Ter sowie die jüngeren Terassen der Küstenflüsse.

Entgegen der Auffassung von Solé Sabarís und Llopis Llado wurde die Selva-Serie in pliozäne und altquartäre Abschnitte eingeteilt, und eine neue Gliederung dieser verschiedenartigen Sedimente wird vorgeschlagen. Sie läßt auf Binnenseeablagerungen während eines warmen, gleichmäßig feuchten Klimas im Pliozän schließen (Graue Serie). Darauffolgend setzte ein wechselfeuchtes, kühleres Klima mit gemischten lakustren und alluvialen Ablagerungsbedingungen ein (Gelbe Serie) – vermutlich am Anfang des Quartärs. Zwischen den Grauen und Gelben Serien schaltete sich eine Rotlehmbildungsphase ein. Auf die Gelbe Serie folgte Kalkkrustenbildung sowie Einschneidung. Die etwas jüngere, Rote Serie entspricht der Hochterrasse des Ter (+ 80 m), die gleichzeitig oder später als das altquartäre 100 m Strandniveau anzusetzen ist. Die Rote Serie entstand aus Flußaufschüttungen unter kühlem und periodisch sehr feuchtem Klima.

Eine tiefgreifende Rotlehmbildung im Mittelquartär bildet einen brauchbaren Leithorizont für die jüngeren Bildungen, in der Hauptsache zwei Flußaufschüttungen, die von einem Braunlehm getrennt werden. Diese jüngeren Terrassen liegen gleichzeitig mit den letzten zwei Hauptregressionen des Mittelmeers, also „Riss" und „Würm". Die nacheiszeitliche Pedogenese führte nur zur Bildung einer meridionalen Braunerde.

Die verschiedentlich wiederkehrenden morphogenetischen Typen lassen sich folgendermaßen aufstellen:

a) Alluviale und kolluviale Aufschüttung mit flächenhafter Abtragung während kaltfeuchter Pluvialzeiten (am Anfang der kaltzeitlichen Regressionen);

b) Absetzung von geschichteten Kalkkrusten, unter noch nicht völlig geklärten Umständen;

c) Lineare Erosion, z.T. in das anstehende Gestein (während feuchterer Epochen des Altquartärs und Jungtertiärs), z.T. in weiche Aufschüttungsprodukte (während der semiariden hoch- und spätglazialen Regressionen);

d) Rotlehm- oder Braunlehmbildung während feuchtwarmer, morphostatischer Abschnitte der Interglaziale.

Zum Schluß werden die allgemeine Morphogenese sowie die heutigen Vorgänge erörtert.

Although the major climatic changes of the Pleistocene did not fail to influence the geomorphic processes of the Mediterranean lowlands, very few intensive regional analyses have been made of the peculiar problems of morphogenesis involved. Considerable climatic-geomorphological work has indeed been done in some of the highland areas, and geological-archaeological work has been common on many coastlines. Yet modern interpretive studies of lowland geomorphology have been notably lacking.

The writer carried out a detailed study of Pleistocene morphogenesis on southern Mallorca, a low-lying semiarid limestone area, during 1959–62 (BUTZER, 1962, 1963a, 1964; BUTZER & CUERDA, 1961, 1962a, b). In 1960 a briefer comparative investigation was undertaken in east-central Catalonia, a subhumid hill country with silicate bedrock. Field study was concentrated between the lower courses of the Ter and Tordera rivers, in the southeastern quadrant of the province of Gerona, which includes the greater part of the scenic coast known as the Costa Brava. Field work was followed by laboratory analysis of soil and sediment samples and a further field check in 1961[1].

This paper is intended to provide a regional outline of the results, and to evaluate the information in a composite geomorphic and stratigraphic context. Important sections have been described in detail, so that the various statements and supporting evidence may be properly documented. In recent years too many geomorphic studies have provided sweeping conclusions without substantive field observations. Indeed if climatic geomorphology is to be more than a sophisticated elaboration of casual observations, minute stratigraphic and laboratory analyses must be undertaken and published. It is hoped that the observations recorded here will aid towards a better understanding of Pleistocene morphogenesis in the Mediterranean region.

[1] The investigation was made possible through the support of the Research Committee and the Geography Department of the University of Wisconsin (Madison). Laboratory facilities were generously provided by the sedimentological laboratory of the Geographisches Institut of the University at Bonn and the Soils Department of the University of Wisconsin. O. FRÄNZLE provided discussion on several pedological problems as well as technical advice in the laboratory work, while JOHN LANGTON kindly analyzed a number of samples collected in 1961. The stimulating company of P. L. BUTZER during the field season is much appreciated. R. A. NEILSON offered valuable suggestions on the manuscript.

Structure and Lithology

Those parts of the province of Gerona which lie between the lower courses of the Ter and Tordera can be subdivided into several geomorphic units, all developed on the great granite batholith known as the Catalan Block. The coastal mountains or Cordillera Costera are bounded by the rugged, irregular Costa Brava coastline and by the Ampurdán depression along the Mediterranean shore, the interior pre-littoral depression to the west (Fig. 1). A brief account of the structure and lithology of the major geomorphic subdivisions to be considered follows, largely based on W. SCHRIEL (1929), H. ASHAUER & R. TEICHMÜLLER (1935), L. SOLÉ & N. LLOPIS (1939), J. CARANDELL (1942–43), J. MARCET & SOLÉ (1949) and LLOPIS *et al.* (1953).

a) *The Sierra de las Gabarras.* The northernmost section of the Cordillera Costera, commonly known as the Gabarras block, consists of a granitic horst with a mantle of metamorphosed Palaeozoic sedimentaries, and rises to 531 m on the Puig d'Arques. The greatest part of the Palaeozoic bedrock consists of Ordovician and Gothlandian schists, mica-schists, slate, graywackes and quartzites. Sandstones and conglomerates of the continental Lower Eocene, and massive nummulitic limestones of the Middle Eocene are embanked against the flanks of the Gabarras at Gerona and along the edge of the lower Ampurdan depression. The Palaeozoic sedimentaries were intensely folded and metamorphosed during the Hercynian orogeny, whereas the faulting responsible for the Gabarras fault block belongs to the Alpine orogeny (here probably mainly Pontian and Upper Pliocene).

The present relief of the 300–500 m upland is comparatively smooth, dominated by erosional surfaces at about 400 m, 300–320 m and 180–220 m (MARCET & SOLÉ, 1949, p. 79–81), into which the lateral drainage lines have incised deep, steepsided valleys.

b) *The Cadiretas Massif.* The adjacent, more southerly section of the Cordillera Costera, between the Aro and Tordera valleys, can probably be best designated after the highest peak, Cadiretas (519 m). The Palaeozoic metamorphics do not cover much area here. Instead a great mass of medium-grained granodiorite with aplitic and pegmatitic subfacies, and

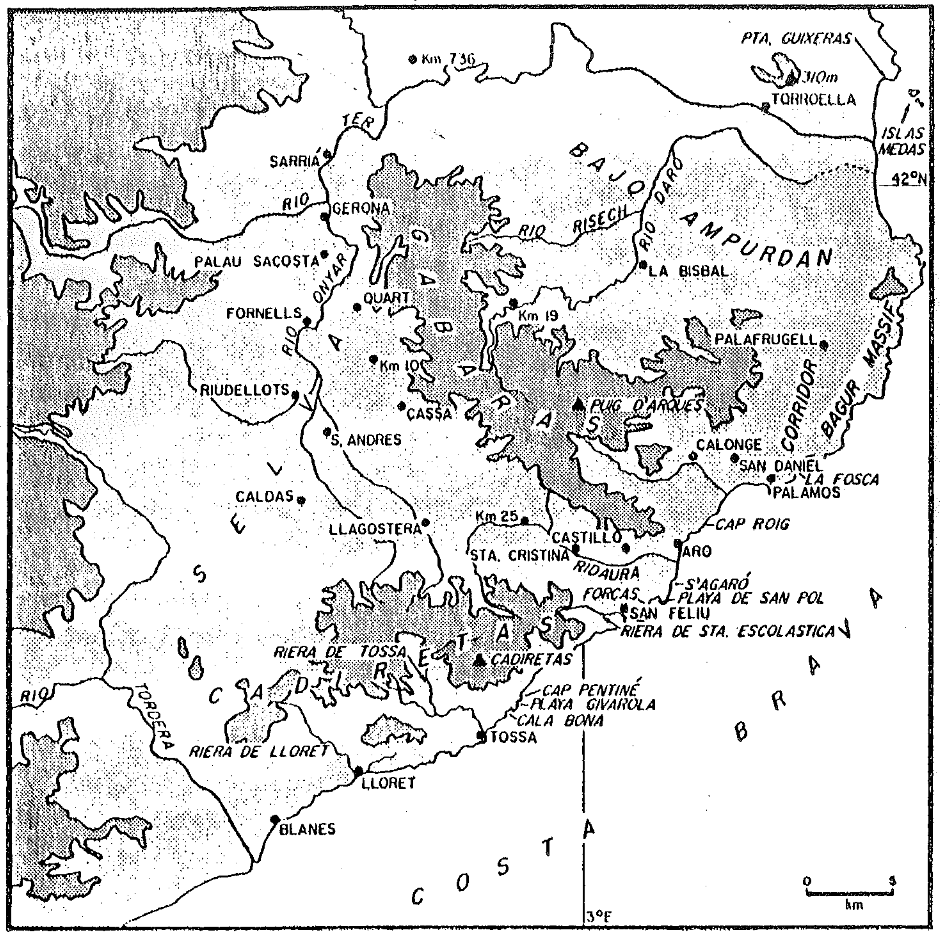

Fig. 1. *The Costa Brava Region.* Elevations over 200 m indicated by dark pattern, 0 - 200 m by lighter pattern.

a great variety of aplitic, pegmatitic, quartz, and felsitic dykes dominate the somewhat rougher tectonic block. The more acidic granites and quartz or quartzitic facies are considerably more resistant, while the porphyritic granites and the granodiorite mass are more susceptible to disintegration, so producing a more noticeable differential erosion.

LLOPIS *et al.* (1953, p. 18—20) recognize erosional surfaces at about 420—500 m, 320—340 m, 240—260 m and 140—180 m, with coastal benches at 70—100 m and ca. 30 m.

c) *The Selva Depression.* West of the Gabarras and north of the Cadiretas massif lies the broad, flat-lying depression of the Selva („forest"),

formed by a basement of granite, with some Palaeozoic sedimentaries in the far north, and a veneer of Plio-Pleistocene sediments. The area is drained northwards by the Onyar system, the more southerly regions drain off to the Tordera. The general level of the plain rises from 100 m in the north to 250 m in the south. Although MARCET & SOLÉ (1949, p. 72—4, Fig. 1 and 13) emphasize block faulting along the northeastern margins, attributing primary origin to late Tertiary tectonic subsidence, LLOPIS *et al.* (1953. p. 20—22) consider the tectonic aspects with considerable caution, placing major emphasis on the erosional (pediment-type?) character of the depression.

The denudation of the southern Selva, responsible for the 140—180 m and 240—260 m surfaces, antedates deposition of tectonically deformed Pliocene sediments near Llagostera, and undeformed Plio-Pleistocene beds widespread in the Selva.

d) *The Lower or Bajo Ampurdán Depression.* North and east of the Gabarras a series of complex faults, with total vertical displacement of some 400 m, define the southern limits of the Ampurdan depression. Over 70 m of Lower and Middle Eocene sediments overlie the Palaeozoic and granitic basement, displaying considerable Alpine deformation. The resulting plain rises slowly land-inward, to 100 m at the foot of the Gabarras, where it may underlie Villafranchian or Lower Pleistocene deposits. The surface morphology underlying these beds is conspicuously erosional, cut across structural features.

e) *The Aro and Palafrugell valleys.* Interrupting the Gabarras and the Cadiretas massif is the transversal tectono-erosional Aro valley. The Gabarras are separated from the lithologically analogous Bagur massif by a small graben-like valley, the Palafrugell Corridor.

Modern climatic features

The Costa Brava region lies within a comparatively moist, summer-dry mesothermal climate with hot summers and mild winters (*Csa* in the Köppen classification). The 1906—1925 January mean at Bagur near the coast is 10.9° C., the July mean 23.8° C. The mean maxima and minima of January are 12.7 and 9.0° C. respectively, of July 26.0 and 21.6° C. The absolute minimum on record is 1.0° C. These same values for Gerona in the interior are 7.1, 22.9, 13.2, 1.1, 29.4, 16.5, and -13.0 C. in that same order (J. WROBEL, 1940). Significant regional differentiation is then confined to winter temperatures: frost is very rare along the coast but common in the interior.

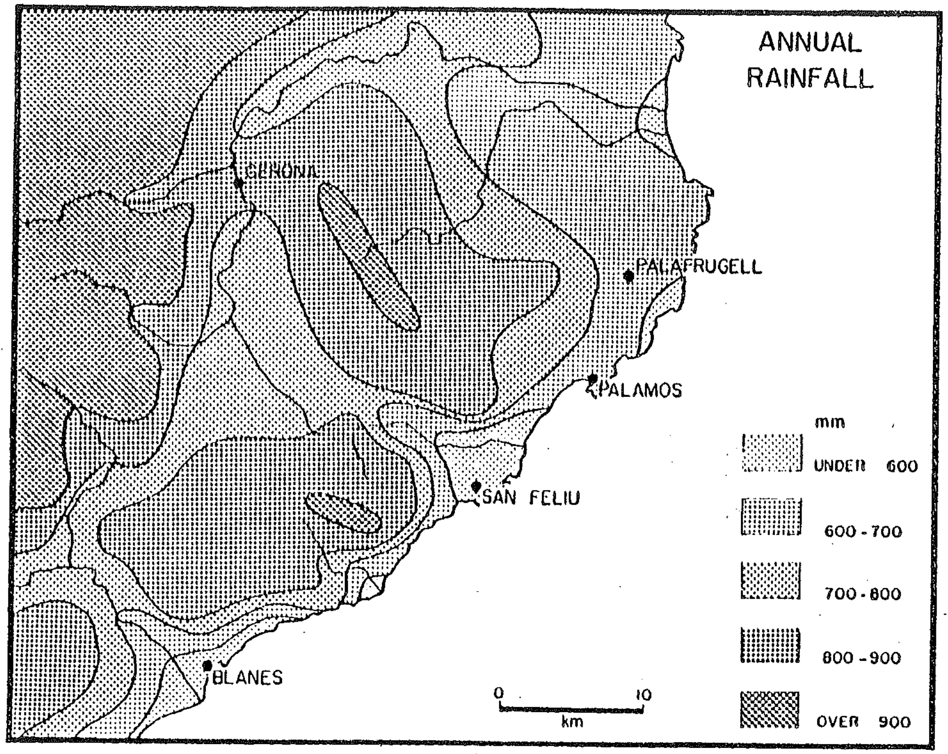

Fig. 2. *Distribution of Annual Precipitation.*

Annual precipitation (Fig. 2) varies from under 500 mm at the coast (San Feliu 476 mm, Islas Medas 388 mm), to over 900 mm in the high country, of which about 90% fall between September and May (Wrobel, 1940). Precipitation is almost exclusively in the form of rain. The coastal stations have less than one day a year with snowfall, whereas the mountains above 500 m have over 4 days with snowfall.

As the significance of the summer drought is not directly proportional to total rainfall amount – despite the limited regional temperature differentiation – DE MARTONNES aridity index was applied to monthly values in the sense of W. LAUER (1952). Months having an index 12p/(t+10) [where p monthly precipitation in cm, t monthly temperature in °C] less than 20 are considered as arid. This data can be employed to determine the approximate number of "arid" weeks per year. Fig. 3 shows the number of "arid" weeks per year, based on 13 stations within the mapped area. The duration of summer

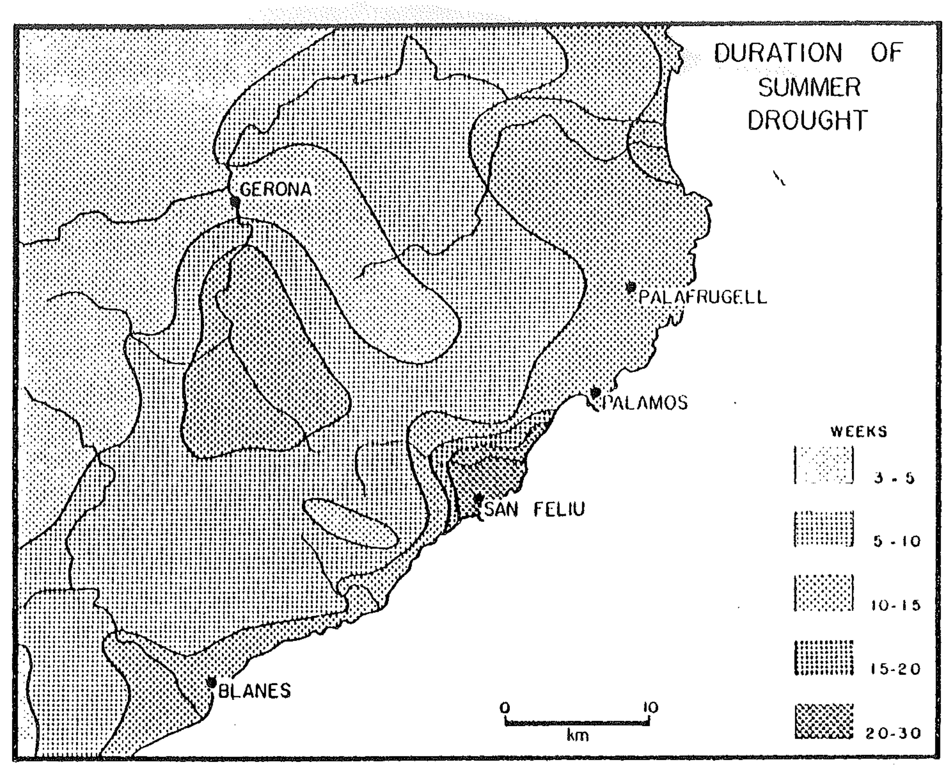

Fig. 3. *Duration of Summer Drought Period in Weeks.* Obtained by use of modified De Martonne aridity index (see text).

drought so defined and described also indicates considerable variation between the coast and the interior (31 weeks at San Feliu, only 4 weeks at Gerona).

Geomorphic characteristics of the Modern Coast

The outline of the Costa Brava between Blanes and Palamós is related to a series of northeast-southwest fractures running parallel to the coast (LLOPIS *et al.*, 1953, p. 27–29), but, as the same authors point out, the absence of deep waters offshore (–80 m isobath at 4–5 km distance) and the moderate crenulation make it difficult to designate this a fault coast.

The topography of the Costa Brava coastline results from differential marine erosion and fluvial dissection by subsequent streams. The greater part of the coast is marked by plunging granite cliffs, occasionally with stacks, headlands or narrow, steep-sided drowned inlets. Other sections are marked by extensive littoral sand bars or *playas* (*platjas* in Catalan).

Differential marine erosion is largely responsible for the irregularity of the cliff coasts. As LLOPIS *et al.* (1953) indicate, the acidic granitic subfacies, or dykes of aplitic, pegmatitic or quartzitic type, are considerably more durable than the more basic granodiorites or porphyritic granites. In effect most of the stacks and small headlands consist of NW-SE oriented dykes of pegmatitic or aplitic granites. Larger promontories commonly consist of the more acidic subfacies. The badly fissured, corroded and limonite-stained granodiorites offer more limited resistance to wave abrasion and in a very general way may be correlated with areas of more advanced cliff recession. Further, caves may be noticed along basic dykes, joint-planes or shatter zones (cf. LLOPIS *et al.*, 1953, p. 28; Pl. 3a, 3b, 4b).

Fluvial dissection was associated with periodic incision of the lowermost stream courses to below modern sea-level. In the case of the smaller streams, narrow, submerged inlets called *calas* were produced while in the case of the largest streams, such as the *rieras* ("streams") of Tossa, Lloret, and Calonge or the Ridaura[1], Late Pleistocene and Recent alluviation was sufficiently great to fill the bedrock channels to about the edge of the cliff coastline. Some intermediate streams excavated broad channels but were too small to refill them during the Upper Pleistocene. The harbour of San Feliu de Guixols and the Playa de San Pol are good examples of this type. Being large enough to permit effective wave action, coastal sand bars have developed, hence the local population refers to them as *playas* ("beaches") rather than *calas* ("inlets") which they properly are.

Small sandy beaches are found in most of the *calas*. Extensive beaches occur on the open coast stretches, such as the 2.2 km long Playa de Aro. The beaches are unconsolidated coarse sand and grit, composed mainly of coarse to granule size quartz crystals derived from granite disintegration. The steepness of the beach slope at the water-mark is proportional to beach width and exposure to wave-attack, with inclinations varying from 5% to over 20%. Beyond a smooth ridge at +2–4 m, aeolian bedding is occasionally noticeable, so that the *playas* are of the beach-ridge coastal type described from Mallorca (BUTZER, 1962). Although typical aeolian mantles and sand dunes are lacking in the southern Costa Brava, they have at times been significant south of the mouth of the Ter. Most of the material of the beach-ridges is derived from Pleistocene alluvium, finer components being selectively removed by wave action.

[1] A Catalan contraction equivalent to „Rio de Aro".

The *calas* of the cliff coasts are not fully typical for the type originally defined by the classical Mallorcan east coast (cf. BUTZER, 1962). Instead, those inlets designated as *calas* on the Costa Brava have V-shaped rather than steepsided, flat-bottomed valleys. By the criterion of H. LOUIS (1960, p. 247) they would then be *rias*, rather than *calas*. This would also be acceptable by F. v. RICHTHOFENS (1886, p. 308–310) original *ria* definition of drowned valleys of a coast transverse to structural grain, in this case the Hercynian folds. However, unlike the *rias* of the Galician coast of Spain, the Catalonian *calas* are due to periodic or episodic streams, i. e. they are drowned torrent valleys of the semiarid zone. The transverse profile of these minor streams is simply a matter of extreme "youthfulness" and has no particular genetic significance. Considering that the larger channels have been subsequently filled with alluvium, and that the large bays of San Feliu and San Pol are genetically true calas, it would be justified to consider the southern Costa Brava as an atypical *cala* coast. The central Costa Brava between Palamós and Bagur is, in fact, quite typical.

Pleistocene coastal features of the Costa Brava

Prerequisites for Shoreline Preservation. The Catalonian beach-ridge coasts are not ideal for Pleistocene shoreline development as a result of repeated continental deposition. Similarly the badly fissured granites, with almost vertical joint planes, offer only limited possibilities for shoreline development or preservation. Modern beach platforms are also poorly developed. Similarly to the Mallorcan cliff coasts (BUTZER, 1962), functional platforms are missing except in the vicinity of the *calas*. The surfaces of such platforms are highly irregular due to the oblique angles of jointing, nowhere are they planed off smoothly, and notches are absent. Pleistocene erosional features of marine origin must then also be limited to rather irregular abrasional surfaces, forming equally irregular coastlines as a response to differential erosion. Cliffs may be expected while marine deposits must be scarce in view of the typical lack of consolidation of beach deposits, resulting from a comparative scarcity of carbonates and an absence of finer components. The molluscan fauna of the coast is also comparatively poor.

Previous work. It is not surprising then that, apart from several Pleistocene marine terraces, only two instances of marine deposits have been reported to date. At Canyellas near Lloret a well profile formerly exposed Upper Pleistocene colluvium over 4 m of sands, 1 m of mud and

3 m of reddish sands with an unidentified molluscan fauna at an unspecified elevation above sea-level (LLOPIS *et al.*, 1953, p. 42). Similarly at Cap Roig, a gritty Late Pleistocene loam overlies coarse marine sands. The writer did not notice any Pleistocene marine beds.

Pleistocene marine erosion has, despite the unfavorable circumstances, left conspicuous features along the Costa Brava. LLOPIS *et al.* (1953, p.

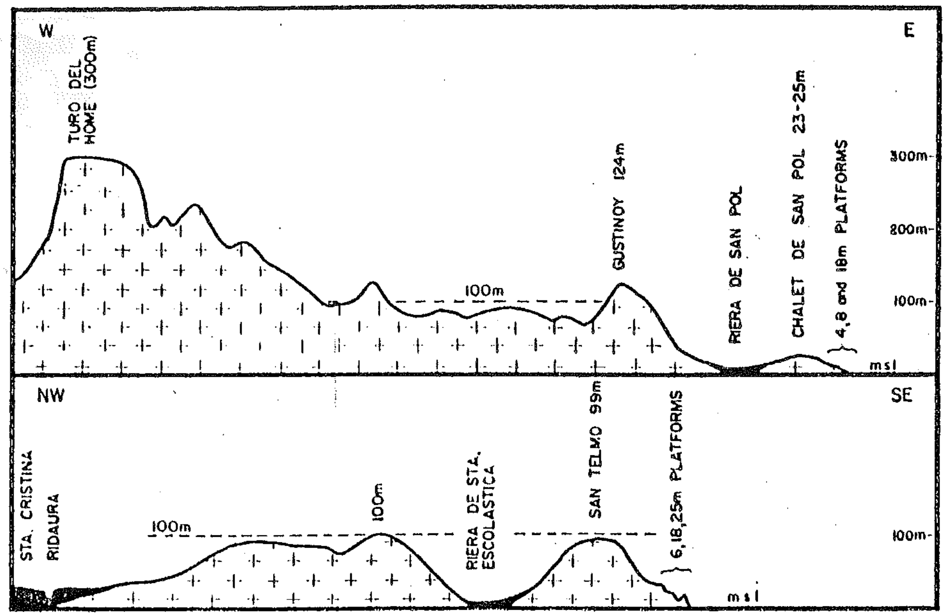

Fig. 4. *Profiles of the San Feliu de Guixols Area* indicating the geomorphic significance of the 100 m marine abrasional platform. Alluvial deposits shown in black, granitic bedrock by crosses. Vertical exaggeration 9x.

18—20) mention the Lloret — San Feliu erosional surface, developed at 80—100 m between Lloret and Tossa, and at 70 m in the San Feliu area. Captions to their photographs (Plates 4a, 7a, 10b) suggest a marine origin. Similarly these authors indicate the presence of a 30 m surface, described as a possible "terrace" at S'Ágaró and Aro. Photographs (Plates 5b, 6a) allude to a lower marine level at 2—3 m. J. CARANDELL (1943) further indicates the presence of abrasional platforms on the Montgri massif, north of the lowermost Ter, and on the adjoining Medas islands.

Older Abrasional Platforms. More intensive study of ancient shoreline features of the southern Costa Brava showed that the highest abrasional

forms of possible marine origin occur at about 145 m at Punta Guixeras on the limestone Montgri massif, and as a number of poorly preserved benches in 124—135 m between San Feliu and Lloret. However none of these features is sufficiently general or distinctive to permit any conclusions.

All the more conspicuous is an almost ubiquitous shoreline at *ca.* 100 m. Although badly dissected, this often rather extensive marine platform with associated cliffs and stacks, or former offshore islands, suggests an extenuated period of development. It is particularly im-

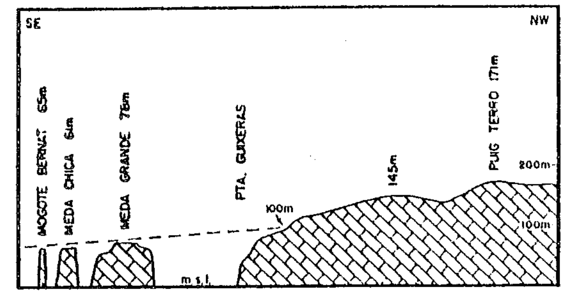

Fig. 5. *Longitudinal Profile of the Islas Medas and Punta Guixeras Promontory* indicating the 100 m shelf, sloping at 1% from the platform and cliff at Pta. Guixeras to the islet Mogoto Bernat. Vertical exaggeration 9x.

pressive around Lloret, south of Tossa, in the general area of San Feliu (Fig. 4), in the piedmont area near Aro, near San Daniel, and at Punta Guixeras, extending across the Islas Medas (Fig. 5). Similarly the deformed Eocene strata of the Bisbal area of the Bajo Ampurdán have been conspicuously planed off at about this same level. Both the prominence and advanced degree of dissection of this 100 m shoreline indicate an early Pleistocene date. The altimetric position suggests the early Sicilian. Any marine deposits once present have been destroyed by pedogenetic processes and subsequent erosion.

The next highest shoreline, convincing, but not too well developed, is found at *ca.* 60 m. It is conspicuous at Fanals — just south of Lloret —, at the Faro and adjacent promontory of Tossa (Photo 1), south of Cala Bona, between Playa Givarola and Cap Pentiné, on the Forcas peninsula, and at Mas Collet, near San Daniel. This shoreline is also of early Pleistocene age, judging by its poor preservation, and may be later Sicilian. At any rate it is the youngest general shoreline recorded by notable platforms and cliffs.

Minor Raised Beaches. Later shorelines, invariably limited to evidence of very local platforms or the more dubious criterion of truncated stacks, cut out of more resistant dykes, were recognized in several altitudinal ranges. They provide an incidental sculpture to the macro-morphology of the Costa Brava cliffs: commonly occurring as small steplike platforms, arranged one beside the other, generally found on prominent headlands or in the flanks of *cala* inlets. The following altimetric units were identified:

30–35 m[1]
22–27 m
16–19 m
12–13 m
4–8 m

Reference is to distinctive marine abrasional features that can be employed for shoreline determination with a reasonable amount of reliability (Photo 2). Since even a weathering mantle is usually missing the absence of marine deposits on these small erosional features is understandable.

These late shorelines are geomorphically comparable and altimetrically approximately equivalent to the Tyrrhenian I, II and III marine terraces of Mallorca (BUTZER 1962, BUTZER & CUERDA, 1961, 1962a, b). Lacking fossil horizons, direct correlation is not permissible. A certain degree of stratigraphic delimitation however is made possible by continental deposits, corresponding to Pleistocene regressional phases, overlying a number of such beaches. These Pleistocene sediments, referred to below, indicate that at least the 16–19 m and 22–27 m shorelines are of pre-Late Pleistocene age, while LLOPIS' section at Cap Roig (1953, p. 42) indicates the same for the 4–8 m shorelines.

[1] These levels were identified at the following localities, which can be readily found on the 1 : 50,000 national topographic series maps Nos. 334, 365 and 366, 2nd. edition. 30–35 m level: Palamós and S'Agaró; 22–27 m level: Playa de Fosca, Palamós, Rocas Planas-Torre Valentina, S'Agaró, Focas, San Telmo, Blanes; 16–19 m level: Playa de Fosca, Cap Roig to Barrio de Fanals (Aro), Pta. Prima, Forcas. San Telmo, San Canet, Cap Pentiné, Tossa (Faro and La Isla promontories); 12–13 m level: Playa de Fosca, Palamós, Cap Roig, S'Agaró, Forcas, San Telmo, Canyet de Mar, Cap Pentiné, stacks between Cala Bona and Tossa, Tossa (La Isla), Lloret (Fanals), Blanes (La Roca); 4–8 m level: Playa de Fosca, Palamós, Playa de Roig, Playa de la Cueva, Playa de Conca, S'Agaró, Forcas, San Telmo, San Canet, Cap Pentiné, Playa Givarola, Tossa and Blanes. Even lower levels in 1–3 m are indicated at Playa de Roig and S'Agaró.

Plio-Pleistocene deposits of the Eastern Selva

Previous Work. The Plio-Pleistocene sediments overlying the abraded bedrock basement of the Selva were classified by MARCET & SOLÉ (1949, p. 39–44) into three, contemporary facies:

(a) 30–40 m of multicoloured, sandy lacustrine clays, partly fossiliferous (northernmost area, exposed at Palau Sacosta);
(b) 40–50 m of arcose beds, resulting from granite disintegration, alternating with conglomeratic horizons (most of the Selva, sections described from Quart and San Andrés);
(c) over 30 m of silicified arcose beds of Caldas (southern Selva).

LLOPIS *et al.* (1953, pp. 33–36) recognize two stratigraphic units:

(i) Upper Llagostera series, considered to comprise MARCET & SOLÉ's Plio-Pleistocene sequence and some 30 m of cobble conglomerates, with an arcose matrix, exposed south of Llagostera. No evidence of tectonic deformation is reported from any of these sections.
(ii) Lower Llagostera series, exposed only south of Llagostera, and comprising over 50 m of rather folded and faulted detrital sandstones and multicoloured clays or marls.

Whereas the (Lower?) Pliocene age of the Lower Llagostera series suggested by LLOPIS *et al.* is quite plausible, despite a lack of fauna, the stratigraphic position of the Upper series, considered at some length by MARCET & SOLÉ (1949, p. 42–43), is inconclusive. The general facies character and the limited, molluscan fauna of Palau Sacosta are employed to show analogy with similar Plio-Pleistocene sediments in the northerly, Alto Ampurdán (cf. J. M. RIBERA, 1950), in Roussillon and the Rhône Valley at Lyon. The fauna in question includes the following species (MARCET & SOLÉ, 1949, p. 110–111, Pl. 13):

Limnaea ovata.
Limnaea canalis.
Limnaea sp.
Cyclostoma elegans.
Cyclostoma elegans var. *ferrugineum.*
Testacella bruntoniana.
Testacella halitoides (?).
Helicella cellaria.
Helix acosmia.
Helix sp.
Clausilia (Tryptichia) maxima.
Clausilia (Tryptichia) sinistrora, var *chiae.*

MARCET & SOLÉ suggest the faunal assemblage could be either Upper Pliocene or Villafranchian, and consider the Upper series as "certainly later than the marine Plaisencian, although impossible to determine whether anterior or not to the Villafranchian" (1949, p. 43). Nevertheless the Spanish authors generally designate the Upper series as "continental Pliocene". Sedimentological evidence will be offered below to suggest that a part of the Upper Llagostera series is Villafrancian, while a more recent stratigraphic reassessment of the Lyon sequence by F. BOURDIER (1953) shows that even the so-called Upper Pliocene species *Testacella bruntoniana*, *T. haliloides* and *Clausilia sinistrosa* occur in the Lower Villafranchian, and are not sufficiently diagnostic to permit stratigraphic differentiation.

MARCET & SOLÉ (1949, p. 45, 47) further recognize some 2–6 m of red conglomerates, tentatively identified with an upper terrace of the Onyar and exposed at Quart, Palau Sacosta and Fornells. The same authors definitely correlate this terrace with the Villafranchian.

The Quart Sequence. The most informative Plio-Pleistocene section of the Selva is found at the quarry of Quart just south of that village, at KM 6.4 of the road Gerona-Llagostera. MARCET & SOLÉ (1949, p. 39–40, Pl. 6) give only a very rudimentary description of the following, well stratified beds on a schist base (top to bottom):

1 m coarse reddish conglomerate
3 m multicoloured clays
4 m reddish clays
0.5 m fine conglomerate
6 m multicoloured sandy clays
0.6 m conglomerate.

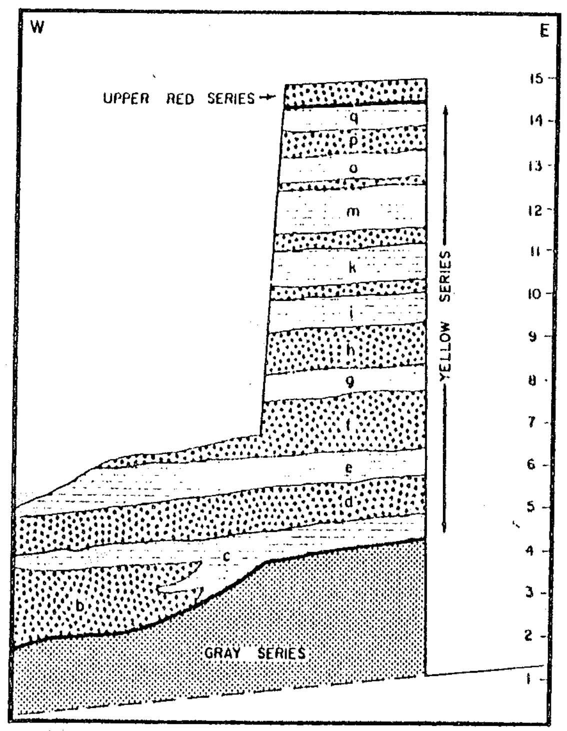

Fig. 6. *Section of main profile at the Quart Quarry.* See scale at right in meters. Vertical exaggeration 2x.

The quarry pits seem to have been somewhat enlarged and deepened since studied by MARCET & SOLÉ, so that the above sequence requires considerable revision. The writer recognized three disconformable series of semi-consolidated sediments (Fig. 6): (1) a basal "Gray Series" of at least 8 m of light gray silt, representing fine, lacustrine deposits, without detrital intercalations; (2) an intermediate "Yellow Series" with up to over 12 m of reddish yellow silt or clay, intercalated with medium-sized gravel horizons, representing a mixed subaqueous deposit; and (3) a surface "Red Series" with about 6 m of coarse gravel with yellowish red sandy matrix, representing an alluvial terrace or fan.

In detail the Quart sequence can be described as follows (from bottom to top):

(i) Gray Series. Over 8 m. A fine-grained, silty-clayey loam with 99% of its material below 200 microns, a maximum in the coarse silts, a secondary maximum in the clays (Tables 1, 2). Carbonates account for 6% by weight, while quartz is the dominant material. Completely uniform as to grain-size, the deposit lacks visible stratification and was later subjected to oxidation and reduction as a result of seasonal waterlogging (*pseudo-gley*). This is indicated by large irregular patches of light gray (2.5 Y 7/2) in a background of reddish yellow (5 YR 6–7/8)[1], studded with 1–2 cm flecks or short, vertical concentrations of iron oxide. Both red and yellow oxides are present.

Table 1. Quart and KM 10 Granulometric Analyses[2] (in percent)

	200—1000μ	60—200μ	20—60μ	6—20μ	2—6μ	< 2μ
Km 10 (vii)	42.7	16.9	12.0	10.1	5.4	12.7
Quart (xx)	59.9	10.4	10.4	6.5	2.7	10.1
Km 10 (vi)	12.5	22.8	22.8	12.9	5.5	23.5
Km 10 (vi)	9.2	21.8	26.5	8.4	13.4	20.8
Km 10 (v)	7.4	24.5	28.6	17.5	6.8	18.0
Quart (xviii)	5.1	9.1	16.9	22.6	8.9	37.4
Km 10 (iii)	2.0	20.6	32.4	20.4	6.6	18.0
Quart (viii)	6.1	31.6	23.0	19.3	6.9	13.1
Quart (ii)	6.4	15.3	17.3	18.1	15.6	27.2
Quart (i) soil	3.1	25.6	19.7	18.2	6.8	26.6
Quart (i)	0.7	5.4	22.0	33.3	15.8	22.8

[1] Colours given refer to the *Munsell Soil Color Charts*, Baltimore, 1954, and are designated for dry sediments.

[2] Grain-size analyses were carried out by the Köhn method, and invariably refer to the fine soil component.

Table 2. Quart and KM 10 Medium Sand Fraction Analyses[1] (percent)

	Waterworn Quartz	Windworn Quartz	Unworn Quartz	Carbonates	pH (H_2O)
Km 10 (vii)	12	2	81	43	7.88
Quart (xx)	10	21	69	2	6.70
Km 10 (vi)	16	1	83	2	7.57
Km 10 (vi)	10	2	88	2	7.08
Km 10 (v)	12	6	82	7	8.55
Quart (xviii)	7	18	75	2	6.54
Km 10 (iii)	9	10	81	13	7.62
Quart (viii)	8	4	88	1	7.07
Quart (ii)	7	10	83	1	7.43
Quart (i) soil	3	3	94	1	7.68
Quart (i)	12	0	88	6	7.17

On the basis of the uniformity, lack of bedding, the overwhelming dominance of unworn quartz grains and a total absence of windworn grains, the Gray Series must be considered as a lacustrine sediment of fine granitic residual materials, deposited in quiet waters, derived from perennial, non-torrential streams with weak gradients (at least in their lower courses). The beds attain about 48 m above the local level of the Onyar aand 123 m above sea level.

A long period of subaerial denudation, dissection, and weathering followed upon the deposition of the Gray Series. At least several meters of the fine lacustrine silts were removed, and the surface planed off to a slope of about 6%, in the direction of the modern river Onyar. Either prior to or after this erosional phase a longer period of intensive chemical weathering — not associated with the pseudo-gley — led to the development of a *rotlehm* type soil on the Gray Series (Fig. 7). Although nowhere observed *in situ*, a light red (2.5 YR 6/8) soil sediment, whose grain-size spectrum (Table 1) leaves no doubt as to derivation from the lacustrine

[1] Micro-morphological quartz sand analyses (cf. CAILLEUX, 1942) were made of the medium sand grain size in order to assess the aeolian component of the silts as well. Although this procedure is more difficult, it is as significant as study of the 300 to 1500 micron components. Of interest is the fact that the quartz micromorphometry of the Selva deposits is rather uninformative. Being a granite bedrock area, coarse quartz grit is rather abundant and long stream transport distances are necessary to round off and polish quartz grains. Commonly this is only accomplished after several generations of transport, i. e. after repeated derivation from older alluvial or colluvial beds.

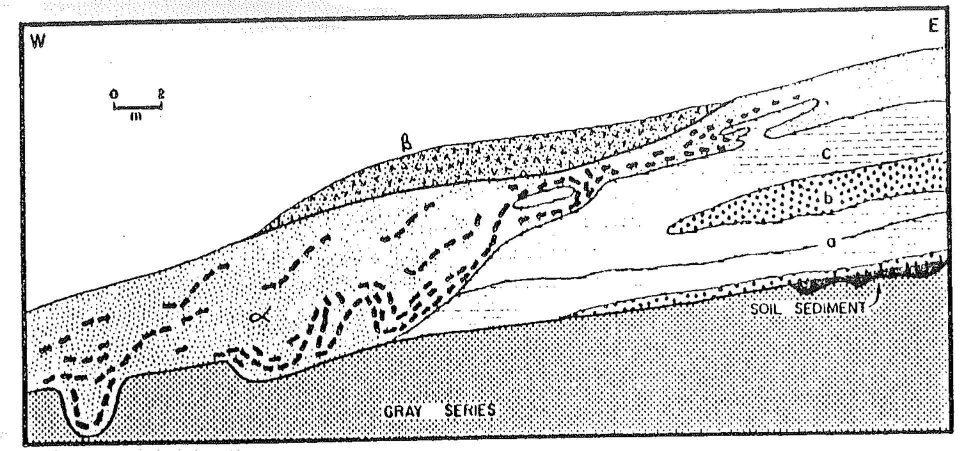

Fig. 7. *Section of western profile at Quart Quarry.* See text. Letters a, b, c refer to the Yellow Series, letter α to redeposited and contorted Yellow Series material (during sedimentation of the Lower Red Series?), letter β to colluvial scree postdating the Red Series. Vertical exaggeration 2x.

beds, is distinctly present at the base of the Yellow Series. The sand component has increased, due to addition of derived materials, the clay component increased as a result of weathering. The carbonate content is reduced to 0.9%. The presence of only 3% waterworn quartz grains precludes distant transport.

(ii) Yellow Series. Bed a. 170 cm. Light red to reddish yellow (2.5 YR 6/8—7.5 YR 7/6) loamy clay (Table 1, 2) with 20 cm of fine rolled schist gravel at base. The noticeable stratification is inclined at 6–8%, bedded N40–50°W. The upper 50 cm of bed (ii) appear to be weathered light red *in situ*, although the evidence is not conclusive.

(iii) Bed b. 95 cm to over 7 m. Medium to coarse, rounded gravel (Table 3) with 9.5% of the pebbles mechanically fractured during or after transport[1]. Matrix of reddish yellow (5—7.5 YR 6/8) coarse sand. Generally well-stratified.

[1] Numerous Catalonian deposits contain appreciable proportions of pebbles that have been *mechanically fractured during or after transport*. In the former case they have been partly or fully rolled, and now show comparatively fresh fractures. In the latter case, the pebble is split *in situ*, with the parts in place or almost contiguous. Although sheer mechanical impact during transport, as well as certain forms of chemical weathering (salt) *in situ* may produce similar features, frost-action appears to be the most significant variable. With due restrictions, then, statistical analyses of 100-specimen samples for such fractured pebbles may give a certain index of frost-action.

Table 3. Morphometric Gravel Analyses
Values of ρ (Lüttig's Index of Rounding)[1]

	Sample Size	Mean ρ (Percent)	Percent ρ ≤ 8 (Percent)	Coefficient of Variation of ρ (%)	Percent mechanically fractured
Quart Quarry (Schist)					
Bed (xx) upper	100	42.3	0	33.8	30
Bed (xx) lower	100	46.4	0	28.2	17
Bed (ix)	100	43.0	2	39.1	25
Bed (vii)	75	45.6	1	36.1	23
Bed (v)	100	49.8	0	36.3	4
Bed (iii) main section	100	45.1	0	30.67	9
Bed (iii) west section	100	52.0	0	30.69	10
KM 10 (Gerona-Llagostera) (Schist)					
Bed (vii)	100	46.1	0	36.1	50
Bed (vi) top	90	47.6	0	31.2	35
Bed (vi) base	80	51.3	0	27.3	36
Bed (iv)	90	42.6	2	40.2	28
Bed (ii)	75	41.3	4	45.3	33
KM 3 (Riudellots — Cassá de la Selva)					
Upper Red Series	90	54.4	0	23.6	17
Lower Red Series	75	45.5	0	28.4	24
Riera de Tossa KM 1.8 and KM1.0 (Granite)					
Holocene recent Fill	50	37.7	16	63.7	—
Low terrace (base)	50	44.3	4	54.0	17
Middle terrace (bed c)	100	45.8	0	34.0	31

[1] The index of rounding (ρ) by LÜTTIG (1956) is obtained by estimating the percentage of a pebble's circumference that is smoothened and convex. The following ranges of mean ρ 's are suggested as useful: 0—10, angular; 11—20, subangular; 21—40, subrounded; 41—60, rounded, 61—100, well rounded. The coefficient of variation of the rounding index expresses the homogeneity of gravel samples rather effectively, and is useful in genetic interpretation.

(iv) Bed c. 60–75 cm. Reddish yellow (7.5 YR 6–7/6–8) clayey loam with light gray (2.5 Y 7/2) flecks. Consists largely of fine quartz debris, with a little biotite.

(v) Bed d. 100—115 cm. Coarse, rounded gravel (Table 3) with 4% fractured pebbles.

(vi) Bed e. 70—115 cm. As (iv), with some pebble intercalations.

(vii) Bed f. 55—130 cm. As (v), laterally with intercalations of finer silts.

(viii) Bed g. 70—130 cm. As (iv), but coarser (Tables 1, 2).

(ix) Bed h. 105 cm. Medium, rounded gravel with 25% fractured pebbles.

(x) Bed i. 60 cm. As (iv)

(xi) Bed j. 30 cm. Medium, rounded gravel.

(xii) Bed k. 90 cm. As (iv)

(xiii) Bed l. 40 cm. Medium, rounded gravel.

(xiv) Bed m. 90 cm. As (iv)

(xv) Bed n. 20 cm. Medium, rounded gravel.

(xvi) Bed o. 55 cm. As (iv) Bed o and some of the adjacent lower beds show secondary calcareous concretions and vertical dehydration fissures filled with highly calcareous detritus.

(xvii) Bed p. 60 cm. Medium to coarse, rounded gravel.

(xviii) Bed q. 60 cm. As (iv), but finer (Tables 1, 2). No secondary calcareous concretions.

The sedimentology suggests renewed deposition of granitic residual materials, while the presence of derived soils, argillaceous residuals of schist bedrock, and local detritus all suggest different environmental conditions. Periodic, notably torrential waterflow of nearby streams indicates a fundamental change of climate. Alternating lacustrine sedimentation of clays and subaerial or subaqueous deposition of alluvial matter suggests location near the shores of a shallow lake or marsh, possibly subject to considerable fluctuations of level and shoreline. The gravel is moderately decomposed, particularly the occasional granites. The whole Yellow Series exhibits reddish and gray flecks due to oxidation and reduction, similar to that of the Gray Series, suggesting that the period of seasonal waterlogging postdates the Yellow Series.

The periodic intercalation of coarse, detrital beds may have resulted from spasmodic uplift of the Gabarras horst. This hypothesis receives some support from the apparent absence of macroscopic schist residuals in the Gray Series. However the changing proportion of mechanically fractured pebbles, and the complex local intercalations of gravel and clay imply that climatic periodicity was at least partially responsible. The fractured pebbles suggest a comparatively cold climate during the deposition of the greater part of the Yellow Series.

(xix) Red Series. Lower part. Over 5.7 m. Exposed only in step-like trenches adjacent to the level railroad crossing, disconformably overlying 1.7 m of detrital silty clay of the Yellow Series, over schist bedrock. At the base are 3.2 m of stratified yellowish red (5 YR 5/6) sand and gravel, showing some evidence of festoon-like solifluctoidal contortions, under 90 cm of redeposited, unstratified materials from the Yellow Series, and 1.6 m of crudely stratified intermixed derived Yellow Series material and quartz cobbles. These beds are clearly embanked against the Yellow Series, indicating extensive prior dissection, and were mistaken by MARCET & SOLÉ (1949, Fig. 7) as a basal conglomerate of the Yellow Series. Possibly contemporary was the redeposition of some 6 m of Yellow Series material in the form of a convoluted reddish yellow (7.5 YR 7/6) slope deposit, exposed on the far western side of the quarry (Fig. 7). The extremely variable and lenticular sorting of fine gravel, sand, silt and clay suggests solifluction, although probably as a result of water saturation and lubrication, with attendant mass sliding on a slope averaging 25%.

(xx) Red Series. Upper part. Over 1 m. Coarse schist and granite gravel, rounded, 17% and 30% mechanically fractured in different samples, bedded on an 8% slope, N40°W towards the modern course of the Onyar. The matrix consists of yellowish red (5 YR 5/8) coarse quartz sand with considerable amounts of mica. Microscopically it can be shown that three-fourths of the medium sand grains are reddened by weathering. The surface forms part of an alluvial terrace or fan at 58 m above the present course of the Onyar, attaining 133 m above sea-level.

The Red Series is only poorly represented at Quart, but at least offers an argument for mixed alluvial-colluvial processes following the dissection of the Yellow Series (Lower Red Series) and later, well-defined fluvial sedimentation (Upper Red Series). The marsh or lake conditions of the Selva had been entirely superseded by subaerial processes prior to deposition of the Red Series. The Lower Red Series was, judging by the presence of weathered Yellow Series material, probably preceded by a period of red soil development. Another period of red soil development either followed or preceded the Upper Red Series. However it is not clear if the discolouration evident is due to the presence of colluvial soil products or to weathering *in situ*.

The KM 10 Section (Gerona-Llagostera). The upper part of the Yellow Series and most or all of the Red Series is exposed at a previously unrecorded pit and in the nearby highway cut at KM 9.9–10.1 (Gerona to Llagostera). The following section (Fig. 8) is exposed at the small quarry section (bottom to top) (Photo 3):

(i) Yellow series. Bed m' Over 140 cm. Reddish yellow (5–7.5 YR 7/8) clayey loam, largely of fine quartz debris with a little mica. Large vertical,

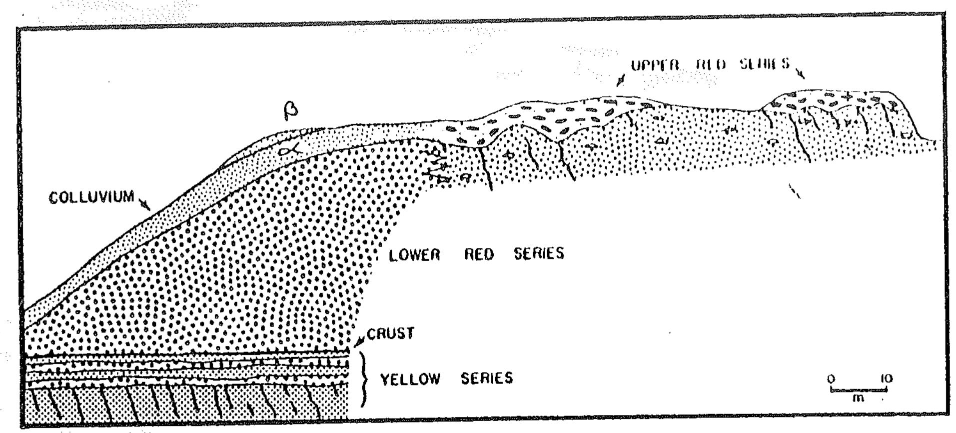

Fig. 8. *Composite section of KM 10 (Gerona-Llagostera) exposures.* See text. Vertical exaggeration 4x.

dehydration cracks extend to at least 1.5 m below the surface, and are filled with secondary calcite and derived fine detritus.

(ii) Bed n' 15–20 cm. Medium, rounded schist gravel, with 33% of pebbles mechanically fractured (Table 3). Matrix consists of red (2.5–5 YR 4/8) coarse sand. Well bedded on an 6–8% slope, N40°W.

(iii) Bed o' 30 cm. Reddish yellow (7.5 YR 7/8) clayey loam (Table 1), without desiccation cracks but with high carbonate and pH-values (Table 2).

(iv) Bed p' 50 cm. As (ii), but coarse, with a yellowish red (5 YR 5/6) matrix, and 28% fractured pebbles (Table 3).

(v) Bed q' 25 cm. As (iii), but lower secondary calcite enrichment (7%), and very alkaline reaction. A 3 cm thick massive calcite crust (*croûte zonaire*) caps the surface, while fine travertine laminae are already present within the bed itself.

Whether or not the upper strata of the Yellow Series at KM 10 (beds m' to q') correspond to beds (m) to (q) at Quart, is difficult to decide. But the presence of dehydration cracks in both, and of a surface crust at KM 10, is suggestive that this is indeed so. The persistance and decline of frost action at both localities, suggested by the fractured pebbles, also supports this. Very probably the uppermost strata of the Yellow Series have not been lost.

The travertine-like calcareous crust, secondary calcification and dehydration cracks are probably genetically related and followed immediately upon sedimentation. Unlike on limestone bedrock (BUTZER, 1963a), carbonate enrichment in a granite and schist area presumably requires reduced solution and hence drier climate. The absence of cracks and reduction of carbonates in the uppermost layers at Quart and KM 10 is possibly due to subsequent removal of calcite by solution.

(vi) Lower Red Series. About 10 m. Coarse, rounded gravel (Table 3) consistently 35–36% mechanically fractured, inclined at 7–8%, N40°W, without major disconformity to bed (v). The matrix is consistently rather clayey (20–25%) (Tables 1, 2), the carbonates about 2%. The materials are redder (2.5–5 YR 5/8) at the base (due to colluviation of red soils?) and at the surface (due to soil development *in situ*?), otherwise reddish yellow (5 YR 6/8). Laterally the gravel facies grades over conformably into clayey loam with interspersed gravel. This lateral change is readily interpreted by coarse alluviation in close proximity to the nearby stream, with finer sedimentation at greater distance during the flood season. Patches of light gray (10 YR–2.5Y 7/2) and ferruginous flecks in the finer facies again suggest pseudogley conditions. The final deposits, judging by sections exposed at KM 11, may have involved massive mixed travertine and alluvial sedimentation in calcite crusts of 1.5 m thickness. Locally, massive dehydration fissures, as much as 15 cm across and largely filled with calcareous evaporites, mark the upper 1–2 m of the finer facies.

The Lower Red Series definitely indicates lateral, fanlike deposition of the Gabarras tributaries onto a higher Onyar floodplain (at about + 58 m, at 139 m above sea-level). The climate was definitely cool, and streams were markedly seasonal. This suggests a cool, pluvial period of considerable duration. Similarly as in the case of the cool, and also moist, climate of the Yellow Series, a period of dry (and warmer) climate succeeded, leading to the formation of calcite crusts and dehydration fissures. Considerable denudation and dissection appears to have preceded the Upper Red Series.

(vii) Upper Red Series. At least 1.5 m. Coarse, rounded gravel (Table 3), with 50% fractured pebbles, and a matrix of yellowish red (2.5–5 YR 5–6/8) coarse sandy loam. The disconformity with (vi) is marked by eroded pockets, filled with rather contorted gravel and cobbles, possibly due in part of solifluctoidal movement. Bedding direction is N45–50°W. The deposit is noticeably weathered, the predominantly schist gravel strongly decomposed. The whole bed appears to represent the truncated lower 1–1.5 m of a *rotlehm*-type soil, whose classical (B) -horizon has been largely lost to erosion. The Upper Red Series has a high carbonate content and a relatively high pH (Table 2). This suggests secondary calcification during a later phase of drier climate. Laterally the deposits grade over into a meter or more of yellowish red (5 YR 5/8) colluvial silts, deposited on the slope of the nearby stream at a much later date, documenting subsequent erosion.

The Upper Red Series, although apparently the product of a brief aggradation phase, was deposited under conditions quite analogous to those of the Lower Red Series — a cool, pluvial climate. The beds are 59 m above the local Onyar, at 140 m above sea-level, i. e. at a more or less identical surface level as the Lower Series. Deposition was probably followed by a longer period of chemical weathering with moderately intense *rotlehm* pedogenesis on a coarse gravel bed.

Other Plio-Pleistocene Sections of the Selva. Along the road from Cassá to Riudellots, a number of sections expose the various Plio-Pleistocene sediments filling the eastern Selva. A detailed traverse of this route (Fig. 9) showed that the road almost everywhere exposes surficially

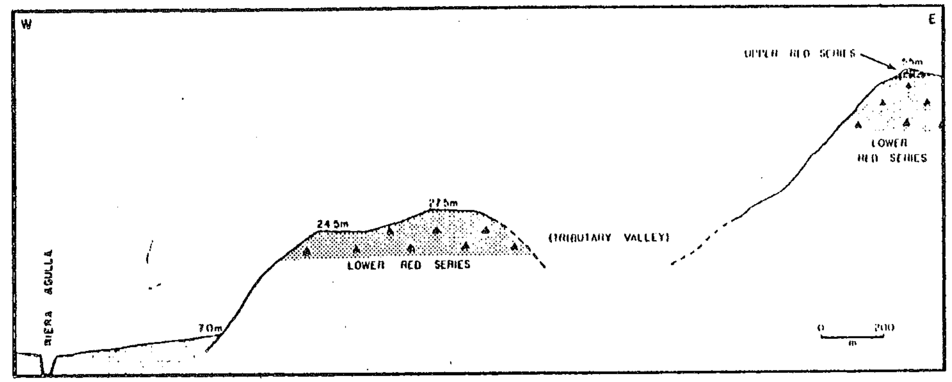

Fig. 9. *Transverse section from KM 1–3 (Riudellots-Cassá de la Selva).* See text. Vertical exaggeration 15x.

weathered loamy or sandy clays and well-stratified gravel (quartz, schist, granite, basalt) recalling the Lower Red Series. The beds have been dissected by tributary streams, and in part form erosional terraces, notably at + 24.5 m (106 m) and + 27.5 m (109 m). A remnant pocket of the Upper Red Series is preserved in + 55 m (136 m) at KM 3. It consists of coarse, crudely stratified, rounded schist gravel, 17% mechanically fractured, in a yellowish red (5 YR 4–5/8) sandy loam. The gravel is more rounded and homogeneous, suggesting longer transport than the more detrital beds at the edge of the Gabarras (Table 3). The *rotlehm* soil with a yellowish red (5 YR 5/6)(B)-horizon of 60–90 m developed on the Red Series nearby has already been described by MARCET & SOLÉ (1949, Fig. 12) as "eluvial Pleistocene". The only other stream feature on this road section was a + 7 m (88 m) terrace of fine unconsolidated yellowish brown (10 YR 6/4) alluvium, of Upper Pleistocene age.

Other analogous sediments were studied at KM 11 and 14 of the Gerona-Llagostera road, where the Lower Red Series is exposed in + 59 m (145 m); at San Andrés de Salou, where the Yellow Series is exposed; and at Fornells, where the Lower Red Series can be observed at + 58 m (133 m). The only additional information provided is that the Lower Red Series is very widespread, represented by a terrace rising from an absolute value of 130 m in the north to 145 m further south. It is part of a graded, alluvial filling of the Selva floodplain. The Upper Red Series *seems* to be locally confined to a thin gravel mantle, possible forming piedmont alluvial fans at the edge of the Gabarras. Only locally are the Yellow and Gray Series preserved below this filling, indicating thorough dissection preceding the Lower Red Series.

Palau Sacosta. The extensive quarries of Can Quintana near the confluence of the Onyar and Ter were visited briefly on two occasions, once in the company of Dr. SOLÉ. The sections are briefly described by MARCET & SOLÉ (1959, p. 39–40, 42–43, and Fig. 8). In order to enable comparison with the preceding sections from Quart and KM 10 the sequence can be synthesized (top to bottom):

(a) 3 m of yellowish red, coarse, well rolled gravels representing the Red Series (Lower?).

(b) 12 m of reddish yellow, alternating series of silty clay and sandy silt, in which the molluscan fauna described belongs to the lowermost 2 m. Despite the absence of coarser detritus, this can be safely equated with the Yellow Series.

(c) over 50 cm of gray silts, possibly representing the top of the Gray Series.

In other words, the Gray Series is so far only typically known from Quart. As a corollary, there is no significant lateral change in facies from north to south, between clays and arcose beds, such as was postulated by MARCET & SOLÉ (1949, Fig. 9 and p. 47). The only change is that of the detrital component within the Yellow Series — the particular formation described by MARCET & SOLÉ (1949) from each of the three critical sections at Palau Sacosta, Quart and San Andrés.

Summary of the Plio-Pleistocene Formations of the Selva

(a) Gray Series. 8 m exposed, original thickness possibly as much as 50 m. Uniform, very fine-grained lacustrine silt, deposited in quiet waters, derived from perennial, non-torrential streams. Climate moist, lacking seasonal periodicity, and presumably warm.

— subaerial dissection, denudation, *rotlehm* development—

(b) Yellow Series. 12 m exposed. Alternating fine beds of clayey silts and coarse beds of moderately rolled gravel or sand, derived from mixed lacustrine alluvial sedimentation near the fluctuating shores of a shallow lake or marsh. Although the clay content of the fine beds of the Yellow Series is usually higher than that of the Gray Series, a rather different regime of sedimentation is indicated by the dominance of the sand fraction in the Yellow Series, as opposed to the silt fraction in the Gray Series. Seasonal waterlogging of fine lower-lying beds took place at this time. The local streams were subject to periodic, torrential discharge. A gradual increase of frost-action to appreciable proportions during the second half of the Yellow Series — on the evidence of pebbles mechanically fractured during or after transport— suggests a notable temperature depression underway during sedimentation. Seasonally rather moist climate, increasingly cool. Crust sedimentation and dehydration fissures suggest increasing aridity during final sedimentation.

—intensive subaerial dissection, probably also *rotlehm* development—

(c) Lower Red Series. 10 m exposed, original thickness possibly as much as 50 m. Coarse, well rolled, cryoclastic gravels and clayey silts with some gravel, derived from strong lateral alluviation into the depression, with fine sedimentation, frequently colluvial, on the margins of the torrential tributaries. The series forms part of a distinct alluvial terrace complex at about 55–60 m above the present Rio Onyar. Seasonal waterlogging of fine, lowerlying beds. A seasonally very wet, cool pluvial climate. Travertine deposition and dehydration fissures suggest increasing aridity during final sedimentation.

— dissection; denudation —

(d) Upper Red Series. 1.5 m exposed, original depth or areal extent unknown. Coarse, well-rolled, cryoclastic gravel or cobble detritus apparently derived from brief and shallow, fan-like deposition on the margins of the Selva by lateral tributaries, conforming to the 60 m floodplain. Seasonally wet, cool, pluvial climate.

— *rotlehm* soil development —

Interpreted geomorphically and palaeo-climatically all but the Gray Series can be considered as Pleistocene sediments. The Gray Series was the product of a climatic environment quite unlike that of the present, and is probably Upper Pliocene. Stratigraphic suggestions for the Yellow and Red Series will be made after discussion of comparable deposits in the adjoining areas.

Pleistocene deposits of the Bajo Ampurdán and the Lower Ter

Previous Work. MARCET & SOLÉ (1949, p. 44–49) identify two alluvial fans adjacent to the Daró and Risscch rivers in the eastern piedmont zone of the Gabarras. These reach from about 90 m elevation in the Ampurdán to about 150 m on the Gabarras slopes. Up to 25–30 m thick, the fans consist of local cobble gravels, with a reddish matrix of sand and clay. They were attributed to the Villafranchian and correlated with the Red Series of the Selva.

MARCET & SOLÉ also refer to low stream terraces on the middle Risscch and Daró, while Pleistocene terraces are briefly described at + 3, + 8, + 45–48 and + 78–80 m above the course of the Ter near Gerona. MARÍN & SAN MIGUEL (1941) do not recognize any Pleistocene deposits at the mouths of the Ter or Daró.

Terraces of the Middle Daró. A reinvestigation of the Middle Daró yielded considerable information. The uppermost parts of the stream have incised steep gorges into the Palaeozoic bedrock, and depositional features or erosional benches only begin at a minor confluence at about 120 m, near KM 19. A low terrace can be recognized as a + 6.5 m erosional platform on one side of the stream, a + 7.3 m depositional terrace on the other. A higher, better developed terrace is present at + 15 m. A little further downstream at KM 19.5–20, the stream broadens and well developed terraces appear (Fig. 10): a "low terrace" at + 8 m, with a later step-like bench cut at + 4 m, a "middle terrace" at + 16–17 m, and

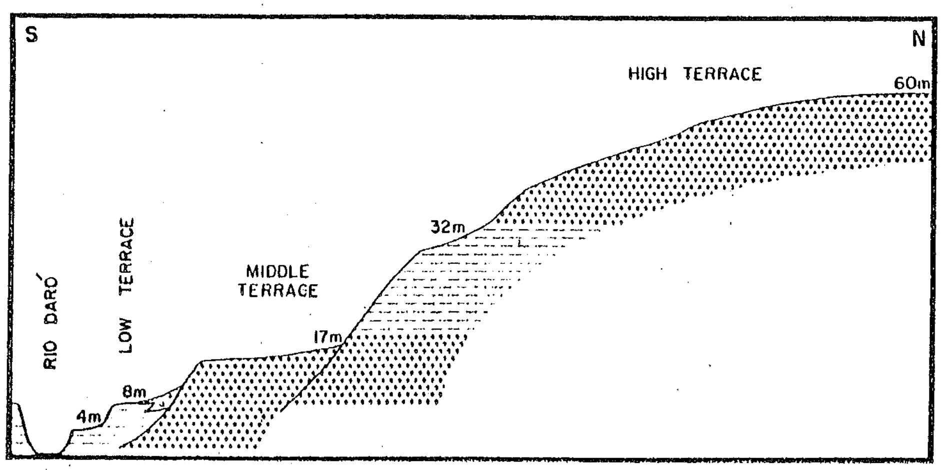

Fig. 10. *Transverse section of the Rio Daró at KM 19.5 Riudellots-La Bisbal).* See text. Vertical exaggeration 10x.

a "high terrace" at about + 60 m, representing the massive alluvial fan described by MARCET & SOLÉ.

The low terrace at KM 19.5 consists of fine, well-stratified alluvium, grading laterally into colluvial screes derived from the middle terrace. The climax soil developed on the low terrace is a meridional *braunerde*, in the sense of KUBIENA (1953). The light yellowish brown (10 YR 6/4) (B)-horizon attains a depth of 40–50 cm under a very shallow A-horizon. Considerable humus of the *mulliform moder* type is present. The clayey loam texture is largely derived, the structure granular or crumb. Due to secondary calcification the carbonates attain 4% by weight, the pH value is 7.5. As can be observed on numerous low terraces of the Costa Brava, this brown, dry-forest soil is the Holocene climax.

The middle terrace consists of coarse, stratified, sorted and rounded gravel with a rather different climax soil. A 30–70 cm A-horizon of light brown (7.5–10 YR 6/4) colour is present, with a carbonate content of only 2–3%, and an acidic reaction of 5.6–5.8. The rich humus is of *mulliform moder* type, the structure polyhedral or crumb. The clay content is somewhat lower than in the underlying (B)-horizon, although microscopic examination shows good dispersal of the colloidal clays present. The (B)-horizon of over 1.5 m depth varies from yellowish red to pink or reddish yellow (5 YR 5/8, 7.5 YR 7/4–6), with similar carbonate content but lower pH values (5.4–5.7). The loamy clay has a subrounded polyhedral structure. Migration of the colloidal clays is evident under the microscope, and dark ferruginous concretions are visible. This soil is then a good example of a relict, silicate braunlehm (cf. KUBIENA, 1953). It is the product of a phase of warm, moist climate, presumably during a part of the last interglacial.

The soil of the high terrace of fan, which is of identical facies as the Red Series of the Selva, has generally been badly eroded. It is however, well preserved in a road section near KM 19.5 where 1 m of middle terrace gravel overlies the edge of the high terrace in the following section (top to bottom):

(a) 35 cm. Fine alluvium, mainly loamy clay.

(b) 65 cm. Coarse, stratified, unsorted and rounded gravel with a matrix of loamy clay. Middle Terrace. Disconformity.

(c) 500 cm. Rounded, crudely stratified and unsorted cobble gravel — in an advanced stage of decomposition — with a clayey matrix. High terrace.

(d) Over 50 cm. Schist bedrock.

The relict or fossil soil profiles present in this same section appear as follows (Tables 4, 5):

(i) 70 cm. A-horizon (10 YR 6/4).
(ii) 30 cm. (B)-horizon (5 YR 5/8).
(iii) 25 cm. A(B)-horizon (5–7.5 YR 6/6).
(iv) 475 cm. (B)-horizon (2.5 YR 6/8).

The fossil A(B)-horizon has a reddish yellow matrix of sandy-clayey loam (Table 4) with crumb structure. Microscopically the basic quartz grains are enveloped in a well dispersed plasma of colloidal clays. The (B)-horizon proper has a red matrix of loamy clay, mainly autochthonous, considering the coarse nature of the deposit. The structure is polyhedral, and under the microscope shows unworn quartz grains and some manganese in a colloidally dispersed plasma. Small red concretions are also visible. The carbonate content is negligible, the pH rather acidic (Table 5). This buried soil is a silicate *rotlehm* (Kubiena, 1953), testimony of very intensive weathering during a long, warm, moist phase – prior to the last interglacial. These three distinctive soils are repeated on several terrace

Table 4. Rio Daró Granulometric Analyses (in percent)

	200–2000μ	60–200μ	20–60μ	6–20μ	2–6μ	< 2μ
Low terrace (B)-hor.	24.4	10.3	13.1	12.6	13.5	17.1
Middle terrace A-hor.	8.7	14.2	22.2	17.6	8.6	28.8
Middle terrace (B)-horizon	15.9	16.8	14.8	11.1	6.6	34.8
High terrace AB-hor.	11.9	20.0	30.7	9.9	4.6	22.9
High terrace (B)-horizon	6.4	16.3	14.0	15.1	5.9	42.3

Table 5. Rio Daró Medium Sand Fraction Analyses (in percent)

	Water-worn Quartz	Wind-worn Quartz	Unworn Quartz	Carbonates	pH (H_2O)
Low terrace (B)-hor.	19	7	74	4	7.52
Middle terrace A-hor.	27	19	54	3	5.73
Middle terrace (B)-horizon	15	3	82	2	5.70
High terrace AB-hor.	11	10	79	6	5.74
High terrace (B)-hor.	5	4	91	1	4.88

sequences in the province of Gerona. The *rotlehm* of the high terrace has stratigraphically dated parallels in a Tyrrhenian I soil on Mallorca (Butzer & Cuerda, 1962) and a Middle Pleistocene soil in Soria (Butzer, 1963b). The deep *ferretto rotlehms* developed on Mindel moraines and outwash in northern Italy (Fränzle, 1959) are also analogous and probably contemporary.

Further downstream on the plain at La Bisbal, analogous terraces may be found at + 6, + 14 and + 50 m above the Daró. The high terrace or fan is last recorded there. Extending to about 90 m above sea-level, it shows no evidence of marine erosion, and appears to be younger than the + 100 m marine platform. This would suggest a pre-penultimate interglacial, post-Early Sicilian age, i. e. Lower Pleistocene.

Further towards the coast, the low terraces of the Ter and Daró coalesce as the intermediate, middle terrace diappears. The low terrace drops slowly in level to about + 4 m at Gualta, before the stream enters the complex estuarine zone with its dunes of historical age. This area is also characterized by previously unrecorded Pleistocene aeolianites.

Terraces of the Ter. Apart from the remarks of Marcet & Solé (1949, p. 48–49) a more detailed terrace study of the lower Ter – between Gerona and the sea – is in process of publication by Dr. Solé. Consequently only a few comments will be made here in order to elucidate the relationships between the Selva terraces and the coast.

The low terrace of the Selva, with its meridional *braunerde*, has a general elevation of + 7 m along most of the lower Onyar tributaries, rising to + 9.5 m at Km 3.5 of the road Gerona-Llagostera, as the Onyar joins the Ter. This low terrace is graded onto the low terrace of the Ter, which is well exposed near Sarriá at 12 m above low water and 9.5 m above a Holocene floodplain. The terrace consists of over 6 m of rounded coarse gravel and cobbles, under a meter or so of colluvial silts. A light brown (7.5 YR 6/3) meridional *braunerde*, with a rather deep (B) and BC-horizon, is developed on it. Further downstream the low terrace drops in level to about 2 m at the mouth of the Ter, where it is obscured by Holocene deposits. The stream profile indicates deposition during a regression of the Mediterranean Sea.

A middle terrace, although frequently indicated by erosional and occasionally also by depositional features in the elevation range of + 15–25 m, is not coherently developed in the Selva nor on the lower Ter.

The high terrace of the Selva, represented by the + 55–60 m surface of the Red Series, can be sporadically, but distinctly traced onto the Ter. The + 78–80 m terrace east and northeast of Gerona is at 130–132 m above sea-level and shows a normal stream profile with the Red Series of the Selva. Furher downstream, northeast of Medinyá at Km 736.5 on the highway Gerona-Figueras, a similar alluvial fan at 100 m (about 80 m above the Ter) is graded onto the same stream profile. The following section is exposed here (top to bottom):

(a) 60 cm. Yellowish red (5 YR 5/8) sandy colluvial silt with occasional pebbles, under a meridional *braunerde* with medium granular structure and *moder* humus.

(b) 30 cm. Medium gravel, mainly quartz, in a matrix of reddish yellow (7.5 YR 6/6) sandy silt.

(c) 0–100 cm. Yellowish red (5 YR 4–5/8) sandy loam of colluvial origin, with some calcareous concretions. Disconformity.

(d) 250 cm. Moderately stratified, unsorted, rounded, granite and schist cobble gravels in a matrix of yellowish red (5 YR 5/8) loamy clay, a product of intensive *rotlehm* pedogenesis *in situ*. All except the quartz pebbles are rather decomposed, and frequently disintegrate upon touch. The gravel is obliquely bedded towards the Ter. This material is quite comparable to the Red Series of the Selva or the high terrace of the middle Daró. The soil development is also identical. Disconformity.

(e) Over 200 cm. Yellow (10 YR 7/6) unconsolidated clayey loam and semi-consolidated medium sand with fine, horizontal stratification. This bed is analogous to the Plio-Pleistocene of the Selva.

The Medinyá terrace shows that the Selva Red Series was truly a floodplain terrace, graded onto an analogous terrace of the Ter. It is also clear that this terrace is contemporary with or a little younger than the + 100 m marine platform, and so, either terminal or post Villafranchian. This permits a correlation of the Red Series *sensu lato* in both the Selva and Bajo Ampurdán. However separation of the Upper and Lower Red Series has so far not proved possible in either the Ter valley or the Ampurdán.

Pleistocene and recent Dunes of the Ampurdán Coast. The occurrence of dunes along the flat coastal plains near the lowermost Ter and Daró is of considerable interest. At least two generations are present: cemented Pleistocene regressional aeolianites and unconsolidated, recent dunes.

The recent dunes were active from the 14th century until successful recolonization with vegetation during the years 1896/1903 (MARÍN & SAN MIGUEL, 1941, p. 25–41). The dunes had apparently migrated southwards from the Gulf of Rosas, and are dominantly oriented NNW–SSE. They rise as much as 15 m above the plain in the area under consideration, showing barchan morphology. Although quite calcareous and alkaline (pH 7.8), the material is mainly quartz sand. An incipient rendzina-type

soil development has led to discolouration of the upper meter or so to a light brown (7.5–10 YR 6/3). The genesis of the dunes is attributed to an artificial change of location of the mouth of the Fluvia during Roman times, which supposedly led to the development of a beach ridge coast with a corresponding increase in deflation along the Gulf of Rosas (MARIN & SAN MIGUEL, 1941).

The Pleistocene aeolianites are exposed at Km 25–26 of the highway Torroella-Palafrugell. At KM 25 one massive, cemented dune, inclined at 4% seawards, is bedded N77°W. Similar but more weathered dunes at KM 26 are bedded more irregularly in southerly directions. Although the quartz component is strong, deflated lime sands from the shelf area are dominant. Reaction is notably alkaline (pH 8.5). These aeolianites, which deserve further study, provide local evidence for one or more Pleistocene regressions of the Mediterranean Sea.

Pleistocene continental evolution of the southern Costa Brava

Previous Work. Pleistocene features of the coastal slopes of the Cadiretas massif and the southern extremities of the Gabarras have been subject to study by LLOPIS *et al.* (1953, p. 26–27, 39–42). "Low" and, in most cases, "middle" terraces were described from the Ridaura, the Riera de Sta. Escolástica at San Feliu, the Riera de Tossa and the Riera de Lloret. These data on stream terraces were combined with other observations to present the following relative stratigraphy of the Pleistocene (LLOPIS *et al.*, p. 40):

C_1 (= *Cuaternario* or Quaternary). Alluvial facies: sandy clays and alluvial silts below a major travertinic crust, considered as a stratigraphic marker. Colluvial facies: gritty loams and slope breccias, cemented by surface travertines.

C_2 Alluvial facies: well-stratified reddish gritty loam of a 10-15 m higher stream terrace. Colluvial facies: red colluvial clays overlying the supposedly diagnostic travetine crust, and gritty loams with dispersed calcareous concretions.

C_3 Alluvial facies: gritty alluvium and sands of a lower terrace. Colluvial facies: fans overlying the lower terrace.

C_4 Alluvial facies: recent floodplain clays and sands. Marine-littoral facies: recent beaches and littoral sand bars.

Since little morphogenetic interpretation is attempted by LLOPIS *et al.*, and since pedogenetic criteria are only touched upon, it was found useful to restudy the terraces of the Ridaura and the Riera de Tossa.

Terraces of the Ridaura. The Ridaura flows along a 20 km valley whose headward erosion has continued since Miocene times aling the line of a shatter belt (LLOPIS *et al.*, 1953, p. 9, 23, 62–63). So far no deposits antedating the middle terrace have been identified, although LLOPIS *et al.* (1953, p. 26–27) consider 25–30 m erosional benches near S'Agaró as probable terrace remnants.

The middle terrace of the Ridaura is present upstream of KM 27.5 of the highway Llagostera-San Feliu. The surface has been somewhat eroded, so that distinct terraces are scarce. Fluvial gravels are however frequently visible. At KM 25 (cf. Fig. 4 in LLOPIS *et al.*) the following exposure is present in the railroad trench (top to bottom) (Photo 4):

(a) 70 cm. Colluvial gritty sand, of strong brown (7.5 YR 4/4) colour, with occasional stratified bands of subangular pebbles.

(b) 60 cm. Intensely weathered, rounded cobble gravels of granite, in a similar matrix. This fluvial gravel is 24.5 m above the modern stream bed.

(c) 70 cm. Crudely stratified coarse, subangular to subrounded gravel, in a yellowish red (5 YR 4/8) sandy matrix. Mixed colluvial-fluvial deposit of the floodplain periphery.

(d) Over 130 cm. Yellowish red, sandy grit of colluvial origin with crudely stratified, unsorted medium detritus.

This section shows that although the apparent terrace edge is at + 15 m, fluvial sedimentation attained + 25 m during the aggradation of the middle terrace. The massive lateral influx of weathered sand, grit and detritus, under conditions of pluvial denudation and erosion, is particularly clear. The reddish colour of the basal sediments reflects the presence of derived soil products. Nearby, an interglacial soil profile is preserved in finer colluvial material: a basal 80–90 cm relict (B)-horizon of sandy loam with coarse polyhedral structure and yellowish red (5 YR 4/8) colour, underlying 30 cm of reddish yellow (7.5 YR 6/6) slightly loamy sand of medium polyhedral structure. The latter represents the top of the relict soil which has been modified and a little eluviated by Holocene *braunerde* development.

Another middle terrace with a similar interglacial *braunlehm* profile is present along a northerly tributary entering the Ridaura near KM 27.5.

The low terrace has a relative elevation of + 8 m in the narrow valley upstream of KM 27, falling off to + 4m at Castillo. The level rises to + 5 m at the mouth, as a result of later Holocene fluvial and aeolian deposition. The mouth is deflected southwards by the beach-ridge, forming brackish water pools that are only episodically connected with the perennial waters of the upper Ridaura. The low terrace proper was deposited during a period of low sea-level, as the gradient is about 20% steeper than the modern one between Castillo and KM 25. The sediments are rather fine, consisting largely of gritty sands with embedded pebbles. Lateral colluvial intercalations are present. Pluvial erosion and aggradation was somewhat less important than during the middle terrace cycle. The subsequent, Holocene climax soil is a meridional *braunerde* with a shallow, light brownish gray (10 YR 6/2) A-horizon and a 40–80cm yellowish brown (10 YR 5/6) (B)-horizon.

The two terraces of the Ridaura are, then, quite analogous to the younger terraces of the middle Daró.

Terraces of the Riera de Tossa. The middle and low terraces are also preserved in the Riera de Tossa.

Upstream the narrow gorge is characterized by widespread colluvial gritty sands or silts, embedding occasional angular detritus, sometimes banded, laterally conformable with the middle terrace. These colluvial screes, occurring on the lower part of slopes inclined at 20–60%, may attain 5 m in thickness (Photo 5). Their sedimentation persisted a little after aggradation of the middle terrace had already ceased. A typical section at KM 6.1 of the road Tossa-Llagostera exposes 60–120 cm of yellowish red (5 YR 5/6) sandy grit over at least 80 cm of crudely stratified, rounded, cobble gravels, with detrital intercalations, in a matrix of sandy grit. The gravel was in part mechanically fractured after transport. Morphologically the transition of fluvial to colluvial facies is barely recognizable. A 2 m section of colluvial scree at KM 7.2–7.3 preserves a soil profile quite analogous to that of KM 25 of the Ridaura: a 35 cm light yellowish brown (10 YR 6/4) Holocene soil over a 65 cm yellowish red (5 YR 5/6), relict (B)-horizon.

The middle terrace proper shows an irregular gradient where preserved, fluctuating from + 12 to + 15 m, as a result of fans formed at tributary confluences. This suggests the poorly graded profile of a torrential stream. Along tributaries the middle terrace fan may attain 20–25 m above the stream bed. Downstream the general terrace level drops off rapidly from + 15 m at KM 3.0 to + 12 m at KM 2.1, and + 7.5 m at KM 1.8. Although the terrace was not recognized further downstream, the gradient of the visible sections again confirms a considerably lower base-level than today. An exposure at KM 1.8 (Fig. 11) shows an excellent crosssection of two aggradation phases of the later Pleistocene, with related pedogenesis (from top to bottom):

(a) 60 cm. Reddish yellow (7.5 YR 7/6), colluvial gritty sand embedding angular detritus, formerly graded onto the low terrace. (B)-horizon of a meridional *braunerde*. Disconformity.

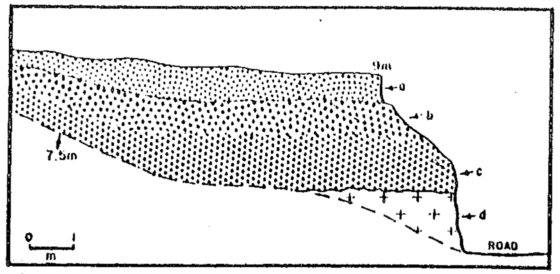

Fig. 11. *Section of KM 1.8 (Tossa-Llagostera).* See text. Numbers refer to elevation above modern stream bed. To scale.

(b) 70 cm. Loam with grit and occasional subrounded pebbles or angular detritus crudely stratified radially toward the stream. Red (2.5–5 YR 4/6), relict (B)-horizon developed on middle terrace. Laterally conformable with scree, at base goes over into

(c) 90 cm. Well stratified, rounded coarse gravel with occasional cobbles, bedded with a matrix of red (2.5 YR 4/6) clay in upper half (Table 6), yellowish red (5 YR 4/6) loam in lower half. The weathered gravel was 31% mechanically fractured during or after transport, being axially deposited to the stream (Table 3). The upper gravel is at 7.5 m above the stream bed. Disconformity.

(d) Over 50 cm. Strongly weathered granite bedrock.

The relict (B)-horizon, extending 110 cm below the disconformity, has a clay component of up to 50%, a negligible carbonate content (1%) and a low pH of 4.8 in its lower, slightly illuvial part. The structure is subrounded polyhedral. Microscopically, the skeleton of quartz grains is immersed in a regularly diffused mass of iron hydroxide sols, with tiny brownish ferric concretions. Even though a small part of the clay is illuvial, another part derived as a result of original sedimentation, these are the characteristics of a silicate plastosol, midway between a *braunlehm* and *rotlehm.* The lowermost 50 cm form a BC-horizon, with similar chemical characteristics and structure, but a somewhat smaller clay fraction.

The bedding of the middle terrace against the bedrock slopes indicates that there has been next to no bedrock incision since the alluviation of the middle terrace. The basic configuration of the stream valleys consequently antedates the Middle Pleistocene.

The low terrace is very much better preserved than the middle, and also grades laterally into colluvial facies, which continue along the lower hillsides as thin mantles of scree (Fig. 12). However, the low terrace colluvia are less significant than those of the middle terrace. The low terrace has a relative elevation of + 6.5–7 m between KM 4.5 and 6.5, dropping to + 4.5 m at KM 1–3 downstream. Near the mouth the low terrace is masked with colluvial scree derived from historical soil erosion. The steep gradient confirms a low base-level during pluvial aggradation. Stream discharge decreased during sedimentation. A 3.5–4 m section

at KM 1.0 shows at least 55 cm of very coarse, rounded gravel (Table 3), below 110 cm of medium to coarse, subrounded gravel alternating with gritty sand, again under 130 cm of gritty sand with rare pebbles. This suggests a declining precipitation. Mechanically fractured pebbles occur throughout the complex.

The climax soil of the low terrace is a 100 cm (B) and BC-horizon of yellowish brown (10 YR 5/4) colour and fine granular structure. The reaction is neutral (pH 6.5), while carbonates amount to only 1%. This is a typical Holocene meridional *braunerde.*

Terraces of the lower Tordera. The lower Tordera drains the pre-littoral depression via a transversal valey of structural location. The modern floodplain is very broad, abutting almost directly against bedrock cliffs. As a result, terraces are poorly developed and difficult to interpret. Near the confluence of the northern and southern branches, however, two terraces

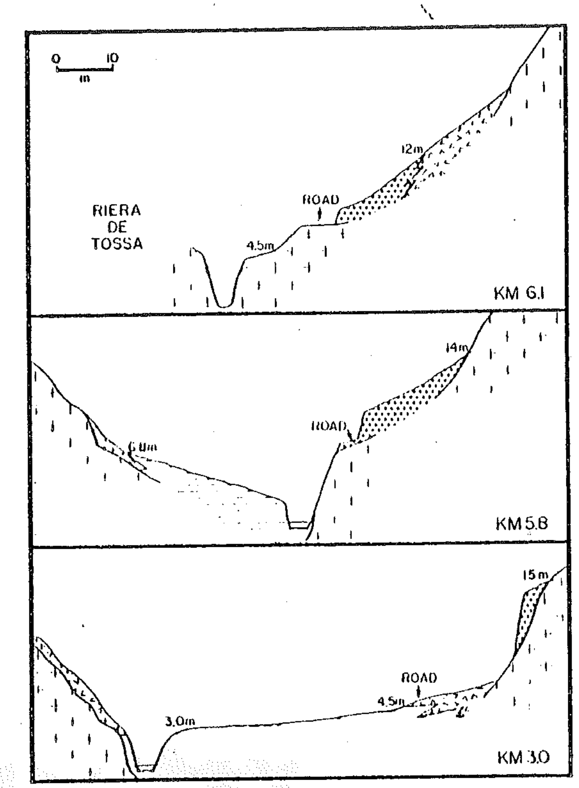

Fig. 12. *Transverse section of the Riera de Tossa.* Kilometer numbers refer to the road Tossa-Llagostera. Vertical exaggeration 2x.

were repeatedly observed along a 6 km stretch. The lower one at + 5 m is analogous to the typical low terrace found on the Daró, Ridaura and rieras of Tossa and Lloret, the higher one at + 17–21 m to the middle terrace.

Colluvial Deposits. The record of the fluvial terraces is complemented by several subclasses of colluvial deposits.

A number of exposures in typical colluvial deposits are found in the S'Agaró area, from which LLOPIS *et al.* (1953, p. 40–41) already described sections in the Masferrer and Pinell brickyards. A good exposure not recorded by these authors is available in the Trias brickyard, just west of KM 2.7 on the highway San Feliu-Palamós. Exposed, from top to bottom, are:

(a) 25 cm. Brown (7.5 YR 4/4) loamy grit of medium granular structure with moder humus. Meridional *braunerde* developed *in situ* on a colluvial sediment. Disconformity.

(b) 55 cm. Local lense of reddish yellow (7.5 YR 5/6), highly porous, carbonate-saturated loam with prismatic structure. Disconformity.

(c) 75 cm. Reddish yellow (5—7.5 YR 5/6) weathered, colluvial loamy coarse sand or grit, with angular detritus. Coarse, stratified grit at base.

(d) 90 cm. Yellowish brown (10 YR 5/6), slightly loamy, coarse sand or grit, with some detritus. Vertical fissures and streaks of calcium carbonate suggest percolation of lime-saturated waters, possibly during the minor erosional phase separating beds (c) and (d).

(e) Over 6 meters. Reddish yellow (7.5 YR 5/6, 5 YR 6/6) gritty loamy clay, with prismatic structure, and quartz grit with manganese precipitates along fissures, suggesting seasonal water-logging at one time. Vertical streaks of illuvial calcareous precipitates occur in the lowermost sections. This colluvial, interglacial soil sediment is employed for manufacture of roof tiles.

Beds (c)-(e) belong to one sedimentary complex resulting from areal denudation under moist conditions, with two drier interruptions coinciding with surface washing by lime-charged waters. Locally, as in the Pinell brickyard, sedimentary calcareous crusts may be present. Bed (c) was subsequently weathered although no good soil profile is preserved. This whole complex was probably contemporary to the middle terrace[1]. The later, Upper Pleistocene colluvial phase(s) recorded in these quarries were not of great significance. The Trias exposure provides a typical example of surface colluviation by sheetflooding, surface washing and mass-movement.

The regional importance of colluviation is seldom obvious. Yet, such processes may be considered responsible for the almost total removal of *rotlehm* or *braunlehm* soils common on the gentler sloping bedrock surfaces prior to formation of the middle terrace. Today, soils of any appreciable depth are developed only upon colluvial sediments, not as residual mantles *in situ*. Most of the slope sediments, showing unmistakable signs of repeated deposition, are contemporary to the middle terrace, as can be shown by lateral intercalations with fluvial deposits or by the last interglacial *braunlehm* soil developed on them. Yet even the latter

[1] At least neither the Trias nor Pinell brickyards provide any evidence supporting LLOPIS *et al.* (1953, p. 40—41) in their distinction of stratigraphic units C_1 and C_2.

soil was mainly developed on sediments rather than primarily on fresh bedrock. The most significant geomorphic process of the later Quaternary was then denudation. A striking example of such activity are the great blocks of pegmatitic granite forming pedestal and castellated rocks in the KM 16—17 area of the road Tossa-San Feliu. Many such boulders are found "stranded" 100 m and more downslope, where they may be immersed and stabilized in several decimeters of colluvium. These distinctive boulders demonstrate that not only fine residual products but also great masses of cobbles were periodically transported great distances downhill on 10—40% slopes by mass-movement and surface washing.

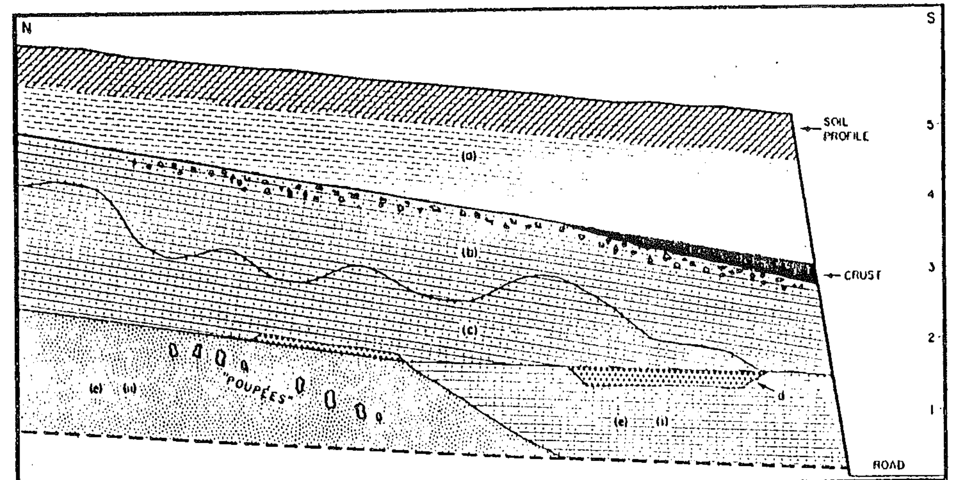

Fig. 13. *Section of KM 8 (San Feliu-Palamós)*. See text. Scale at right in meters. Approximately to scale.

A different form of colluvial sediment is exposed between KM 6—9 on the road San Feliu-Palamós. An instructive section is located at KM 8 in a small abandoned quarry (Fig. 13) (from top to bottom):

(a) 150—220 cm. Reddish yellow (7.5 YR 6/6), calcareous, clayey loam, with some grit and quartz detritus and a coarse prismatic structure. The surface, under a Holocene pararendzina type soil, inclined at 10%, is bedded obliquely toward the nearby torrent valley. With good vertical cleavage and lack of visible bedding, this has the appearance of a loess-like colluvial sediment, derived in large part from aeolian materials. The grain-size distribution of the unaltered sediments (Table 6) is not that of a true loess however. Disconformity.

(b) 80—140 cm. Light brown (10 YR 6/4, 7/3), medium sandy loam with grit; prismatic structure. Calcareous concretions in upper 20 cm grade over into calcareous surface crust, locally attaining 40 cm thickness. Surface slope at 15%.

(c) 0–200 cm. Yellowish red (5 YR 4–5/6), gritty loam; prismatic structure. Low carbonate content but with chalky vertical streaks in upper 40 cm, due to illuviation.

Table 6. Tossa and Aro Granulometric Analyses (in percent)

	200–2000μ	60–200μ	20–60μ	6–20μ	2–6μ	< 2μ
Riera de Tossa						
KM 1.8 (Bed c)	13.9	15.9	9.7	7.7	3.7	49.7
KM 8.0 San Feliu – Palamós						
Bed a	7.5	8.0	38.6	16.5		29.4
Bed b	4.5	59.3	13.4	10.3		12.5
Bed c	24.5	26.5	14.2	15.6		19.2
Bed c/ii	16.5	10.5	35.6	18.1		19.3

(d) 0–20 cm. Pocket of crudely stratified, heterogeneous coarse detritus with 5% slope, related to a band of stratified grit at a 15% slope, overlying bed (e).

(e)(i) Over 130 cm. Yellowish red (5 YR 5/6) loam with grit and crudely stratified detritus. Coarse prismatic structure and low carbonate content. Laterally conformable with bed (e) (ii), from which it is derived by gentle erosion and redeposition.

(e) (ii) Over 180 cm. Yellowish brown (10 YR 5–6/4), semi-aeolian clayey loam with some fine detritus and coarse prismatic structure. No visible stratification. Highly calcareous with horizon of hollow loess *poupées* at 15–25% slope. Lacks true vertical cleavage.

The semi-aeolian beds (a), (b) and (e) (ii) contain a good percentage of calcite grains in the sand component, the only possible source of which are epicontinental lime sands of molluscan origin. The distinctiveness of these sediments is also emphasized by the abnormally high pH values (Table 7). The general location on seaward slopes is significant. At KM 7.3 these silts overlie a granite cliff at 9 m elevation with an inclination of 10–15%. They must have formerly extended to below sea-level. An identical section is exposed at the coast near KM 8.8. Unfortunately the exact stratigraphic position of the silts could not be clarified: whether one or two sedimentary complexes are present, and whether these are all younger

than all of the minor raised platforms. On the basis of the typical Holocene soil profile they must pertain to an Upper Pleistocene marine regression, and possibly also to an earlier regression.

The origin of the beds exposed at Km 8, and analogous sections at KM 7.1, 7.2 and near 8.8, is that of aeolian silts and sands, intermixed with varying amounts of granitic residual matter. This material was subsequently deposited by colluviation in drainage channels or on lower slopes, occasionally to below present sea-level. All of these sediments are detrital to some degree, and the grain-size distribution is not that of a loess: all contain too much coarse sand (5–25%) and only beds (a) and (e/ii) have a moderate maximum in the silt-fine sand fraction. There is an obvious dominance of colluvial sedimentation in each case. Since much of the material is derived from freshly deflated shelf sands this is a special littoral subfacies. Due to the short transport distances involved, the quartz grain micro-morphology (Table 7) is uninstructive. These sedi-

Table 7. Tossa and Aro Medium Sand Fraction Analyses (in percent)

	Water-worn Quartz	Wind-worn Quartz	Unworn Quartz	Carbo-ates	pH (H_2O)
Riera de Tossa					
KM 1.8 (Bed c)	9	15	76	1	4.78
KM 8.0 San Feliu – Palamós					
Bed a	8	32	60	8	7.5
Bed b	11	32	57	14	7.1
Bed c	13	14	73	2	7.3
Bed e/ii	7	29	64	17	7.5

ments are similar, although not quite comparable, with the semi-aeolian silts (not loess as alleged!) of Sant Adriá de Besos, near Barcelona, described by VIRGILI & ZAMARREÑO (1957, p. 7–16).

A third subclass of colluvial deposits is that with mixed alluvial character. These include (a) channelled colluvial beds, which usually contain cruddly stratified, angular detritus, and (b) lateral intercalations of slope colluvia with stream alluvium, ranging from amorphous sheets to detrital fans.

Road sections between Tossa and Playa Givarola expose numerous shallow, smoothly concave rills cut into bedrock inclined at 10–40% and subsequently filled with a mixed colluvial-fluvial product. Most common are gritty reddish (5 YR 5/8) loams with angular detritus, bedded parallel to the slope — when seen in transverse section. Many of these rills are 10—15 m wide, some as much as 25 m. Depth of sediment may attain 1.5—2 m, on occasion 5 m or more. Minor irregularities of slope topography are thus largely obscured, while mixed colluvial-fluvial mantles converge in larger depressions leading to major drainage channels. The greater part of this local fill is contemporary with the middle terrace. Photo 6 shows a 5 m filling of older, reddish yellow (7.5 YR 6/6) gritty sandy loam, with a 130 cm relict (B)-horizon of yellowish red (5 YR 5/8) loam, under a 20 cm, pale brown (10 YR 6/3) AB-horizon representing a Holocene *braunerde* in development. On occasion, the major, reddish yellow filling of the rills was subsequently dissected, with later deposition of a brownish colluvium. Whereas the older fill has a *braunlehm*-type soil profile, the secondary filling has a *braunerde*-type soil.

The gradual transition from colluvial to alluvial facies is nicely exhibited along the steep coastal torrents. So for example the drainage channel abutting in the drowned valley or *cala* of Playa Givarola has as much as 5—6 m of coarse, detrital gravels graded onto terrace-like beds of alternating stratified gritty sand and gravel, suspended some 40 m above the valley floor. These strata are inclined at 5—8% towards the valley upstream, towards the sea at the mouth. They must have once formed a fan with concave transverse profile in the valley, dropping off rapidly at the coast to a sea-level at least as low as today. The valley floor has a 3—4 m filling corresponding to the low terrace. Similar situations are common in this area. They document that the vertical bedrock incision of the torrents and adjacent *calas* antedates the middle terrace. The last two regressional complexes of the Pleistocene were synchronous with periodic denudation and aggradation of residual products, followed by more dissection of valley fill.

A synthesis of Pleistocene Morphogenesis

Stratigraphy. The preceding regional discussion of Pleistocene sediments, soils and stratigraphy may be synthesized as follows, beginning with the tectonically undeformed Plio-Pleistocene of the Selva:

(i) Gray Series. Lacustrine deposition in the Selva. Perennially moist, probably warm, climate. Upper Pliocene.

(ii) Dissection, denudation.

(iii) *Rotlehm* pedogenesis. Upper Pliocene?

(iv) Yellow Series. Mixed lacustrine-alluvial sedimentation in the Selva, presumably also aggradation elsewhere. Alternating wet and dry seasons, increasingly cool climate. Lower Villafranchian?

(v) *Croûte zonaire* sedimentation and dehydration cracks. Villafranchian.

(vi) Dissection.

(vii) *Rotlehm* pedogenesis?

(viii) Lower Red Series. Alluviation of piedmont zone and larger rivers (High Terrace). Seasonally very moist, cool. Upper Villafranchian or Lower Pleistocene.

(ix) *Croûte zonaire* sedimentation and dehydration cracks.

(x) Dissection; denudation.

(xi) Upper Red Series. Alluviation of piedmont zone. Seasonally moist, cool. Lower Pleistocene. The widespread, major shoreline of + 100 m (Early Sicilian) belongs somewhere between units (vii) and (xi).

(xii) Dissection?

(xiii) Major *rotlehm* pedogenesis during warm, seasonally very moist climate, probably contemporary with the Tyrrhenian I (Middle Pleistocene)[1].

(xiv) Middle Terrace. Coarse stream alluviation during lower sea-level. Intense pluvial erosion and colluviation. Possibly interrupted by two (or more) phases with local *croûte zonaire* sedimentation. Middle Pleistocene.

(xv) Dissection of major streams in response to very low base-level and reduced discharge. Colluviation persisted at first, then also ceased. Local deposition of aeolianites probable. Middle Pleistocene.

(xvi) *Braunlehm* pedogenesis, during warm, seasonally very moist climate, contemporary with the Tyrrhenian II—III or last interglacial. Upper Pleistocene.

(xvii) Low Terrace. Fine stream alluviation during lower sea-level. Moderate pluvial erosion and colluviation, with admixture of derived aeolian materials at coast. Probably interrupted by one (or more) phases with local *croûte zonaire* sedimentation. Upper Pleistocene.

(xviii) Dissection of major streams in response to very low base-level and reduced discharge. Deposition of aeolianites in the eastern Ampurdán. Upper Pleistocene.

(xix) Meridional *braunerde* pedogenesis, with modern climate. Late Upper Pleistocene-Holocene.

This survey indicates that the Pleistocene continental record of east-central Catalonia is remarkably complete, although there remain certain lacunae. The lack of marine deposits and the rather loose correlation of

[1] A similar *rotlehm* at Tirvia in the southern Pyrenees, referred to the Upper Pleistocene by BUTZER & FRÄNZLE (1959), must now be considered as Middle Pleistocene. This implies the presence of a pre-Rissian glaciation in that area.

the one, stratigraphically important shoreline of + 100 m, are major drawbacks. Alternatively, the last two major regressional complexes, presumably to be correlated with Würm and Riss (in the conventional sense), permit a relative chronology including the middle and low terraces, and the previous, intermediate and subsequent climax soils. The Middle Pleistocene *rotlehm* is of such development and distinctiveness that it can almost certainly be correlated with the Tyrrhenian I, so providing the earliest correlated unit of the sequence. Possibilities of direct identification of units (iv) through (xi) are not available at the moment, although the suggestions offered are reasonable and likely. A major difficulty is that of subdividing the Red Series outside of the Selva.

Unfortunately, and not surprisingly so, the *croûtes zonaires* have no stratigraphic value. Although RIBERA (1950) and LLOPIS *et al.* (1953, p. 40—2) only recognize one such crust, at least 4 temporally distinct crusts were identified in the course of the field work. Although reasons have already been given to question a stratigraphic unit C_1 as described by LLOPIS *et al.*, the broad units C_2 and C_3 — incomplete in themselves — can be correlated with our middle and low terrace complexes.

Morphogenetic Types. The Pleistocene record of east-central Catalonia includes several morphogenetic types common to the Mediterranean region (cf. BUTZER, 1963a).

(i) Alluviation, colluviation and areal denudation. The most conspicuous morphogenetic type was characterized by deposition of local alluvial fans, widespread stream terraces and colluvial sediments, presumably contemporary with pluvial erosion and denudation of higher-lying surfaces. While the presence of cryoclastic features attests a cooler climate than that of today, the absence of congelifluction, ice wedges and involutions (cf. BUTZER, 1964) shows that the area was not within a true "periglacial" zone (cf. TROLL, 1948). Nevertheless as base level was lower than at present a general correlation with glacial periods is possible. Comparative gravel analyses and general transport capacities indicated by stream deposits prove that stream discharge was greater, more torrential in character, and of longer duration. Rainfall was greater and also more intense than today, undoubtedly being quite seasonal in type. Hence east-central Catalonia should have been wooded at the time, presumably an open heliophytic forest with incomplete vegetative mat, as is the case today. The typical gritty, colluvial loams derived from granitic residual products — and in part from aeolian components — offer a close counterpart to the *limons rouges* found on limestone bedrock (BUTZER, 1963a). These features provide evidence in favour of morphodynamic, cool pluvials, essentially characteristic of the early glacial regressions.

(ii) Sedimentation of calcareous crusts. *Croûtes zonaires* are commonly found at the close of sedimentary phases during the Villafranchian and Lower Pleistocene, where their association with dehydration cracks suggests relatively dry climate. As found in Middle and Upper Pleistocene beds, such crusts coincide with interruptions of colluviation. As calcite enrichment only seems possible with drier climate in this granitic area, the particular climatic-geomorphologic interpretation seems to favour greater drought and more limited solution. The association of such crusts with colluvia requires an explanation. Since all of the Pleistocene sediments of the area show an incidence of 5—20% windworn quartz grains, a large part of the calcite present in unweathered sediments is probably aeolian material derived from regressional deflation at the coast. In fact the calcite of normal deposits often consists of rounded, ellipsoidal grains in the sand and silt fraction. However, just what process led to calcite solution from surface sediments and subsequent laminar accumulation by lime-charged surface waters, is open to debate. No certain palaeoclimatic or stratigraphic associations are possible yet.

(iii) Vertical dissection. Linear or vertical erosion probably occurred on various occasions, possibly contemporaneously with areal denudation.

Presumably, major dissection *of alluvial fill* followed shortly after aggradation, while base-level was low and discharge waning during the maximum of glacial regressions. Dissection would probably be most active with a progressively declining, yet greater discharge than today. At any rate it is certainly inaccurate to simply equate dissection with the interglacial intervals separating the pluvial aggradation phases. Probably most of the dissection of Pleistocene deposits took place during the second half of the glacial regressions.

Dissection *of bedrock* need not be equivalent to fill cutting. Considerable quantities of water and moderately steep gradients are required to promote active bedrock dissection. There has been no such cutting in Catalonia since the early Middle Pleistocene, by which time the *calas* and stream valleys had attained modern dimensions. Whether or not appreciable bedrock dissection occurred during the Villafranchian and Lower Pleistocene is not clear. Much of the local stream sculpture is certainly of later Tertiary age.

(iv) Red soil formation. Pedogenesis of the *rotlehm* or *braunlehm* type involved a much greater intensity of chemical weathering than is possible under modern climatic conditions. Maximum warmth does not now coincide with maximum moisture (during the transitional seasons), so that at least an appreciable part of the rainy season must have been considerably warmer than today. At present *rotlehms* are developing in tropical Africa only in areas having a seasonal drought (KUBIENA, 1957) so lending support to the theoretical arguments of REIFENBERG (1947) when considering the analagous process of *terra rossa* pedogenesis. Thus we may specify that the red soils of Catalonia formed under conditions of high temperatures coupled with summer drought and relieved by a protracted rainy season-necessary for the development of deep soil profiles under a complete vegetative mat. Yet torrential reins were either uncommon or ineffective. It appears then that the phases of intensive pedogenesis were characterized by a warm, moist climate, marked by a brief yet intensive dry season.

Geomorphically, these periods were morphostatic (in the sense of DURAND, 1959), with a minimum of erosion and deposition, a maximum of weathering *in situ*. Since the heliophytic mediterranean woodlands of today seldom support a protective vegetative mat, except in areas with edaphic water sources, vegetation physiognomy must have been decidedly different.

Geomorphic Evolution. Although bedrock dissection may have been limited during the Pleistocene, the area was nevertheless subjected to considerable landform modification.

Information concerning tectonic activity is a little vague. Total absence of visible deformation in the Plio-Pleistocene beds of the eastern Selva, or of the Red Series fan spanning the contact of the Gabarras and the Ampurdán, suggests that stability has prevailed at least since the time of the Red Series. There is however a possibility of differential movements between the Gabarras and Selva during the Villafranchian, although the recurrent suggestions of a continental flexure on the basis of the (rather to be expected) seaward dip of the + 100 m platform are quite unfounded. Similarly the absence of well-developed Tyrrhenian shorelines cannot be rated as evidence of later Pleistocene down-warping or downfaulting of the Costa Brava, as has been variously suggested by LLOPIS (1945), BOURCART (1947) and RIBERA (1950). On the contrary, the terrace gradients of the coastal streams negate the possibility of coastal subsidence since at least the early Middle Pleistocene. The evidence available suggests that except for the Caldas area, tectonic activity was not significant during the post-Villafranchian.

Instead, Pleistocene geomorphic evolution was largely a matter of climatic morphogenesis. Repeated morphostatic phases with pedogenesis led to the development of deep residual mantles and the smoothening of surface forms.

Such periods were followed by dynamic pluvial phases, during which residual soils were stripped off, and partly disintegrated bedrock swept into torrential streams as a cobble or coarse gravel load. This surface denudation was certainly concomitant with some slope dissection. Increased mechanical weathering, in part attendant upon greater frost weathering, must also have led to steepening of rock faces and slopes created by denudation, e. g. the castellated rocks and sugarloaf forms common in the mountains. Simultaneously the lower slopes and valleys were mantled in colluvial or alluvial sediments derived from former (B), BC, or C_1 soil horizons. The valley fill was ultimately dissected as the pluvials waned and sea-level fell to the lowest level of the glacial regressions. The incision of the *calas* was also a consequence of deep cutting by the coastal streams during the Pontian and the early Pleistocene, with subsequent drowning of the minor valleys by the sea. Since the pedogenesis of the Upper Pleistocene was ineffective for bedrock weathering, present surface forms are largely a result of the geomorphic activity of the penultimate pluvial. The last pluvial only added incidental details of sculpture and deposition.

Littoral morphogenesis has also played a role. Yet, apart from the 100 m and 60 m platforms, marine abrasional features are limited to the immediate coast. Pleistocene littoral deposits, almost exclusively of aeolian origin, are considerably less extensive than the modern beach-ridges. They are confined to a few aeolianites near the mouth of the Daró, and the colluvial silts of mixed origin prominent near Cap Roig. In effect then, continental evolution, as influenced by eustatic fluctuations of sea-level, was far more important.

Contemporary Processes

Where they are not influenced by human activity, contemporary processes are largely in equilibrium, with only limited erosion and deposition. Yet stream activity in the *rieras* is notable through 6—9 months of the year so that the potential for erosion is considerable. The completely defunct character of contemporary morphogenesis common to the drier Mallorcan lowlands (BUTZER, 1962) does not apply to the moister, northern fringe of the mediterranean lowland climates. This contrast of modern forces is enhanced by the porous, permeable limestone bedrock of Mallorca, the less permeable but rather jointed granite of Catalonia.

Excepting part of the lacustrine clays and silts of the tectonically active Caldas area (MARCET & SOLÉ, 1949, p. 51–52), no certain Holocene deposits of prehistoric date have yet been recognized in east-central Catalonia. A possibility, unfortunately not dated, is that of the alluvium found adjacent to the coast at the mouths of the major *rieras*. This alluvium is much finer than the low terrace, and coarse bands are unknown. Rising about 5–6 m above the modern stream beds, these fan-like deposits, which disrupt the profile of the low terrace, may be the result of fine alluviation in response to higher Holocene sea-levels. Comparable features are known from Mallorca (BUTZER, unpublished).

Whether the coastal alluvium is early Holocene or not is immaterial to the fact that morphogenesis would normally be insignificant today. Comparable processes would be next to unrecognizable in the Pleistocene geomorphic record, so that there is but little chance to identify past periods with limited chemical and mechanical weathering, and with temperature and precipitation analogous to that of today. A good part of the Pleistocene probably qualifies for such conditions. The stratigraphic units outlined in the previous section are then only representative of processes deviating from modern patterns.

Human interference has produced conspicuous features in the landscape. The observer may readily note that the modern stream beds frequently expose coarser materials than those of the low terrace and the coastal alluvial fill. In the larger *rieras* coarse gravel and cobbles are common, being derived from short, steep tributaries adjacent to the lower stream courses. If anything, the streams are aggrading. Larger rivers such as the Tordera also exhibit all the symptoms of coarse alluviation resulting from accelerated runoff.

Closer investigation shows that only a small area suffers from soil erosion and disrupted equilibrium. The lower hillsides adjacent to the coastal lowlands and the lowermost stream courses have colluvial mantles not unlike the Pleistocene colluvia. A dated section at Tossa exposes 2 m of sandy, gritty brown (7.5 YR 5/4) loam with occasional unstratified detritus overlying a Roman latifundium ("Villa Romana"), abandoned 400 A. D. The material was carried down a slope averaging about 25%. Similarly, near the railroad stop at S'Agaró, some 40–60 cm of gritty, detrital loam, over bedrock inclined at 20–25%, contains crude red pottery. These features, under a grassy vegetative mat or woodland, are no longer forming today. Their explanation is relatively simple. The lower slopes of the Costa Brava were cleared during the 1st century A. D. to make room for olive plantations and vineyards. A barbarian raid in 258 A. D. marked the beginning of economic

decline for commercial farming, and the latifundia were finally abandoned during the 5th century A. D. The terraces fell into disuse, and the unprotected, loose soil was subjected to surface washing and swept off. Alluviation within the lower stream courses followed.

In other words, accelerated surface runoff and stream discharge under quite artificial conditions in historical times produced analogous features to those of pluvial colluviation and alluviation. Reforestation of the Costa Brava with cork oak and pines, mainly during the last few centuries, has stopped slope washing in many areas. But gritty loams continue to encroach laterally on many ploughed fields at 5–10% inclinations, near denuded bedrock slopes. These man-induced processes are noticeably concentrated in coastal areas with irregular rainfall and a protracted dry season, and are therefore useful for an understanding of Pleistocene morphogenesis.

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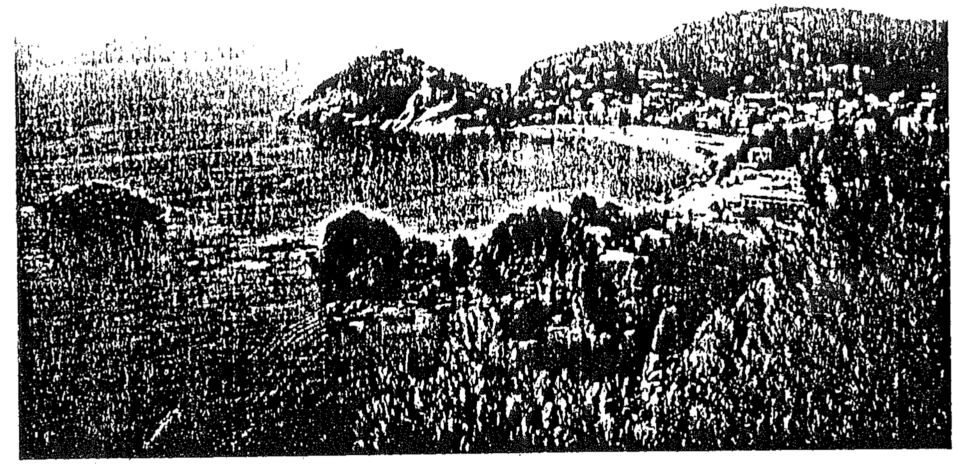

Photo 1. ***Tossa del Mar.*** The 60 m platform is conspicuous at the lighthouse and on the adjacent promontory, offset by a well-defined cliff from the 100 m shelf extending off to the right. A 16–19 m terrace is developed on the promontory in the foreground and in the break interrupting the 60 m platform, while the offshore island (La Isla) is planed off at 12 m. Lower platforms are barely visible. A beach-ridge joins the two promontories.

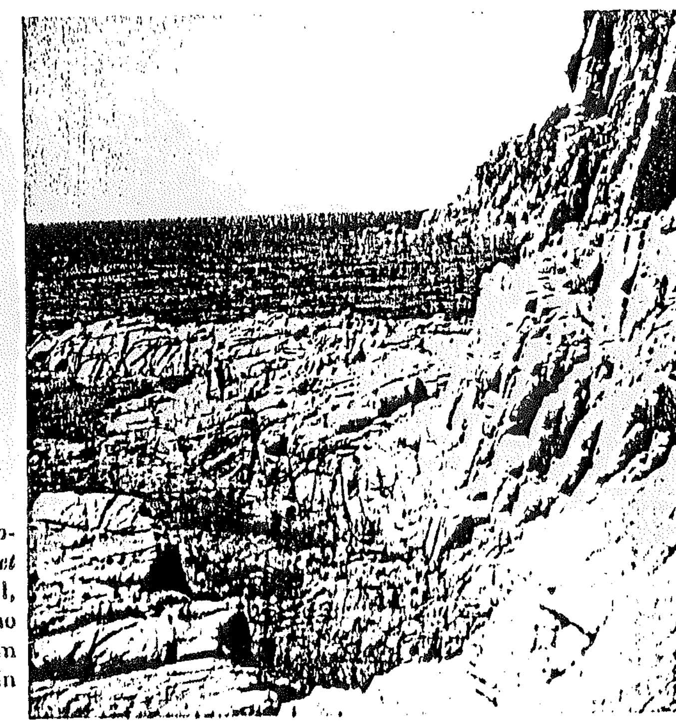

Photo 2. ***Fanals Promontory south of Lloret*** illustrating the jointed, fissured character of the granitic bedrock. A 3.5 m platform is apparent in the foreground.

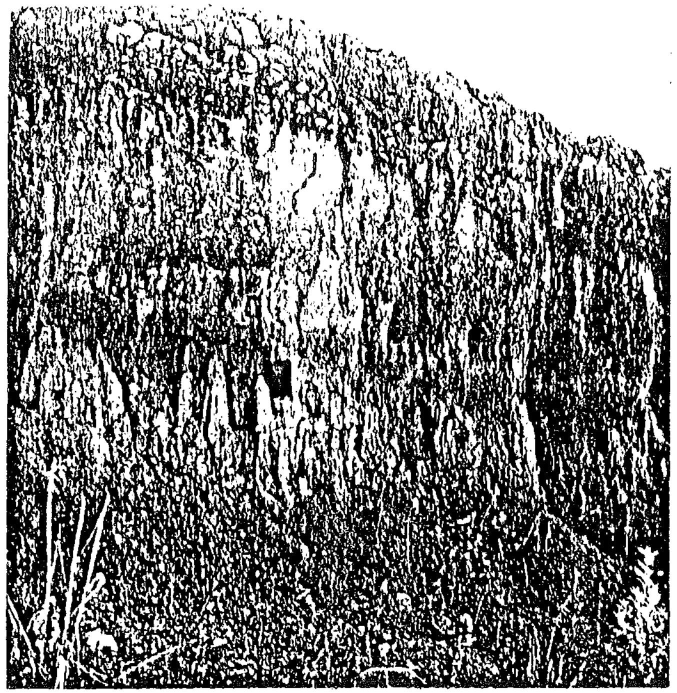

Photo 3. *Upper Yellow and lower Red Series at KM. 10 of road Gerona-Llagostera* (see text description). Bed (ii) just above book, bed (vi) at top. Fine loamy beds (i), (iii) and (v) appear conspicuously lighter.

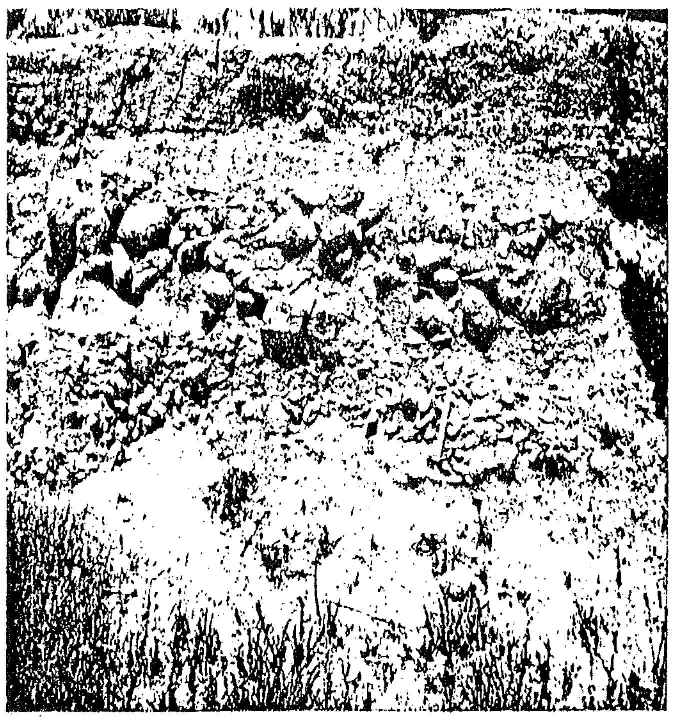

Photo 4. *Colluvial and alluvial beds at margin of middle terrace of the Ridaura* (see text description), exposed at KM. 25 of the railroad Gerona-San Feliu.

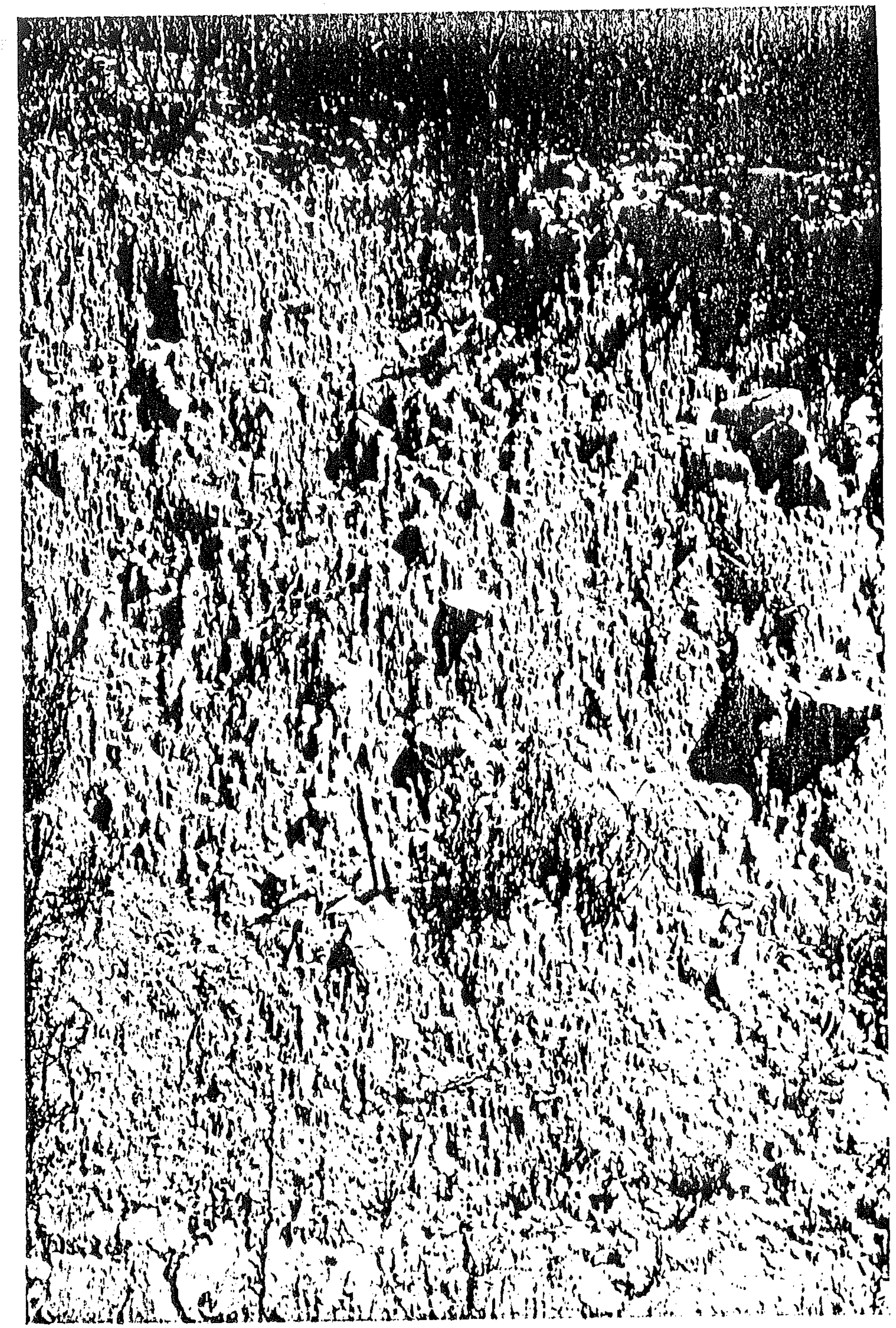

Photo 5. *Colluvial series of detrital character* exposed near KM 7 of the road Tossa-Llagostera. The beds are laterally conformable with the middle terrace and show remnants of a relict *braunlehm* (B)-horizon.

Photo 6. *Channelled colluvial deposit* in a slope rill near KM 2 of the road Tossa-San Feliu de Guixols. Description in text.