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Sedimentology and Stratigraphy of the Pleistocene sediments in Lake Llauset (Southern Pyrenees, Spain)-a first approach

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ABSTRACT

The high alpine valleys in the Southern Pyrenees are characterised by a many small lakes and ponds. They occur above 2000 m and are said to have been formed by glacial erosion. The sediments in these basins should, therefore, contain stratigraphic information since deglaciation, at least.

An interesting and may be one of the most important of these basins is Lake Llauset in the Alta Ribagorça. The Llauset basin has recently been developped for hydropower production. In conection with the construction of the retaining wall at the "Riegel" the sedimentary filling of the lake basin could be investigated, and the first sedimentological and stratigraphical results are presented.

RESUMEN

En las cabeceras de los altos valles de la Ribagorça existe una gran cantidad de pequeños lagos, la mayoría de los cuales se encuentra alrededor de los 2.000 m. Su origen está relacionado con la acción erosiva de los grandes glaciares que allí existieron durante el Período Cuaternario. Los sedimentos que colmatan estas cubetas lacustres contienen una valiosa información estratigráfica la cual registra, como mínimo, el retroceso de la última Glaciación así como todo el Período Postglacial.

En la comarca pirenaica de la Alta Ribagorça, el Lago de Llauset presenta unas condiciones especiales, según las cuales se puede considerar actualmente como la localidad más importante para el estudio de la evolución del cuaternario reciente del Pirineo. Este lago está siendo utilizado desde hace poco tiempo para la producción de energía hidroeléctrica. Este hecho ha posibilitado la realización de un buen muestreo de sus sedimentos para un posterior estudio. En el presente trabajo se exponen los primeros resultados obtenidos, tanto en el aspecto sedimentológico como en el estratigráfico.

RESUM

A la capçalera de les altes valls de la Ribagorça hom hi troba una gran quantitat d'estanys i estanyols. La gran majoria es troba al voltant del 2000 m d'alçada, i és conegut que el seu origen es deu a l'acció erosiva de les glaceres quaternàries. Els sediments que rebleixen aquestes cubetes lacustres, ens pot aportar una valiosa informació estratigràfica que enregistra, com a mínim, la retirada de les glaceres de la darrera Glaciació així com tots els temps postglacials.

A la comarca de l'Alta Ribagorça hi ha el llac de Llauset el qual presenta unes condicions especials, per la qual cosa hom podria considerar-lo actualment la localitat més important per a l'estudi de l'evolució del quaternari recent de l'alta muntanya pirinenca. L'Estany de Llauset està essent utilitzat des de fa poc temps per a la producció d'energia hidroelèctrica. Aquest fet ha possibilitat el mostreig i posterior anàlisi del seu rebliment sedimentari. En el present treball, es fa una exposició dels primers resultats obtinguts tant en els aspectes sedimentològics com en els estratigràfics.

INTRODUCTION

This paper report on the initial part of an extensive study on the reconstruction of Upper Pleistocene lacustrine environments, their evolution and possible paleoclimatic and stratigraphic implications as given in the sediments of Lake Llauset. The geological, geomorphological and physical characteristics of the Llauset basin as well as the preliminary sedimentological investigations are discussed.

Llauset Valley, of about 10 kilometers in legth, drains a catchment area of 25.75 km^2 and is a tributary of Noguera Ribagorçana River (Fig. 1). Lake Llauset is part of this valley system and its presence is related to an overdeepened glacial basin. This valley is located at the southern limit of the Ma-

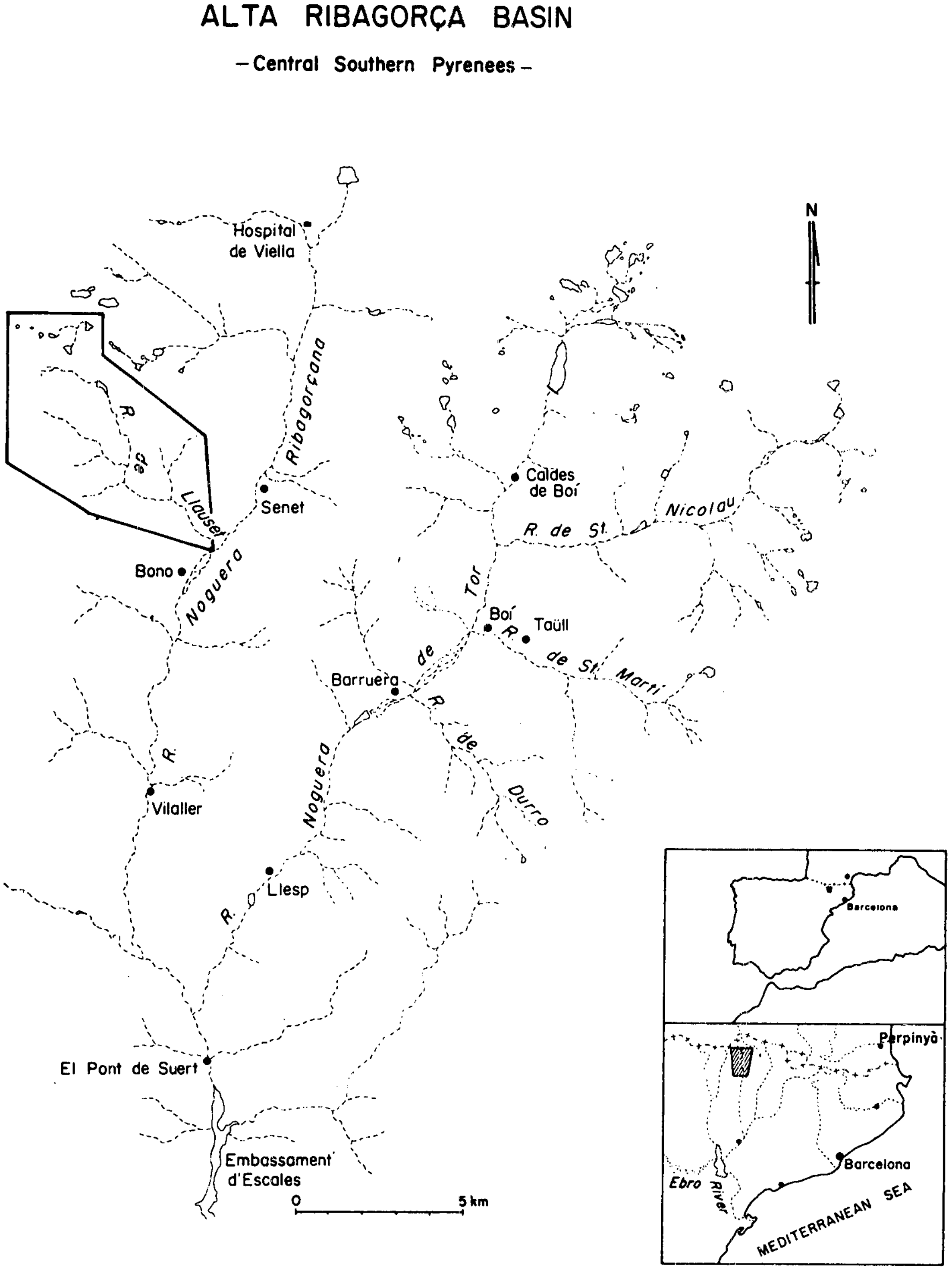


Figure 1. The Llauset Valley in the Alta Ribagorça Basin (Southern Central Pyrenees).

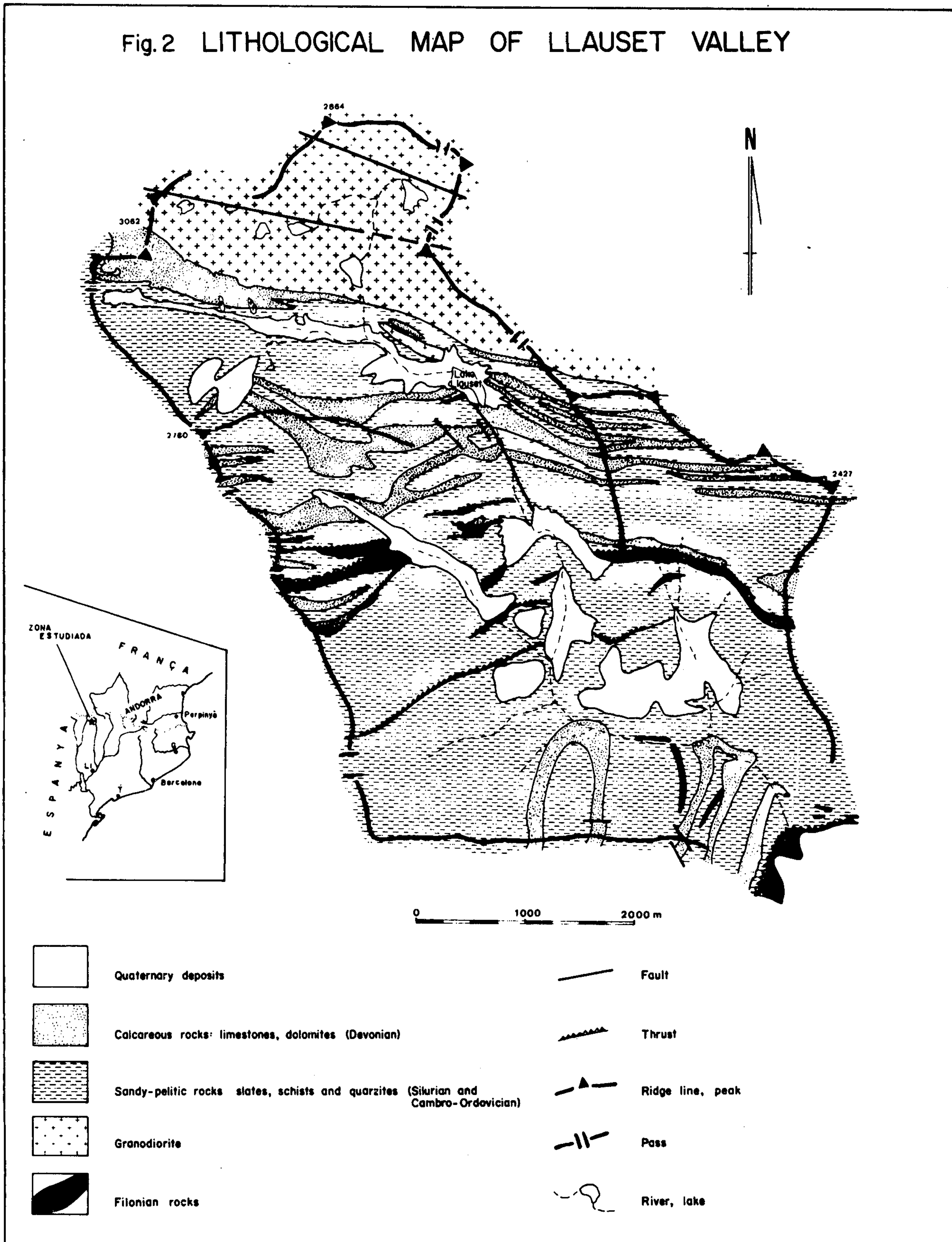


Figure 2. Lithological map of Llauset valley.

ladeta Granodioritic Pluton, and its contact with the Sierra Negra unit. Granodiorites form the northen sector of Llauset Valley, as shown in the lithological sketch map (Fig. 2). To the south follows an alternation of Cambrian-ordovician shales, schists and quarzites, Silurian black shales and Devonian limestones. Pleistocene and Holocene sediments are of glacial, lacustrine, fluviotorrential and colluvial origin, and are given in the geomorphological map (Fig. 3).

The glacial landforms dominate the upper part of Llauset Valley: A glacial erosive landscape prevails from the valley head (3.062 m a.s.l.) to Lake Llauset, and it is marked by glacial cirques and small overdeepened basins (Fig. 3). The glacial erosive landscape is followed downvalley by morainic accumulations and ice-marginal deposits (Serrat *et al.*, 1983). A detailed geomorphological analyses of Llauset Valley is given by Vilaplana (1983-b).

LAKE LLAUSET

At present this lake basin is developped by the electrical power company ENHER. The construction of a retaining wall asked for drainage of the lake, giving direct access to the lake sediments and to stable ground for a drilling operation. The physical characteristics of Lake Llauset are summarized in Table 1.

Naturally, Lake Llauset occupies an overdeepened glacial basin eroded by Llauset Glacier during the Quaternary glaciations. It is limited upvalley by a large delta-plain extending over more than 450 m. The open water surface occupied a maximum extension of 460 m long and 160 m wide (see photograph I-1). Topographical and bathymetrical data are related to the 1:1000 scale map prepared out by ENHER (Fig. 4).

Lake Llauset receives the stream discharge from the upper LLauset Valley and the large Vallhiverna-Botomàs cirque, a total catchment area of 8.9 km². The stream is reaching the lake at the right bank by where a braided channel system has developped the large delta. The flat surface of the delta displays numerous abandonned channels with peatbogs (Fig. 4).

The natural water level was at 2.132 m and the bathymetrical data show a shallow water body (average depth of 4-5 m). The deepest point (8 m) is located at the maximum width of the lake, just off the prodelta zone. The shallowest zone (3 m) is near the "Riegel" of Devonian limestones, where the outlet of the lake follows a small gorge.

Both, seismic and drilling data allow the reconstruction of isobath and isopach maps (Fig. 4b and 4c-d, resp.) of the central and distal parts of the basin. The geometry of the lacustrine sediments as well as the complex palaeobathymetry of the lake are given in these maps. The palaeobathymetry-map displays several funnel-shaped irregularities (up to 40 m deep in the center of the basin), most probably reflecting glacial excavation of the paleozoic bedrock.

TABLE I-PHYSICAL PARAMETERS OF LAKE LLAUSET

Maximum length (water area + delta plain	930 m
Maximum length (water area only)	460 m
Maximum width	150 m
Maximum depth	8 m
Mean depth	4, 5 m
Surface	0,06 km^2
Volume	0,27 km^3
Altitude (above sea level)	2132 m
Drainage area	8,9 km^2
Mean altitude of drainage area	2800 m
Mean water-discharge per month (theoretically calculated)	1,3 hm^3

The slopes of the paleozoic bedrock are very steep: they are barren rock-walls with avalanche channels and debris cones at the base. These debris cones are active since deglaciation to the present time by the combined action of gelifraction and snow avalanches, with occasional meltwater as an additional geologic agent. The development of debris cones along both sides of the basin and their progradation into the lake –simultaneous to the lacustrine sedimentation–(see Fig. 4d) have largely contributed to reduce the volume of the lake (see also Photograph I-1).

SEDIMENTOLOGY AND LITHOSTRATIGRAPHY

The Pleistocene and Holocene accumulations in Lake Llauset comprise two genetically different sedimentary units: (1) lacustrine deposits per se, and (2) transitional facies associations to subaerial environments..– Lacustrine formations are sediments deposited in submerged conditions and are characterized by a hectometric lateral continuity. Lithostratigraphically, three different lacustrine sediment

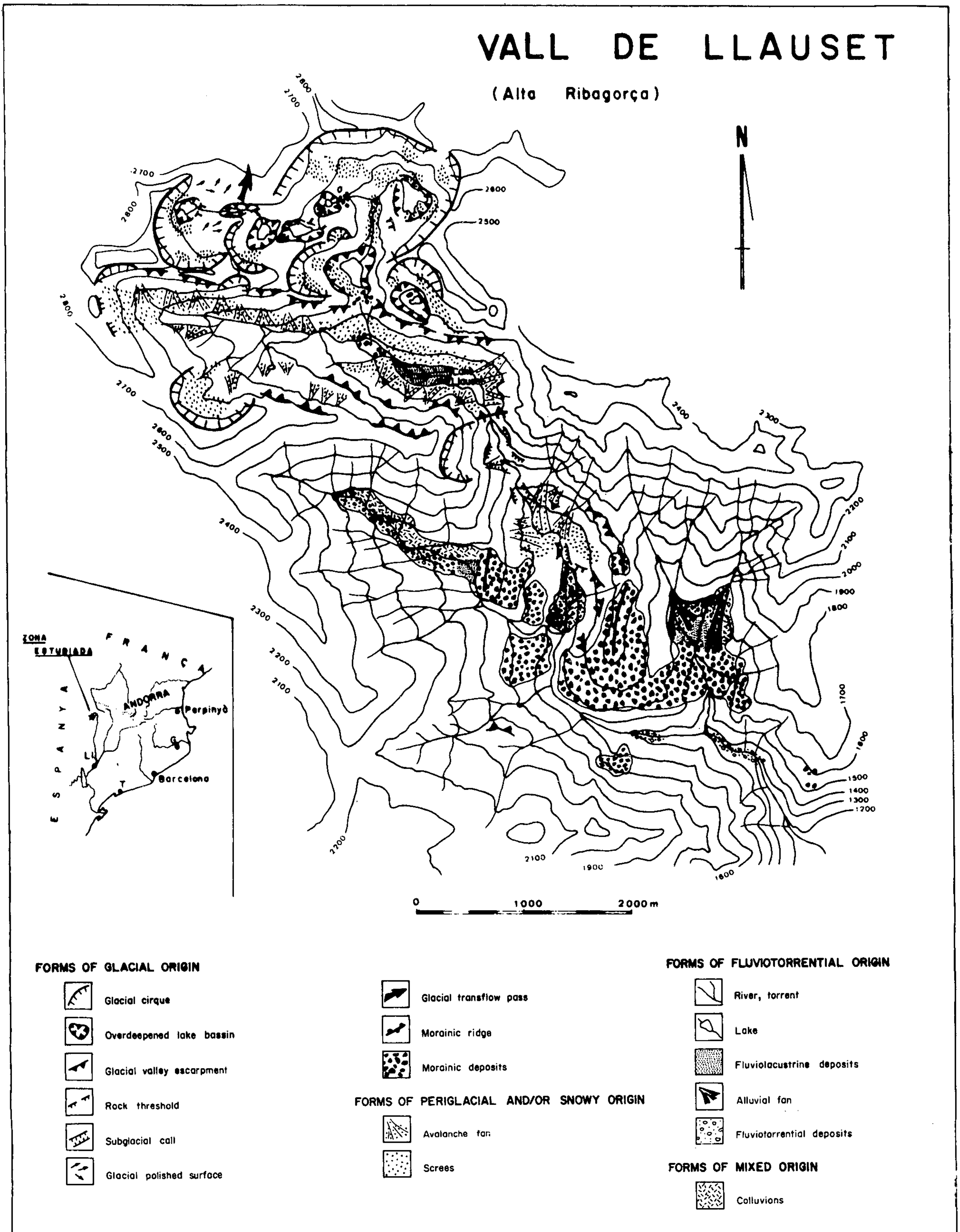
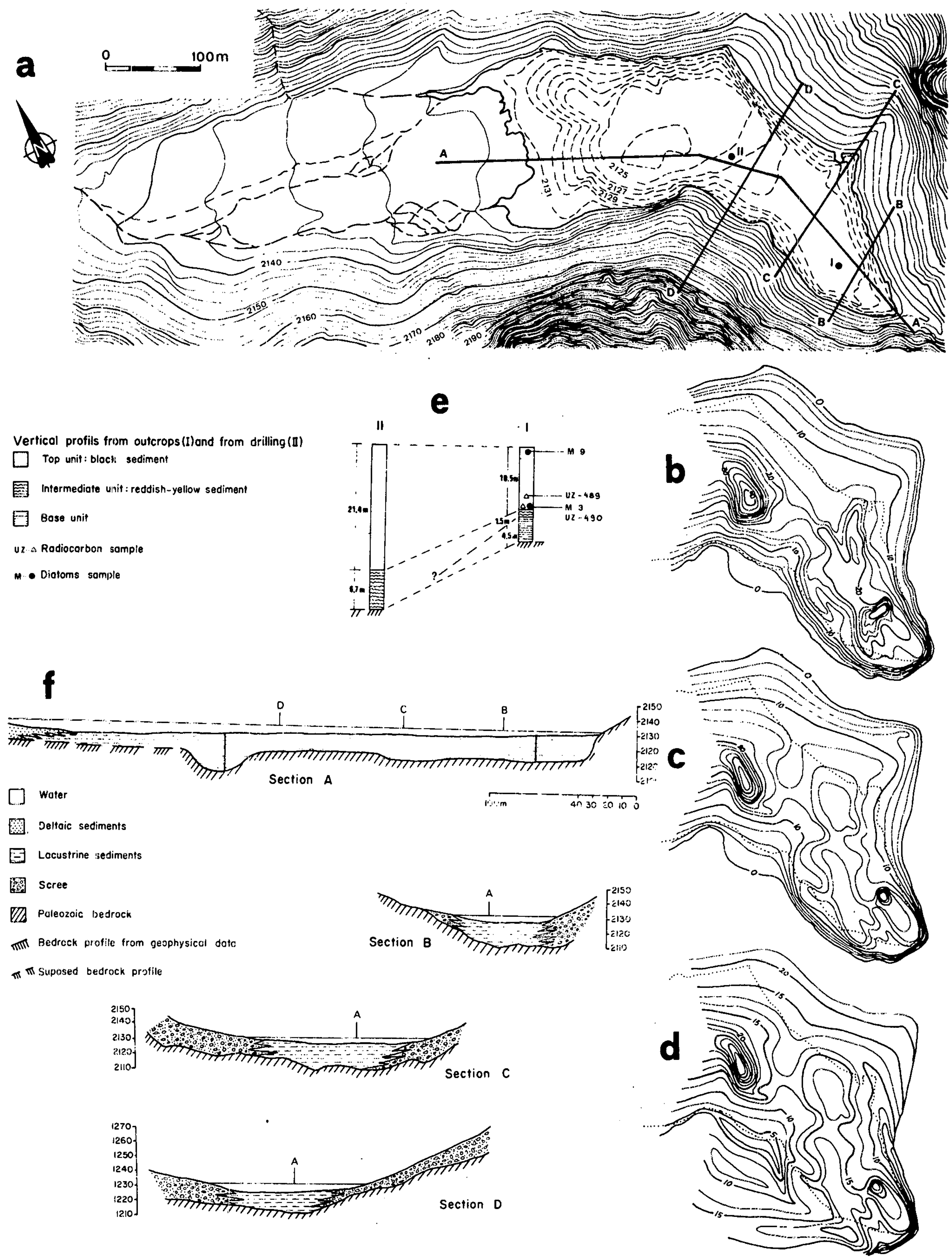


Figure 3. Geomorphological map.


a
0
100m
A
B
C
D
I
II
2125
2127
2129
2131
2140
2150
2160
2170
2180
2190
e
Vertical profils from outcrops (I) and from drilling (II)
Top unit: black sediment
Intermediate unit: reddish-yellow sediment
Base unit
UZ △ Radiocarbon sample
M ● Diatoms sample
M 9
UZ - 489
M 3
UZ - 490
21.4m
18.5m
1.5m
4.5m
6.7m
b
c
d
f
Section A
Section B
Section C
Section D
Water
Deltaic sediments
Lacustrine sediments
Scree
Paleozoic bedrock
Bedrock profile from geophysical data
Suposed bedrock profile
2150
2140
2130
2120
2110
1270
1260
1250
1240
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1210

types are distinguished: (a) the basal unit of grey-brown muddy laminites and lithoclastic cobbles, (b) the intermediate unit of yellow muddy laminites of biochemical precipitates and (c) the top unit of a black laminated mud (Fig. 6).– Two transitional facies associations replace the pure lacustrine sedimentation: the prograding delta of the Llauset River and the marginal border facies which occurs along the lake shores between the delta and the "Riegel".

Lacustrine deposits

a.– *Basal Unit:* Big erratic cobbles partially cover the bedrock (Fig. 6). A grey-brownish laminite mantles and covers these basal cobbles and the bedrock in the area to the "Riegel". Lithologically, it is a silty clay slightly sandy with dropstones. Granulometrically, it is a bimodal sediments responding to decantation lines, and the sorting is poor (Fig. 5-2). The grains are mainly of silicoclastic origin with some neoformic gypsum crystals near the top, with pyrite and occasionally some diatoms. Lamination is extremely fine (Plate II) and laterally continuous. Deformation is locally due to dropstones which fell off the slopes, and reached the lake-bottom. This unit is interpreted genetically as a proglacial lacustrine sediment.

b.– *Intermediate unit:* It rests on top of the basal unit. The contact is vaguely defined and is locally gradual or abrupt. This unit is thicker towards the central part of the basin and thinner towards the "Riegel". It is a reddish-yellow, laminated, slimy mud with a water content of 22,3 to 50%. The granulometry displays a slight coarsening upwards tendency with a few up to a centimeter thick beds of fine sand at the top (Fig. 6).

As a whole it is a very fine clayey sediment, since 50% of its grain-size composition is less than 0.1 micron in diameter (Fig. 5-1). The grain size distribution of its sand-fraction shows a better sorting. Dropstones are also very frequent. The top sandy laminae, fairly well sorted, result from a saltation transport in an subaqueous environment (Fig. 5-4). The sand grains are basically of silicoclastic origin. Grains are rubefied and neoformation of gypsum crystals is frequent. The fine fraction consists almost exclusvely of goethite microspherulites and other ferric hydroxides (Plate III), most probably as pseudomorphs of coccous mould pyrites. The sediments at the top present some different characteristics in the sand fraction. There, rubefied lithoclasts are abundant and intraclasts of yellow mud, some neoformic gypsum and pyrite are present. Lamination is irregular, discontinuous in some or approximately parallel, although undulating, in other cases (Plate II).– The paleoenvironmental interpretation of this deposit is dealt with below. The available results indicate so far that this sediment is of a biochemical precipitation in origin.

c.– *Top unit:* This is the most extensive and thickest true lacustrine deposit in Lake Llauset. It follows paraconformably on top of the reddish-yellow mud. This unit displays a rhythmitc bedding of fine sand and black mud, also with a slight coarsening upwards tendency (Fig. 6). The sandy or muddy composition of the beds depends on the distance of the sampling point to the lake shores or to the area of the clastic sediment input to the basin. Sand beds are obviously thinning out towards the center of the lake. The central facies display bimodal grain size compositions responding to saltation transport of the coarse and to uniform suspension of the fine fraction (Fig. 5-3;8). The marginal facies associations are thicker and better sorted (Fig. 5-7), and correspond to paleobeaches. In some restricted areas where terrigenous input is minimal and where decantation prevailes the marginal facies associations are reduced or lacking. The composition of these sediments is quite different from the lower units: clastic components dominate and gypsum neoformations almost disappear while diatoms proliferate, and form diatom oozes in restricted areas. There are pyrite neoformations to be found and even some diatoms are internally pyritized. Some yellow mud intraclasts appear locally. Plates II and III (Fotos 4 to 7) show the rhythmical nature of the sediment. The rhythmic sedimentation between more or less sandy beds are observed in Plate II-4

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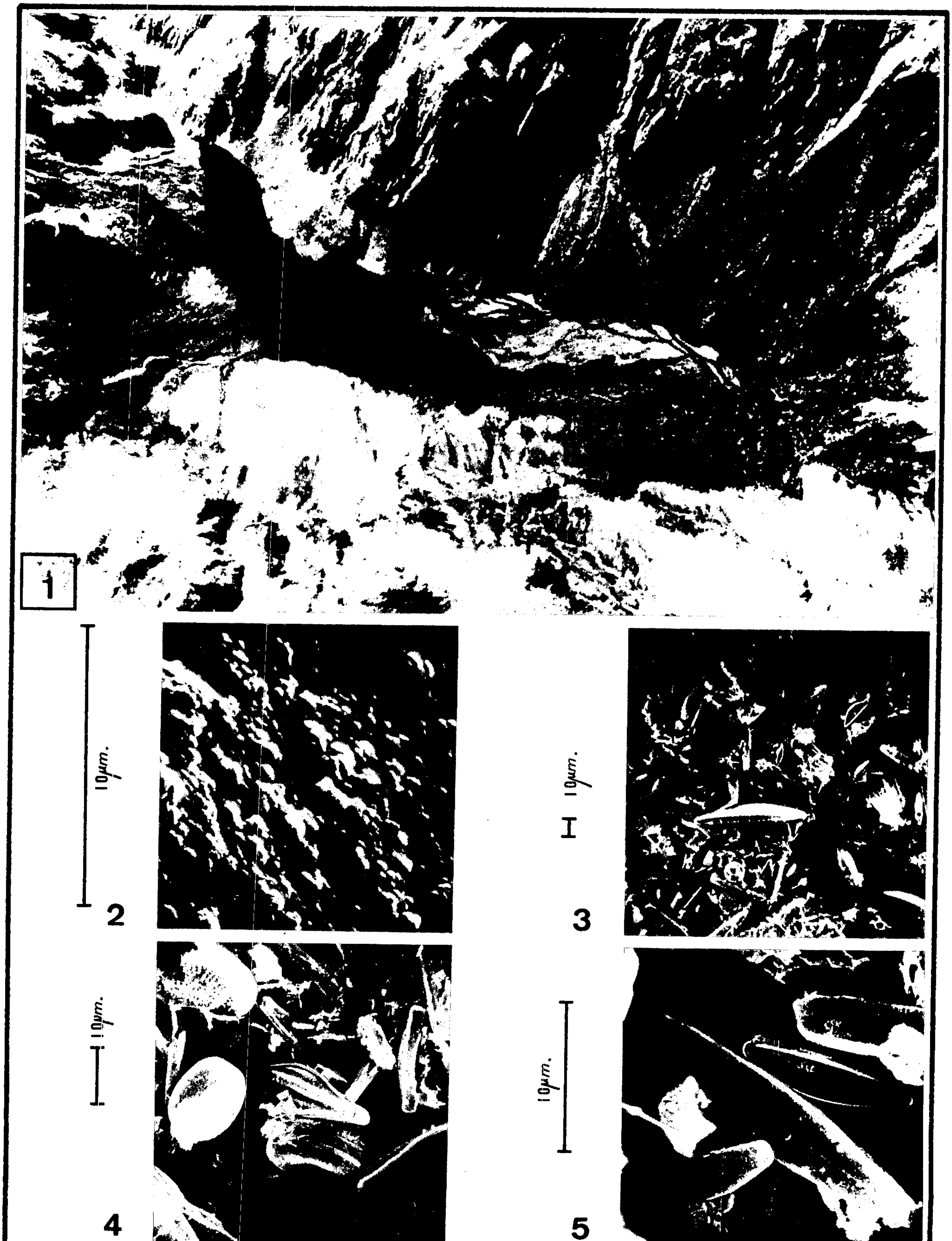
Figure 4. Morphology of Lake Llauset basin and geometry of its deposits.
Legend: **a)** Topographical and bathimetrical map. **b)** Morphology of bedrock surface. **c)** Isopach map of lacustrine fill. **d)** Isopach map of lake basin deposits (lacustrine sediments and debris cones). Thickness variations in relation to map c occur because the lateral sedimentation from marginal debris cones is included. **e)** Vertical profiles from outcrop (I) and borehole (II)-see location in **a**-UZ-489 and UZ-490 = samples for radiocarbon dating. **f)** Longitudinal and transverse cross-sections (see location in **a**).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and its terrigenous appearance becomes more and more noticeable (Plate II, Fotos 5 and 6) until the deposition of sand dominates in some beds (Plate III-7). There are units with less well developped rhythmic laminae (Plate III-8) in the prodelta area, displaying sometimes disturbances due the burrowing organisms. (Plate III-9)

This sedimentary unit is interpreted as lacustrine rhythmite with seasonal cycles.

Transitional facies associations

a. *Lake shore deposits and transitional units:* These formations occur along the lake shore between the "Riegel" and the delta. They are formed by the interaction of the lateral debris cones and the sedimentation in the lake perse. These deposits reflect resorting of the clastic input from the debris cones. Well sorted beach deposits are produced which which may be correlative to well-sorted sands which extend not far beyond the shores. In general these sediments are characterised by major coarse lithoclastic fan deposits. In places where the coarse lateral lithoclastic in put reaches the muddy deposits of the central lake bothom deformations of the rhythmites occur. These lateral transition units are granulometrically characterised by isolated large boulders, boulder beds and well sorted well sands which are interlayered along the lake-shore with the lacustrine black muds (Fig. 6).

b. *Llauset river delta:* This delta complex is a prograding accumulation on top of the black laminated lacustrine sediments. The prodeltaic facies (Plate II-6) consists of silty muds, rich in organic matter and of ten disturbed by burrowing organisms. Bottom-set beds at the delta front are characterised by some wavy sandy intercalations in the grey muds (Plate III-10). The subaerial top of the delta displays well developped braided channels where gravelly-sandy sediments are deposited in the channels. The coarser channel sediments alternate with sapropelic-silty overbanck deposits (Fig. 5 to 9) and with well sorted laminated sands (Plate III-11, 12). Some megaripples are present in the sandy fluvial facies. The lithology is dominated by silicoclastic components except for the sapropelic-muds where some diatoms and numerous fossil plant remnants cause a peaty appearance of this deposit. Most part of the subaerial top of delta are stabilized by vegetation.

CHRONOSTRATIGRAPHIC AND PALEOCLIMATIC IMPLICATIONS OF THE LAKE LLAUSET SEDIMENTS.

The basal sedimentary unit is recording the retreat of Llauset Glacier upvalley of the present lake basin. Its genetic and chronostratigraphic position between the glaciolacustrine deposits of the Llestui (Vilaplana, 1983-a,c) and the overlaying black top-unit in the Llauset basin gives an age between 35 000 and 21 000 ^{14}C-years B.P. for this basal unit. The intermediate sedimentary unit (reddish-yellow mud) implies a change in the geoecological environment of the lake of such an extent that Schlüchter & Vilaplana (1983) favour a hypothetical "climatic crisis" to produce this deposit. Vilaplana (1983-a) has stressed the relationship between this ferruginous deposit and the bog iron ore which is formed by anaerobic bacteria that precipitate ferric hidroxides from solution, by oxidizing ferrous salts. The presence of large gypsum cristals (Selenites) in the reddish-yellow sediment are interpreted as indicators of a semiarid climate at the time of deposition of this sediment. Some authors describe the formation of gipsum crystals in the relationship to bedrock mineralogy rich as pyrite bearing shales and limestones in semiarid american lake environnements (Wedepohl, 1978). We refer to the hypothesis that these microsferulites of ferric hydroxides may have been pyritized coccous mould which became oxidized at a later diagenetic stage (Plate I).

The diatoms in two check-samples of the top unit have been studied in detail. X. Tomás has identified the diatoms of one sample at the bottom (n.º 3) and the top (n.º 9) of the black mud (Fig. 4e). The dominant species and its quantitative variation have been determined as a first approach to the paleoecological conditions in Lake Llauset at the beginning (± 21.000 ^{14}C-Y.B.P.) and at the end of the sedimentation of the black mud.

The results of the investigations on the diatoms are given by Vilaplana (1983-a). They give evidence for an oligotrophic Lake Llauset at the time

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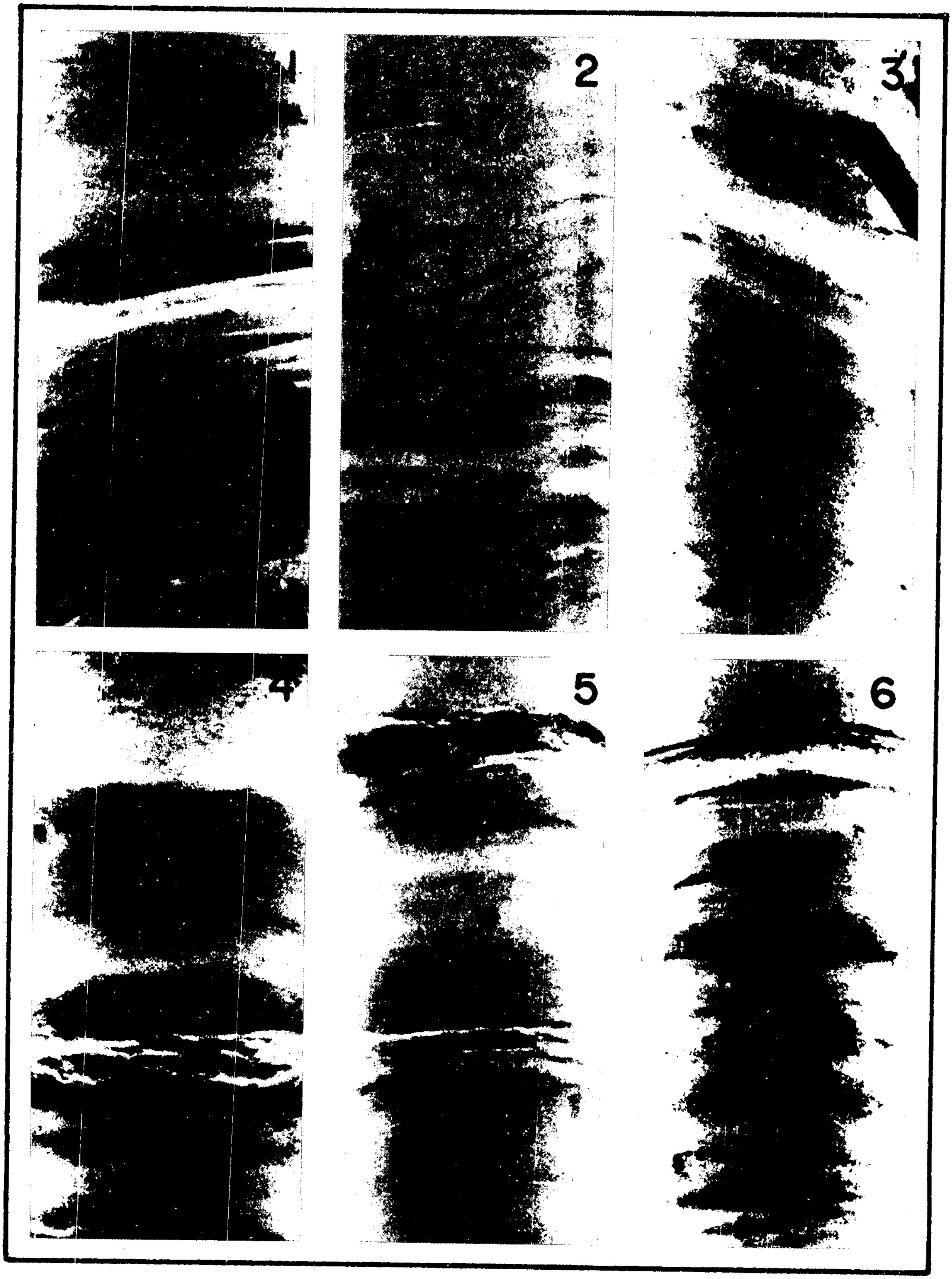
PLATE I. 1) Vertical aerial view of Lake Llauset taken in 1975. The maximum lenght of the lake basin (lake and delta plain) is 930m. The North is located in the lower part of the photography. 2) Scanning photography of reddish-yellow sediment particles (Intermediate lacustrine unit in the text). 3) Scanning photography of the bio-clastic components of the black sediment (Top lacustrine unit in the text). 4) Scanning photography of the diatoms of the black sediment: 1- *Cyclotella comta;* 2- *Denticula tenuis* v. *crassula;* 3- *Achnantes* sp.; 4- *Cymbella affinis.* 5) Scanning photography of the diatoms of the black sediment: 1- *Gomphonema* sp.; 2- *Achnantes* sp.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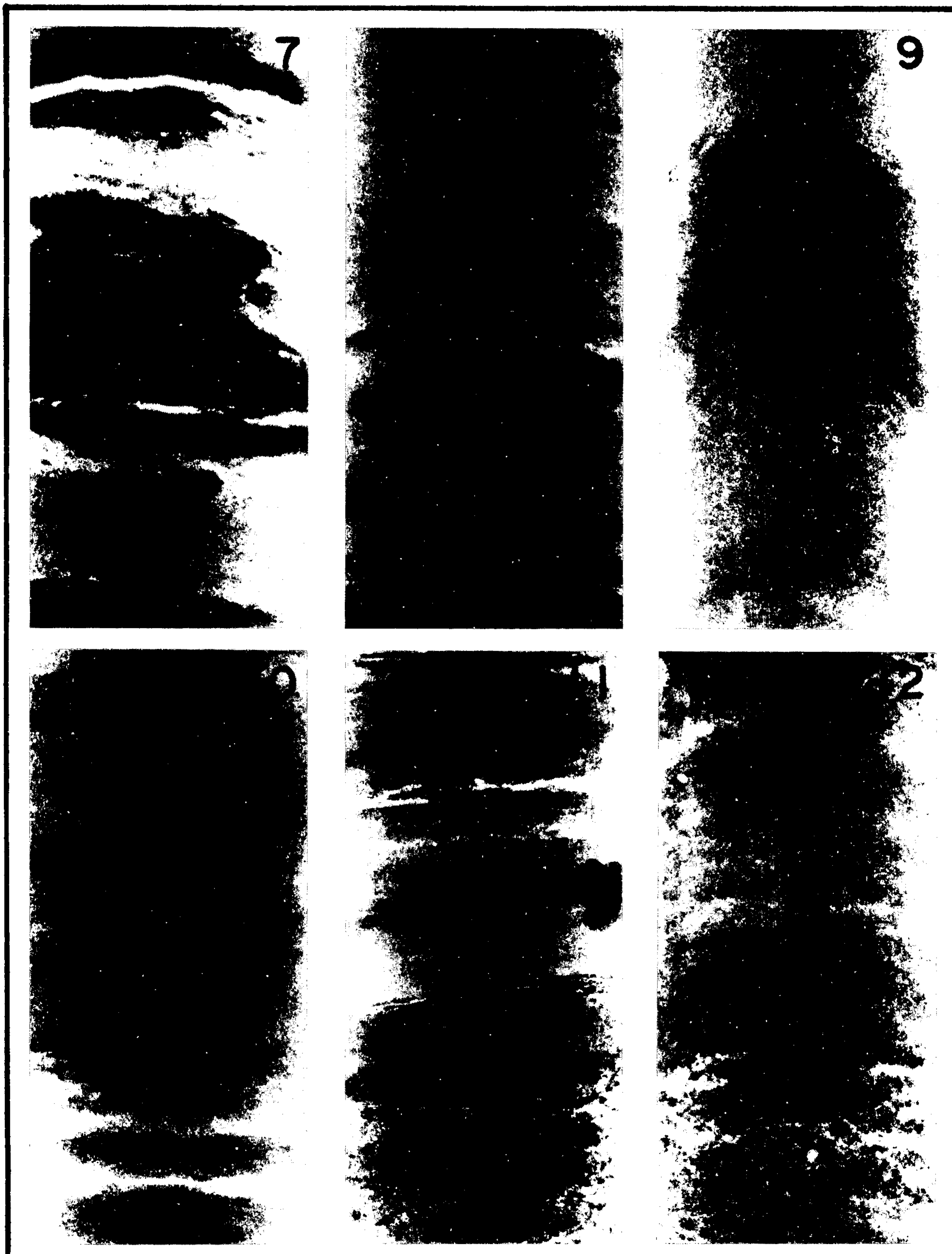

PLATES II and III. X Ray photographies of the cores with sediment structures. The discussions are given in the text, (vertical size of each core segment is 5 cm).

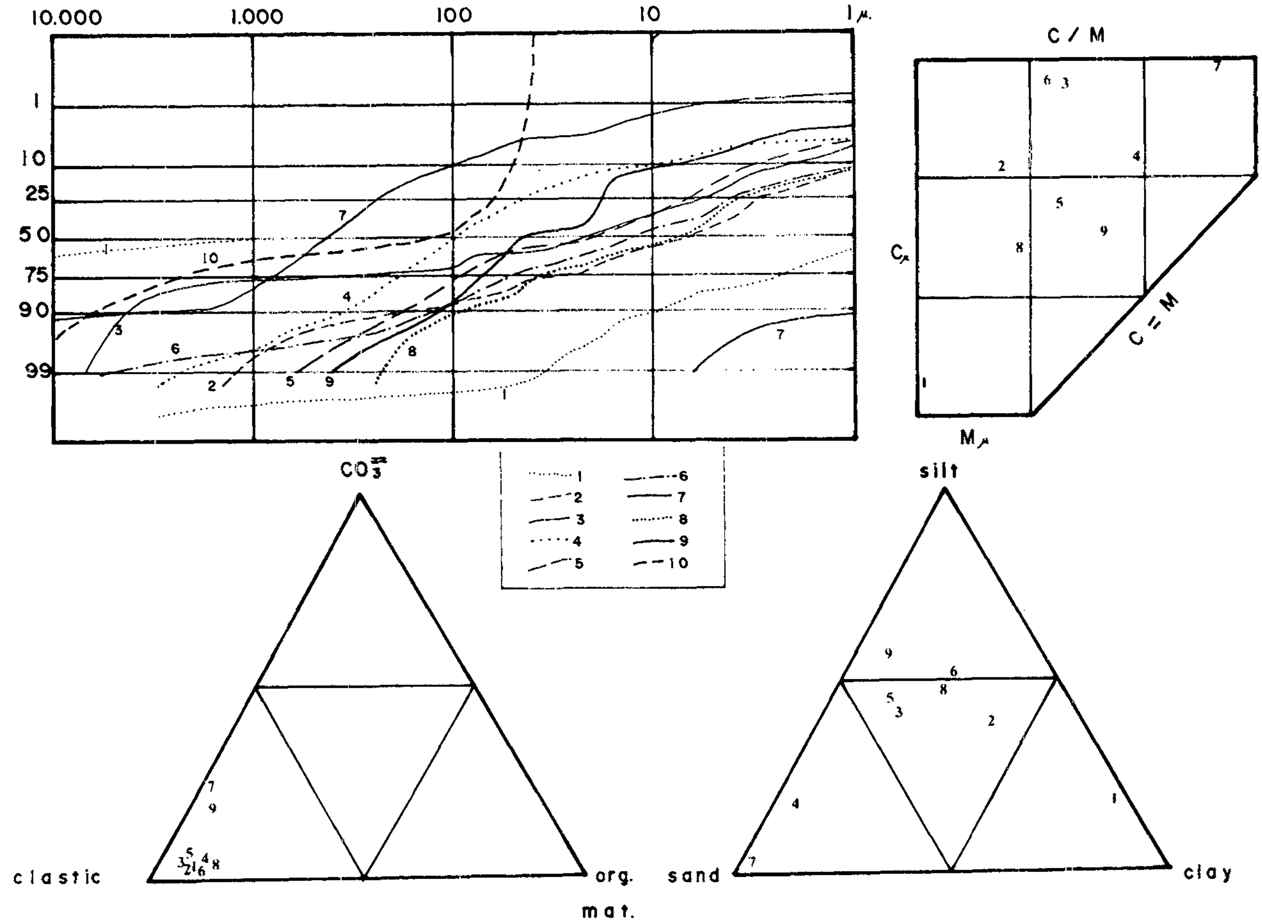

Figure 5. Cumulative grain size distribution curves, Passega's diagram and triangular diagrams displaying the different samples referred to in the text.

of deposition of the black mud with oxygen-rich waters and a low sedimentation rate. The pH of the water at that time was slightly alkaline (≥ 7). The diatoms *Cymbella, Gomphonema* and *Achnantes* indicate a certain organic production in the lake. The main difference between the samples 3 and 9 indicates that sample n.º 3 contains a broader variety of species and non-litoral forms than sample n.º 9. Referring to the temperature conditions in the lake, then the diatoms identified in sample n.º 3 point to slightly warmer water than those of sample n.º 9. However, both samples do not contain typical diatom communities of cold freshwater bodies.

DISCUSSION AND CONCLUSIONS

For the preliminary study, on which is reported here, only the sediments of the distal and central parts of the lake basin and of the delta top-sets have been accessible. These investigations will be extended by boreholes and by continuos seismic reflection profiles in the near future.

The stratigraphy as outlined here is based on the first results obtained from the analysis of profile I (Fig. 4e), and on the knowledge of the regional evolution during the Upper Quaternary events as proposed by Vilaplana (1983-a, c). A more detailed study of the litho and biostratigraphy of the lake sediments will be carried out on profile II (Fig. 4e), supplemented by a series of radiocarbon age determinations.

At present, the following conclusions on the evolution of Lake Llauset are possible:

1) Erosion of the lake basin:

The recent lake basin has been eroded and overdeepened to the present level by Llauset Glacier

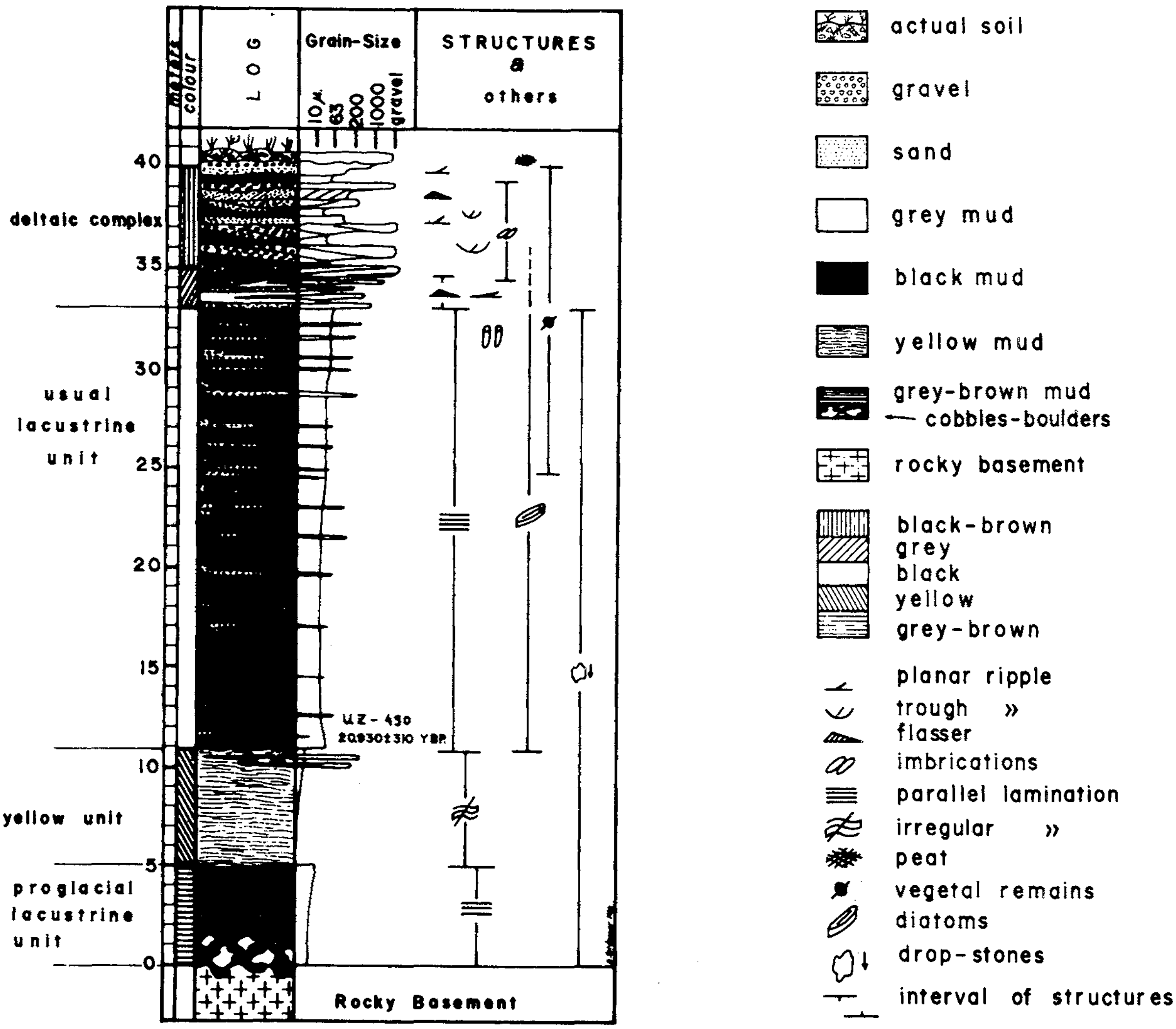

Figure 6. Composite section of Llauset lake.

during the last glacial maximum, chronostratigraphically situated by Vilaplana (1983-a, c) between 70.000 and 50.000 Y. B.P. At this stage, Llauset Glacier joined Noguera Ribagorçana Glacier in the main valley.

2) Sedimentation in Lake Llauset

The basal grey-brownish mud correspond to the period when Llauset Glacier retreated from the present lake basin and when a proglacial lake was formed there for a certain period. The characteristics of this sediment are similar to those of other glaciolacustrine deposits in the Pyrenees as describe by Vilaplana & Serrat (1979) and Serrat *et al.* (1983). However, the presence of some crystals of gypsum and pyrite in the upper parts of this sedimentary unit and of some diatoms seems to indicate that not a completely glacially controlled paleoenvironment persisted at the time of deposition.

The contact between the basal and the overlying intermediate sedimentary unit is locally gradual or abrup. The intermediate sediment is best explained as a biochemical lake deposit displaying a more detrital facies upwards. The presence of dropstones in the reddish-yellow mud may indicate that the lake surface became frozen at some occasions. Orthominerals of sulphate within this sediment favour its biochemical origin, (see section 4). But it must be noted that bedrock consists of pyrite and iron rich limestone in the source area of the River Llauset and, therefore, it may be possible as well that the geochemical anomaly is of detritic origin. The pH-/Eh-/ temperature conditions favoured a diagenetic transformation of the organic matter by coccous rather than by bacterial action. The coccous acted as a crystallization-nucleous of pyrite. This was oxidized later to geothite and selenite formed. Climatically, this period of sedimentation has been most probably cool or temperate cool and dry; the input of clastic detritus to the lake being low.

The top unit is related to the recent lacustrine sedimentation with most probably an annually rhythmic deposition.

The diatoms as determined in the sediments (see section 4) indicated that the algal assemblage of the lower sample corresponds to a warmer climate that those of the upper sample. And finally the growth of the delta is controlled by the large amount of clastic detritus brought to the lake basin by the actual River Llauset.

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