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Lithological Units of Glaciolacustrine Border during the last glaciation in the Jura Range (France)

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ABSTRACT

During the last glacial period (Würm), the Jura range was covered by an ice cap independent of the alpine cap; its length was about 100 km in the NE-SW direction and 40 km in the SE-NW direction.

From up-stream, basal tills may be noted, progressively going along to ablation tills, then to coarse deltaic cones and finally to laminated small sized deposits.

Numerous sedimentary structures are described in each of the lithological units, showing the glacial effect in the formation of these deposits.

RÉSUMÉ

Pendant la dernière période glaciaire (Würm), la chaîne du Jura fut recouverte par une calotte de glace indépendante de la calotte alpine, d'environ 100 km. de longueur dans la direction NE-SW et de 40 km. dans la direction SE-NW.

La glace s'écoulait essentiellement depuis la haute chaîne (1700 m d'altitude) en direction de la zone occidentale et les dépôts uniquement calcaires de la marge glaciaire, se sont accumulés entre 500 et 700 m d'altitude.

Les écoulements glaciaires perpendiculaires aux structures jurassiennes ont barré les combes anticlinales et monoclinales dans la marge du glacier. De nombreux lacs proglaciaires se trouvaient à la périphérie de la glace et se sont remplis de dépôts glacio-lacustres.

De l'amont à l'aval, on peut voir les moraines de fond (basal till) passant progressivement aux moraines d'ablation (ablation till), puis aux cônes deltaïques grossiers et enfin aux dépôts fins laminés.

De nombreuses structures sédimentaires sont décrites dans chacune de ces unités lithologiques montrant l'influence glaciaire dans la mise en place de ces dépôts.

Les données chronologiques montrent que cette extension glaciaire a eu lieu lors de la phase terminale du Würm ou période du Pléniglaciaire supérieur.

RESUMEN

Durante el último período glacial (Würm), el sistema montañoso del Jura estuvo recubierto por un casquete de hielo independiente del casquete alpino, con unos 100 Km de largo en la dirección NE-SW y 40 Km en la dirección SE-NW.

El hielo fluía esencialmente desde la parte más alta (1700 m de altura) hacia la zona occidental y los depósitos únicamente calcáreos del margen glacial se acumularon entre 500 y 700 m de altura.

Los flujos glaciales perpendiculares a las estructuras jurásicas taponaron las combas anticlinales y monoclinales en la zona marginal del glaciar. En la periferia del hielo habían numerosos lagos proglaciales que se colmataron con depósitos glaciolacustres.

De aguas arriba hacia abajo encontramos sucesivamente las morrenas de fondo (basal till) que pasan progresivamente a las morrenas de ablación (ablation till) después a los conos deltaicos groseros y finalmente a los depósitos finos con laminación paralela.

Se han descrito numerosas estructuras sedimentarias en cada una de estas unidades litológicas demostrando la influencia glacial en su formación.

Los datos cronológicos demuestran que esta extensión glacial tuvo lugar durante la fase terminal del Würm o período del Pleniglacial Superior.

During the würmian maximum, the Jura range was covered by an ice cap independent of the alpine cap (D. AUBERT, 1965; M. CAMPY, 1982).

Figure 1 shows a sketchy production of the distribution of the main glacial ensembles during the würmian maximum on the North-West slope of the Alps in contact with the Jura:

– The principal axis of the alpine glacial vector was originated from the upper Rhône valley upstream of the present Lake Leman. This major gla-

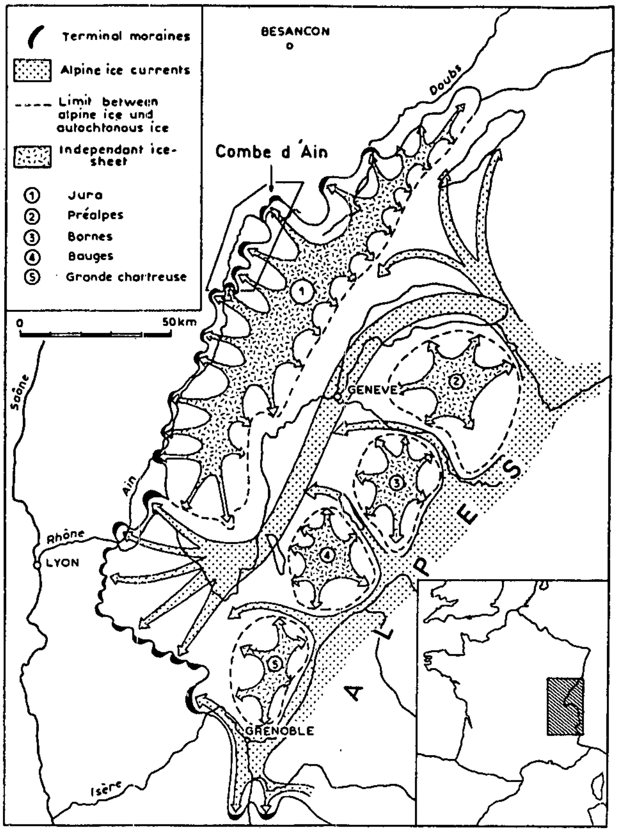

Figure 1. Distribution of the main ice ensembles on the North-West slope of the Alps in contact with the Jura range.

cial stream flooded the lemanic plain and stopped against the Jura mountain at about 1000 m ± 100 m high. Part of the ice went up North towards Lake Neuchâtel where it met the ice coming from the Bern Alps and running along the Aar valley (SCHLÜCHTER, 1973). The main part of the icy mass went South-Westwards towards Lyon and spread in a large glacial cone in the area of the Lower Dauphiné hills, at the extremity of which the terminal moraines of the "internal moraines complex" were accumulated. This main ice mass received on its left bank the glacial deposits coming from the internal Alpine Mountain through the neighbouring valleys separating the different subalpine mountains. These, from North to South: Prealp mountain (2), Bornes (3), Bauges (4) and Grande Chartreuse (5) had their own glaciers coming from the more internal Alps.

– At the North-West, the Jura range was itself covered by an ice-cap, about 100 km long, 40 km wide and whose summit was about 2000 m in its central part. The glacial stream was centrifugal. On the east slope of the range, part of the ice met, at about 1000 m in altitude, the big alpine glacial stream, while on the North-West slope, the other part was running towards the edge of the Jura range where it deposited a whole series of clearly distinct frontal moraines (M. CAMPY, 1982).

The most beautiful deposit ensemble of this glacial margin was studied in the area "Combe d'Ain", 80 km South of Besançon. This is where the main characteristic lithological units have been described.

CARTHOGRAPHY OF THE LITHOLOGICAL UNITS OF THE GLACIAL LAKE BORDER IN THE COMBE D'AIN (Fig. 2)

The Combe d'Ain is a monoclinal hollow orientated mainly North-North-East - South-South-West, 30 km long and 4 to 5 km wide. The river Ain flows along it and it is about 500 m high. It is limited at the East by the "plateau de Champagnole" whose height ranges from 600 m at the West to 800 m at the East, where it joins the first summits of the Jura range. This plateau is cut by dead-end valleys (blind valleys) which are linked to the Combe d'Ain. To the West, the Combe d'Ain is limited by the heights of the Euthe range, 750 m high.

During the würmian glacial maximum, the east edge of the ice-cap coming from the Jura range split into independent glacial necks following the hollows of the Champagnole plateau. These glacial necks have deposited their frontal moraines on the east edge of the Combe d'Ain. The main mapped lithological units are the following.

1) The proper glacial deposits sensu stricto: moraines.

Three types of tills have been revealed:

– The ground moraines (Basal Tills): on the Champagnole plateau and in the hollows that cut through it.

– The ablation moraines (Ablation Tills): in the morainic ripples, near the melting area of the glacier when this area gives birth to a proglacial cone made of rough material.

– The subaqueous moraines (Waterlain Tills): when the morainic ripples are in direct contact with the lake and glacial lake deposits (silty laminites).

2) The proglacial deposits

A glacial neck overflowing at the South provoked a dam lake which spread all over the Combe

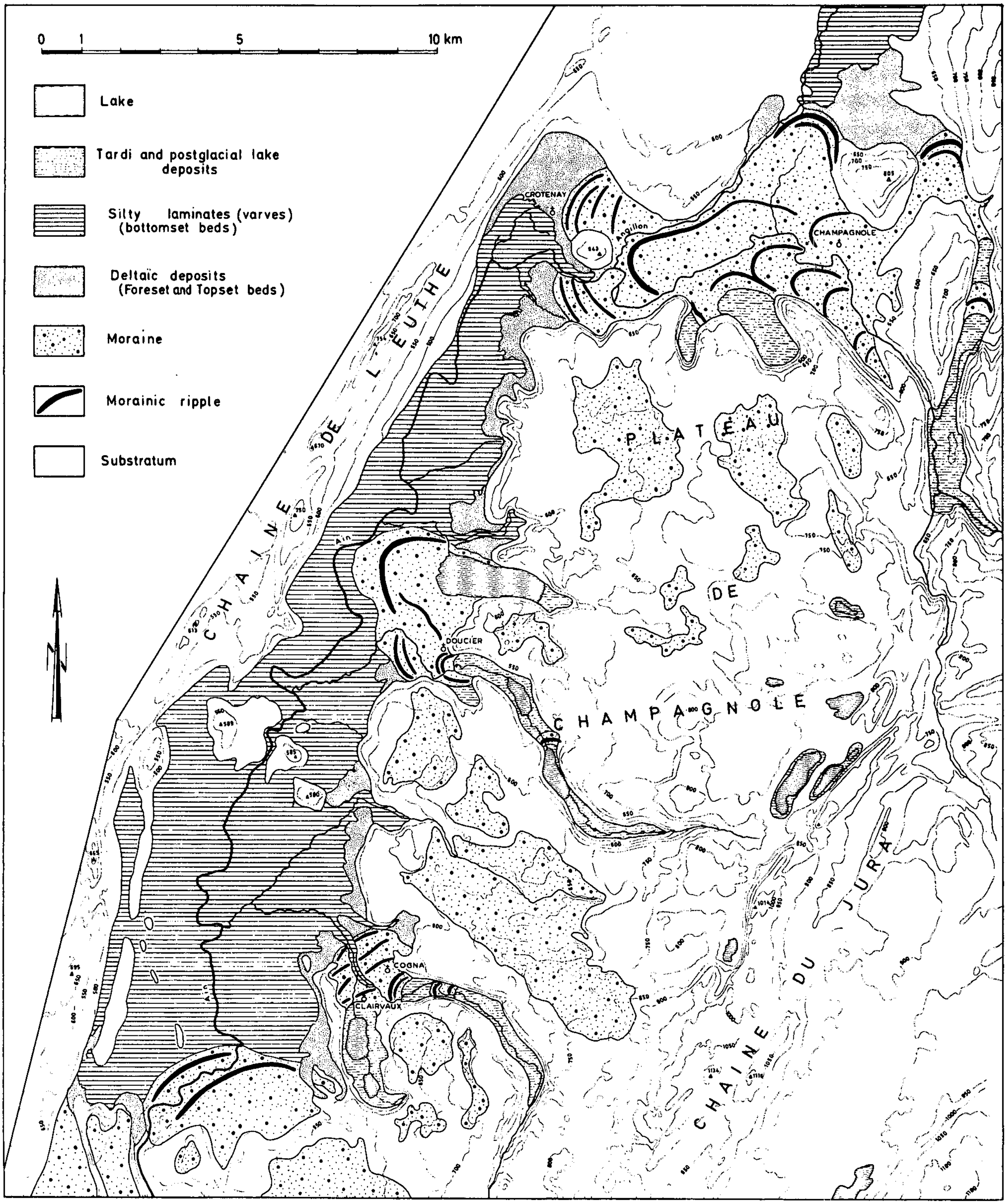

Figure 2. Cartography of lithological units of the glacial like margin of the "Combe d'Ain".

d'Ain at the glacial maximum. The proglacial deposits are then essentially represented by two types of glacial lake deposits:

- Rough deltaic deposits which are always 525 m high. Under the horizontal deposits (Topset beds), we find deposits with a marked slope of the type "Foreset beds". These rough deltas are present immediately down stream of the terminal moraines when the glacial neck was not directly in touch with the lake waters (area of Crotenay and Clairvaux). When the glacial neck was in contact with the water of the lake, these deltas are situated on each side of the terminal moraines and set back from these moraines (area of Doucier and the far South of the Combe d'Ain).
- Fine varved deposits (laminites) essentially composed of silts. They spread all over the depressed area of the Combe d'Ain and they can be as far as 30 m thick. They represent the Bottom-set beds accumulated in lake still water surroundings. Numerous drop stones are present in this ensemble, they are interpreted as blocks transported on ice rafts.

The depressions situated up-stream of the terminal moraines, developped during the glacial retreat, have been occupied by lakes, a great number of which still exist now (lakes of Clairvaux, Doucier, Chalain, etc...). But most of the time, these lakes have been filled by former and post-glacial deposits and consequently progressively dried up.

SEDIMENTOLOGICAL CHARACTERISTICS OF THE DIFFERENT LITHOLOGICAL UNITS

A) The glacial deposits sensu stricto

1) Ground moraines

They are the most frequent in the studied area. They appear as slack shaped coatings covering the eastern plateaux of the Jura range and they are seldom more than 10 m thick. The sedimentological studies were made on 24 outcrops set close to each other inside the complex of the internal tills.

–Definition of the lithological unit

It is an heterometric formation (diamictite) composed of calcareous, angular sub-blent blocks, pebbles and gravels, set in a very compact, coherent, light-beige matrix. The rough elements are included in the matrix, they form one piece with it and split uneasily.

–Typical locality and typical profile

Among the 24 samples studied in the different described cuts (M. CAMPY, 1982), the cut of the Crillat pass (x = 865,7; y = 181,8 and z = 705) can be used as a typical profile.

–Lithological characteristics

a) Granulometry. The heterometry of the moraines necessitates an important sampling. Each of the studied samples weighs as least 20 kg. which lengthens considerably the laboratory handings. In our opinion, the results give a statistically convenient idea of what we consider as the lithological unit "ground moraine".

The representative granulometric diagrams (Fig. 3) bring about the following comments:

- The percentage of fine fractions is very low (2). It always represents less than 6% of the whole sample. The other textural classes are more or less equally dispatched, but the greatest variability appears in the silty fraction (from 12 to 38%).
- The grain-size distribution is no doubt that of a diamictite, that is of a deposit without a perfectly defined model class.

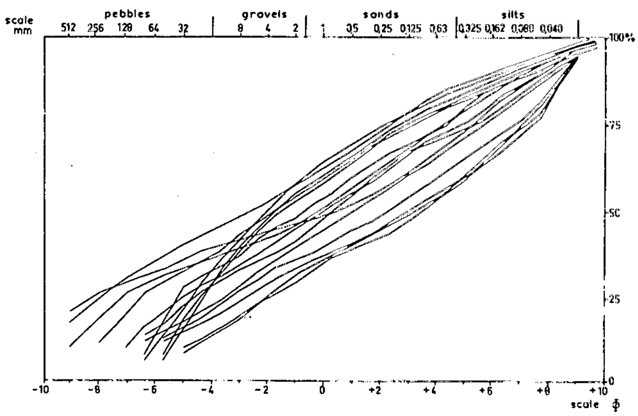

Figure 3. Ground moraines: granulometric diagrams.

b) Morphometric analysis. The morphology of the calcareous pebbles from the Jura ground moraines, as well as the compaction of the fine matrix is the most determining characteristic element, mostly as far as the fragments of micritic limestones are concerned.

All the characteristics defined by the different authors (A. CAILLEUX and J. TRICART, 1959; R.F. FLINT, 1971; Ch. SCHLUCHTER, 1979) are present in and on the blocks included in the ground moraines.

- General polyhedric shape, more or less isodiametric, with only slightly blunt edges, or even sometimes with sharp angles. The extreme types defined in a picturesque way as "laundry iron", squat, their front tip slightly blunt and rounded with truncations are numerous and their number is always superior to 15% of the whole.
- Presence of numerous concave truncations tending to slim the pebble at its extremities.
- Percussion signs and scratches most of the time short and more or less sub-parallel to the biggest axis.

These characters are difficult to measure and to count, so that, following Ch. SCHLUCHTER, 1976, we have applied ourselves to studying more particularly the value of the index of flatness and of the degree of roundness on a given grain-size fraction (20 to 70 mm).

The degree of roundness (Fig. 4) gives very low global values (from 20 to 275) and the value of the median particle diameter calculated on 120 to 150 measurements ranges from 60 to 150 according to the samples. We can be surprised by the lowness of these values and most of all by the extreme contraction of these values in comparison with the extremes. Indeed, the results that Ch. SCHLUCHTER got from micritic limestones, with a swiss facies, show a wider spreading of the values of the degree of roundness (from 0 to 650).

In our opinion, this characteristic of the Jura ground moraines facies can be explained in two manners:

- The facies of the Jura limestones are characteristic of a deposit of a little subsiding carbonated platform and the strata, less bulky than these of the Swiss facies, split more easily into polyhedrons of a smaller size.
- In the Jura range, before the glacial advance, there were much fewer ancient glacial and fluvioglacial deposits than in the big alpine valleys. These ancient deposits, blunt beforehand, knocked over by the glaciers and included in the basal moraines give the pebbles contained in these tills an inherited blunting. On the contrary the rocky cliffs numerous in the Jura have abundantly fed the moraines during the glacial advance, with elements free from any previous wear.

–Biostratigraphic data and absolute age

Up to now we possess no biostratigraphic data that would permit us to date these ground moraines. This lack is linked to the very nature of these formations, azoic by definition, but we don't gibe up hope to find a ligneous fragment torn off during the glacial advance and vehicled among these formations. Let us precise that these morainic deposits are part of the complex of the internal moraines, the age of which will be discussed in the conclusion.

2) The ablation moraines

The ablation moraines show some facies much more varied than the ground moraines. The very changing conditions of their settling (melting of the ice) determine as many types as there are outcrops observed. Moreover, the extremely diversified topography of the Jura range makes these conditions more complex, being thus different from the big areas of glacial edges (North American or North European shield) where these facies have been most of the time described and studied.

–Definition of the lithological unit

This formation presents a large heterometry and a lack of fine particles if compared to the ground moraines formerly described. The general cohesion is also much reduced and the provoked outcrops (quarry or slope rectification) are less erosion resistent than the former.

–Typical locality and typical profile

Among the 9 studied cuts (M. CAMPY, 1982), the Marigny cut (x = 864,8; y = 192,7; z = 510) can be used as a typical profile.

–Lithological characteristics

Often interbedded with fluvio-glacial deposits, they represent in this case the upper part of the terminal moraines at the western front of the complex of the internal moraines (MA 1, MA 2, MA 4, MA 5, MA 6, MA 7, MA 8). More rarely, they lie on the ground moraine and represent, in this case, the

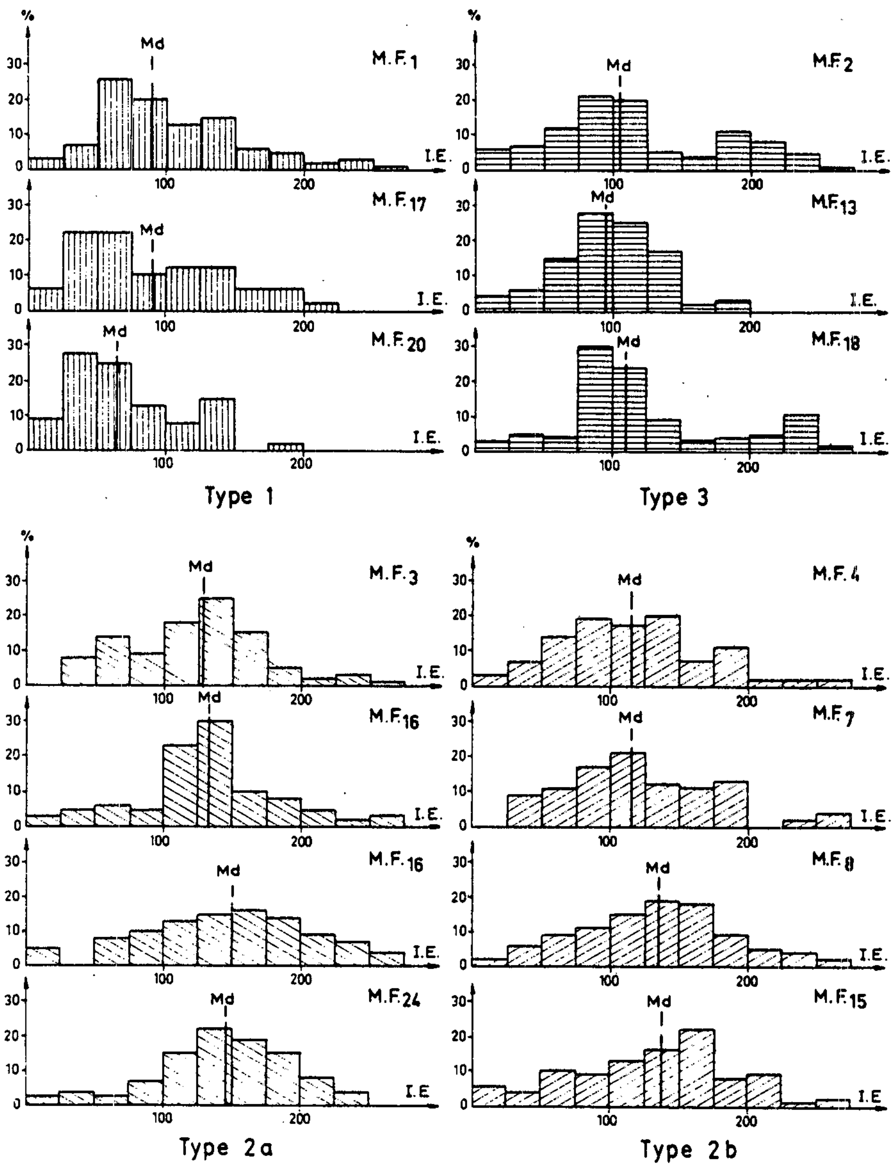

Figure 4. Ground moraines: values of the degree of roundness in each of the types.

interglacial content deposited during the ice melting of the last recess (MA 2, MA 9). In the first case, they can be thick and we have never been able to see what formation they covered; in the second case, they lie directlyand without transition on the ground moraine.

a) Granulometry. The granulometric curves give an idea of the texture of these deposits which have in common two typical characteristics: (Fig. 5)

- Absence or very bad representation of the fine particles (silts and clays); they always represent less than 15% of the total deposit.
- Bad sorting of the rough material and great granulometric heterogeneity of the various samples.

These characteristics show very well the wide-scale washing during the melting of the ice in the edgy and supraglacial areas: all the fine particles trapped and compressed in the ground moraines have been in this case drawn away by the melting waters.

b) Morphometric analysis. The so particular morphology of the pebbles contained in the ground moraines which were studied before, is largely diminished here. The polyhedrons are rare or absent, the truncations are exceptionally visible, but very reduced, the signs of percussion and the scratches are exceptional. We measure how quickly the typi-

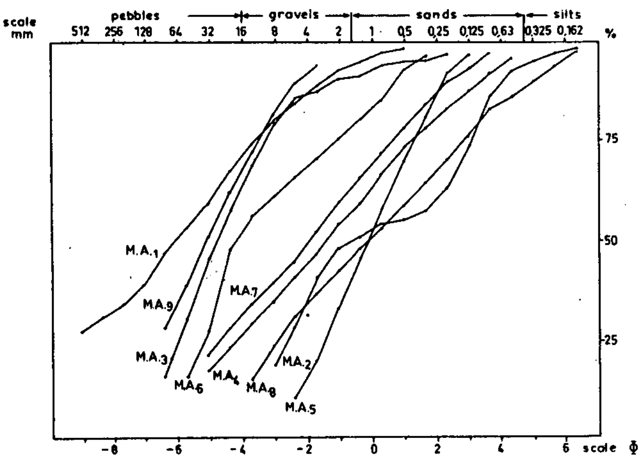

Figure 5. Ablation tills: granulometric diagrams.

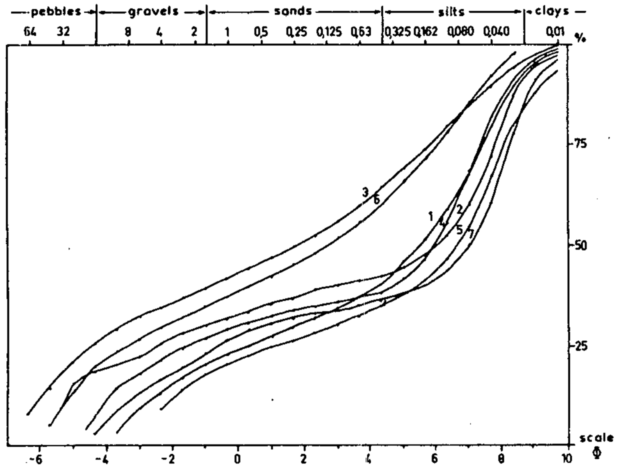

Figure 6. Waterlain tills: granulometric diagrams.

cally glacial morphology is lost when the melting waters take hold of the sub or intraglacial morainic material.

–Biostratigraphical data and absolute age

No biostratigraphical element permitting an absolute dating has yet been revealed in this type of formation.

3) *Subaqueous moraines*

A particular bed formation, the characteristics of which are different from the moraines *sensu stricto* previously studied, caught our attention. Well represented in the South of the Combe d'Ain, at the East of Doucier, it crops out at the flank of the groove dug by the river Ain in the so-called glacial lake basin of the Combe d'Ain. At its surface, it shows a slack morphology less varied than for ground moraines and a fortiori for the frontal ablation moraines.

–Definition of the lithological unit

It is a heterometric formation, but whose principal element is a grey or greyish-white matrix, locally bedded. The rough elements are scattered in an irregular way and it was nowhere possible to show off gravel or blocktrain concentrations. These seem to be dispersed at random in the matrix. The grounds developed on this formation are thin and wet. They bear a natural vegetation (scanty grass).

–Typical locality and typical profile

The best cut presently visible is situated in a bulge at the flank of the Ain valley, close to the village of Barésia (x = 858,6; y = 178,5; z = 460).

–Lithological characteristics

Seven samples have been taken from bottom to top of the cut, that is about every 80 cm to be granulometrically and morphometrically characterized.

a) Granulometry. The aspect of the granulometric curves (Fig. 6) presents an obvious homogeneity which cannot be compared to the curves obtained with the other types of moraines. They are characterized by:

– a preponderance of the extreme granulometric classes (rough pebbles and rough gravels on the one hand, silts on the other hand) in comparison with the middle granulometric classes (fine gravels and sands).

– the fine fraction (silts and clays) represents from 35% to 65% of the total percentage, which is exceptional for the types of Jura moraines that we have studied. Let us notice, however, that this fine fraction is mainly represented by the silts, the clays remaining rare, which links this morainic type with all the Jura moraines in a remarkable way compared with most of the moraines present in other regions.

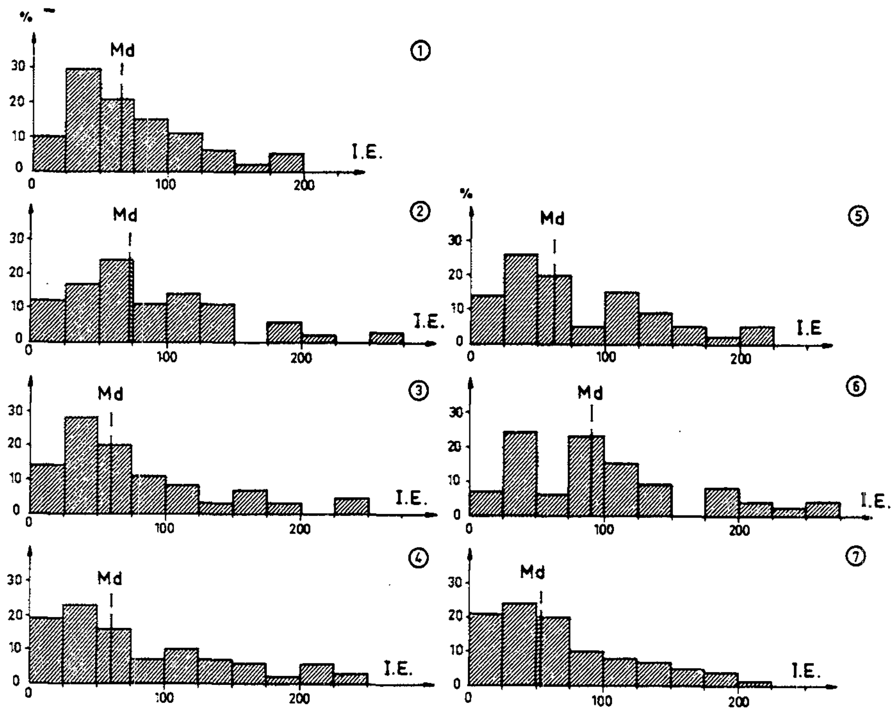

Figure 7. Waterlain tills: values of the degree of roundness (I.E.).

b) Morphometric analysis. The morphometric analysis have been made on the seven samples of the outcrop of the Epinay Farm. As the rough fraction is less abundant than in basal moraines, the number of gravels between 2 and 7 cm long was also less important. The values of the medial that we are using (Fig. 7) result from the measure of 60 to 95 elements according to the samples.

The morphometric characteristics are as follows:

- Compared to the values obtained for the basal moraines, the relations between the degree of roundness (D.R.) and the index of flatness (I.F.) give a distribution area slightly different with an important overlapping zone (Fig. 8). We can nervertheless establish that the middle value of the medials relative to the subaqueous moraines is at the same level as the weakest values of the medials relative to the basal moraines as well for the degree of roundness and for the index of flatness.

- The degree of roundness (Fig. 7) considered alone gives medial values wholly inferior to these of the basal moraines, as we have just seen, but the value of the modal classes is much inferior to that of the basal moraines: the best represented class is the class 25 to 50, however the value of the medial is superior to 50.

–Biostratigraphic data and absolute age

As for the other formations, no dating element can be proposed.

4) Conclusion

Lithological differences between these three types of moraines.

A first study has been done by positioning on a triangular diagram (Fig. 9). To the great granulometric dispersion of the ablation moraines is opposed the relative concentration of the ground moraines and of the subaqueous moraines. But these show a larger scale for the fine fractions in comparison to the ground moraines. Two of the studied samples are embedded in the dispersion area of the ground moraines. This fact is difficult to explain, but we can think that the "subaqueous" influence could be more or less noticeable during the deposit: when a glacial flow came massively, the ground moraines could be completely integrated without any retaking or any aqueous intervention changing their granulometry.

A second approach was realized by comparing the values of the granulometric parameters taken

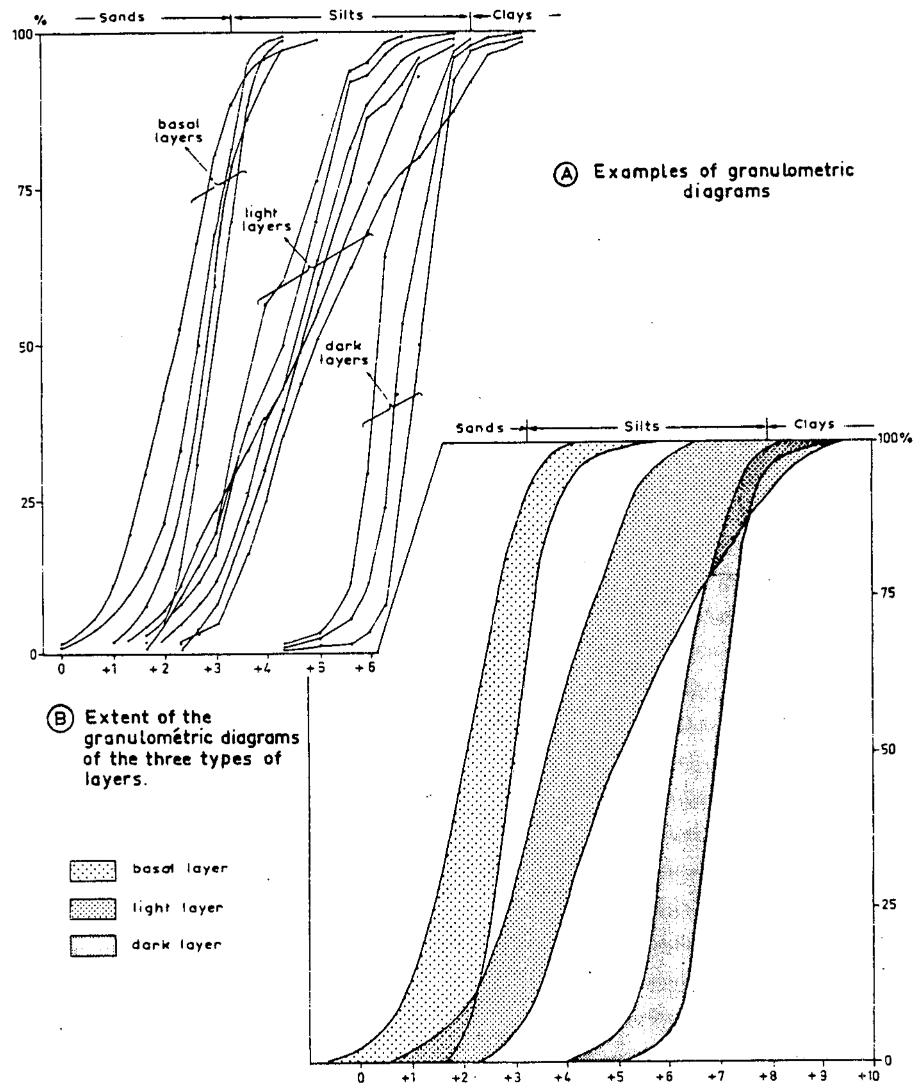

Figure 19. Bottomset beds: granulometric diagrams.

the regularity of the laminites is not interrupted in the limits of the outcrops observed. On the contrary, near the lacustrian margins, the laminites are often affected by deformations contemporary or slightly posterior to the deposits.

Convolutions, undulating beddings and current ripples (Fig. 22): The convolutions have variable dimensions, ranging from a few cm to 1 m. They appear as located hollows of rough levels in some finer levels. They affect either the limit between two immediately close levels (a-b, b-c, c-d, g-h) and can be in this case called undulated beddings, or several levels (e1, e2, e3, e4 ensembles) and determine in this case convolute beddings.

The sedimentary figures present in the upper levels (J-K) are slightly different: the axis of the warping is regularly inclined and can show a slump, contemporary with the differential hollow.

The contacts between lower sands and upper silt are frequently stressed by current ripples very clearly dissymetric (e4-F, h-i). They express the orientation of the water currents during the settling of the deposit. In this precise case, the currents seem to be conform to the polarity of the settling of pro-glacial slopes (SE-NW) but, in some other cases, the dissymetry of the ripples indicates a quite contrary current (schematically NW-SE). The interpretation of this anormal variation is given by the existence of counter currents at the bottom of the progradation slope, that is in depth, with a dir-

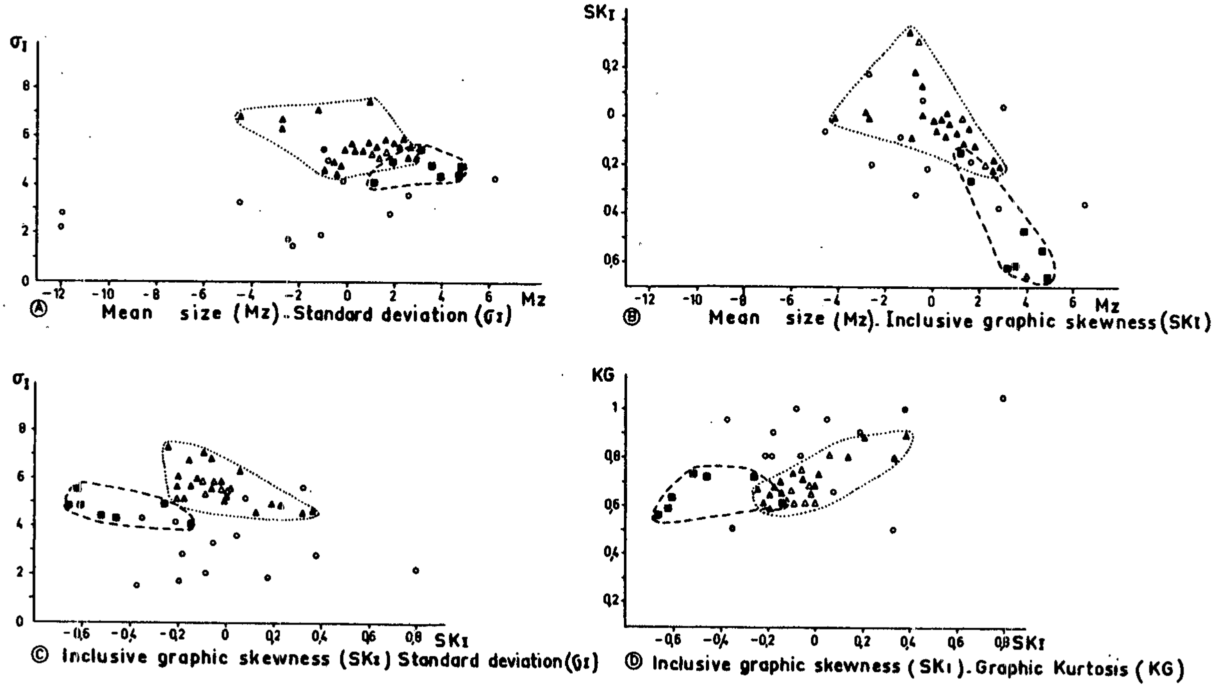

Figure 10. Waterlain tills (■): values of the granulometric parameters taken two by two in comparison with ablation tills (○) and ground moraines (▲).

sandy-silty lenses, sandy lenses with a good granulometric sorting.

Locally, it is possible to see certain levels from the upper ensemble (top layers) extending and slanting in the lower ensemble.

Morphologically, this formation constitutes a regular terrace with a slight slope towards the centre of the basin, resting up stream (that is, most of the time, at the East) on the morainic ripples and diving suddenly down stream in a characteristic festooned escarpment. (Fig. 12)

The pits are generally situated in the upper part of the terrace and they rarely uncover more than 10 m of the formation. However, some borings (Buchille Farm) or some intensive exploitations (Chalumeau Farm in Largillay) show that this formation can reach about 20 m in thickness and that it lies most of the time on a fine, silto-sandy ensemble of the laminite type ("varved" formation).

–Typical locality and typical profile

Among the 30 cuts visible in this formation, we have chosen the two cuts of Charcier (x = 860,8; y = 185,5; z = 525) and of Vertamboz (x = 861,1; y = 183,1; z = 523) as a typical profile.

–Lithological characteristics

a) Granulometry. *Charcier cut:* The granulometric analysis have been made on 22 samples taken from top to bottom of the outcrop (Fig. 11) in the most representative levels of the outcrop. The weight of the samples ranges from 1 kg (sandy levels) to 20 kg (rough levels).

The representative granulometric diagrams (Fig. 13) give a first idea of the texture of various sampled levels. We notice:

- a nearly general lack of the fine fraction (the rough silts are exceptionally present),
- a middle granulometric sorting of the extreme textural units (levels 14 and 5 for the very rough and levels 2, 4, 6, 11, 15 for the finest),

Figure 11. Deltaic cone of Charcier. Longitudinal outcrop. (photo).

Figure 12. In front of deltaic cone. In foreground the horizontal level of bottomset beds.

– a bad granulometric sorting for the other levels, the value of the median particle diametre ranging from - 3 for the roughest to + for the finest. These bad sortings remind us of certain data concerning the ablation moraines (outcrop of Porcherie) without reaching the biggest values.

A good idea of the roughness and of the sorting of each of the sampled levels is given by the diagram showing the evolution of the graphic mean value (Mz) combined with the value of the typical deviation (I). We notice (Fig. 14): the regular cycle of levels or of series of levels mainly sandy and relatively well sorted (2, 4, 6, 11, 15, 17, 19) with levels or series of levels rich ingravels and relatively badly sorted. The passage from one type to the other is either done suddenly and without transition (eg: in the alternating top series of the samples 1 to 6 or 14 to 18) or by a progressive transition towards a textural refinement and a better sorting (layers 14 to 11) or inversely (layers 11 to 7). This evolution with a great variability of the granulometric characteristics shows well enough a regime of sudden or progressive floods interrupted with periods of low waters. These features evoke perfectly a glacial front with sudden floods during the summer melting and more stable periods in the winter time.

The greatest textural variability appears at the level of the horizontal layers of the topset beds. It is logical enough to think that it is at the level of the channels immediately proglacial that the reactions of the thawing waters are the most immediate. Then, it is normal to notice that it is at this level that the granulometric characteristics are paroxysmal (the finest and the best sorted levels suddenly alternating with very badly sorted rough deposits).

b) Morphometric analysis. Seven levels among the roughest have been studied. The values of the degree of roundness represented in frequency histogram are particularly characteristic. We can notice that (Fig. 15):

– the spreading of the values is much more important than this of the moraines since it goes into the seven studied levels from O to 900,

– The homogeneity of the seven samples is very striking and we notice that the degree of flatness presents clearly pluri-modal values, contrarily to the fluvio-glacial materials (Ch. SCHLUCHTER, 1978) whose extent is comparable, but whose representative diagram is most of the time unimodal or exceptionally bimodal. In the case of Charcier, the seven samples present from 3 to 5 modal values which are 200-300, 350-450, 600-700, and more ralely 50-100 (sample 3), 100-150 (samples 7, 9, 16, 22), 450-500 (samples 7, 9, 14, 16).

This material is then very heterogeneous as for the values of the degree of roundness. This can only be interpreted by a mixture of material presenting stages of wear degree very different and reincorporated in the sedimentary process before their deposit in the deltas, and as frequently happens the value of the degree of roundness is higher.

c) Sedimentary figures. The deltaic formations are rich in sedimentary figures related to the conditions of their setting.

– Criss-crossed structures: the cuts made perpendicularly to the biggest dip in the progradation levels permit to see many criss-crossed structures with a decreasing graded bedding upward. Each sedimentary ensemble is truncated towards the summit by a new ensemble which has come to cover it in a non conformable way.

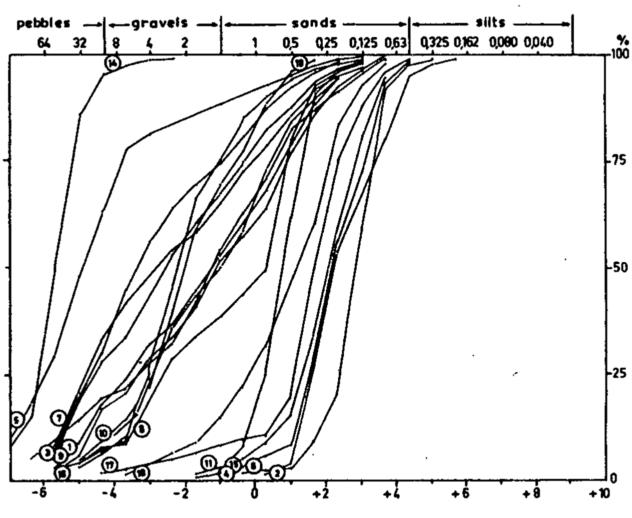

Figure 13. Deltaic cone of Charcier: granulometric diagrams.

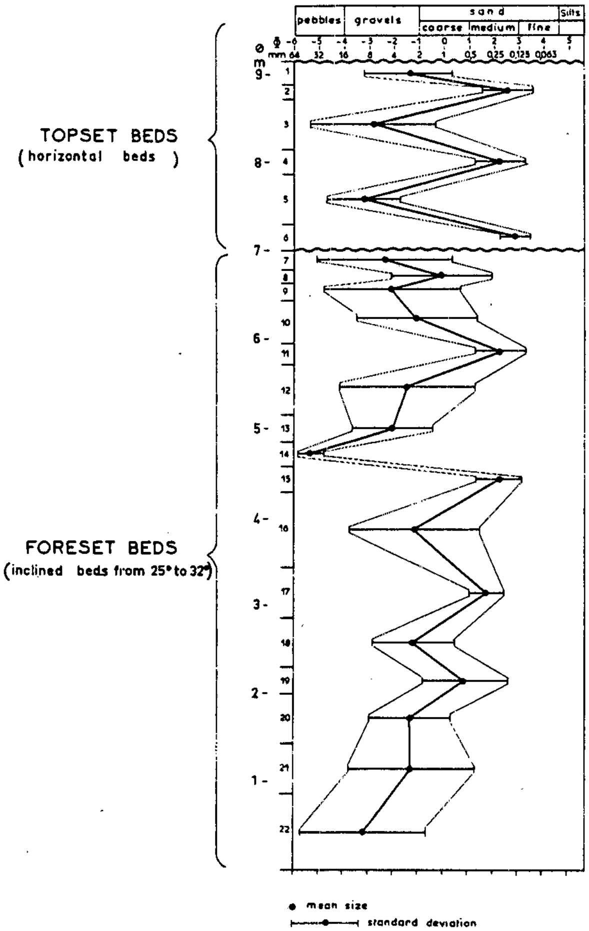

Figure 14. Deltaic cone of Charcier: vertical variation of two granulometric parameters.

– Collapsed layers: these structures are attributed to the melting of ice blocks, rich in limestone fragments, then incapable to float at the surface of the lake and drawn by the proglacial channels to the flank of the slope. The ice block would get steady and be huried under the later detritic deposits. The thawing of the icy binder would provoke a vacuum responsible for the warping of the overlying layers. Obviously, the ice block melted quickly, since the upper levels resume very quickly their regular stratigraphic polarity (Fig. 16).

– Ice-rafted blocks: these huge blocks in the deltaic deposits can only be explained by an embedding in an ice raft, drawn by the proglacial streams, the ice melting little by little and freeing its rocky burden. We shall find these ice-rafted blocks again in the varved deposits. The Anglo-Saxon literature called these "sedimentological accidents" by and expressive term: drop-stones.

– Load casts and current ripples: the granulometric texture of the silty-sandy and silty-argillous layers of the foreset beds permits the development of numerous sedimentary features essentially represented by load casts (s.l.) and by current ripples. The upper part of the cut represented is constituted by a cycle of rough silts, fine sands and medium sands. All the layers limits present current ripples showing a steady direction from East to West. The horizontal amplitude of the ripples is about 10 cm, the vertical amplitude is never superior to 2,5 cm. The lower part of the represented cut, with a less rough granulometry (fine and middle sized silts) is affected by simple, decimetric convoluted figures. The axis of the warpings, slightly slanted westwards, shows that a tiny creep of the slopes downwards (slump phenomenon) is added to the phenomenon of differential density responsible for the convolutions.

–Biostratigraphical and chronological data

These formations do not contain fossils, which is not surprising. All the data tend to attest an immediate proglacial environment, then deprived

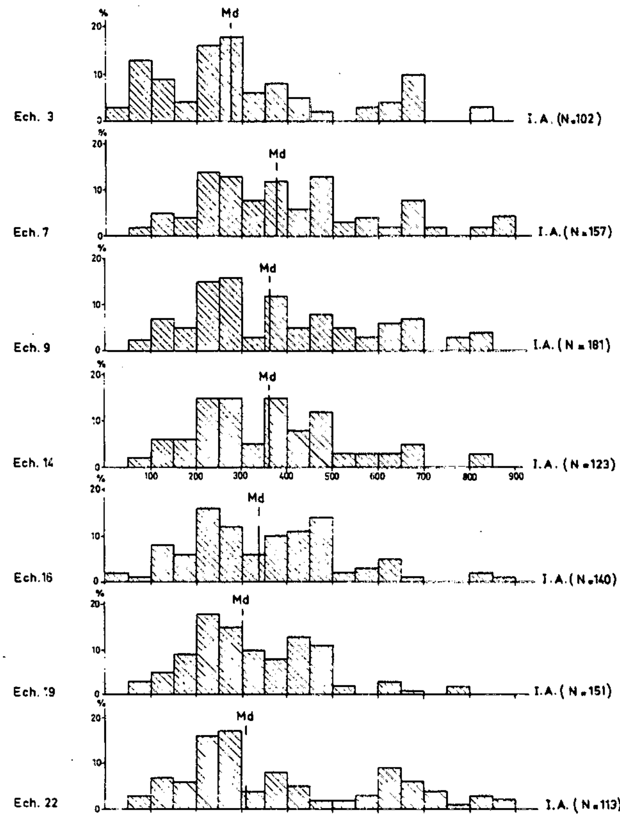

Figure 15. Deltaic cone of Charcier: frequency histogram of the values of the degree of roundness.

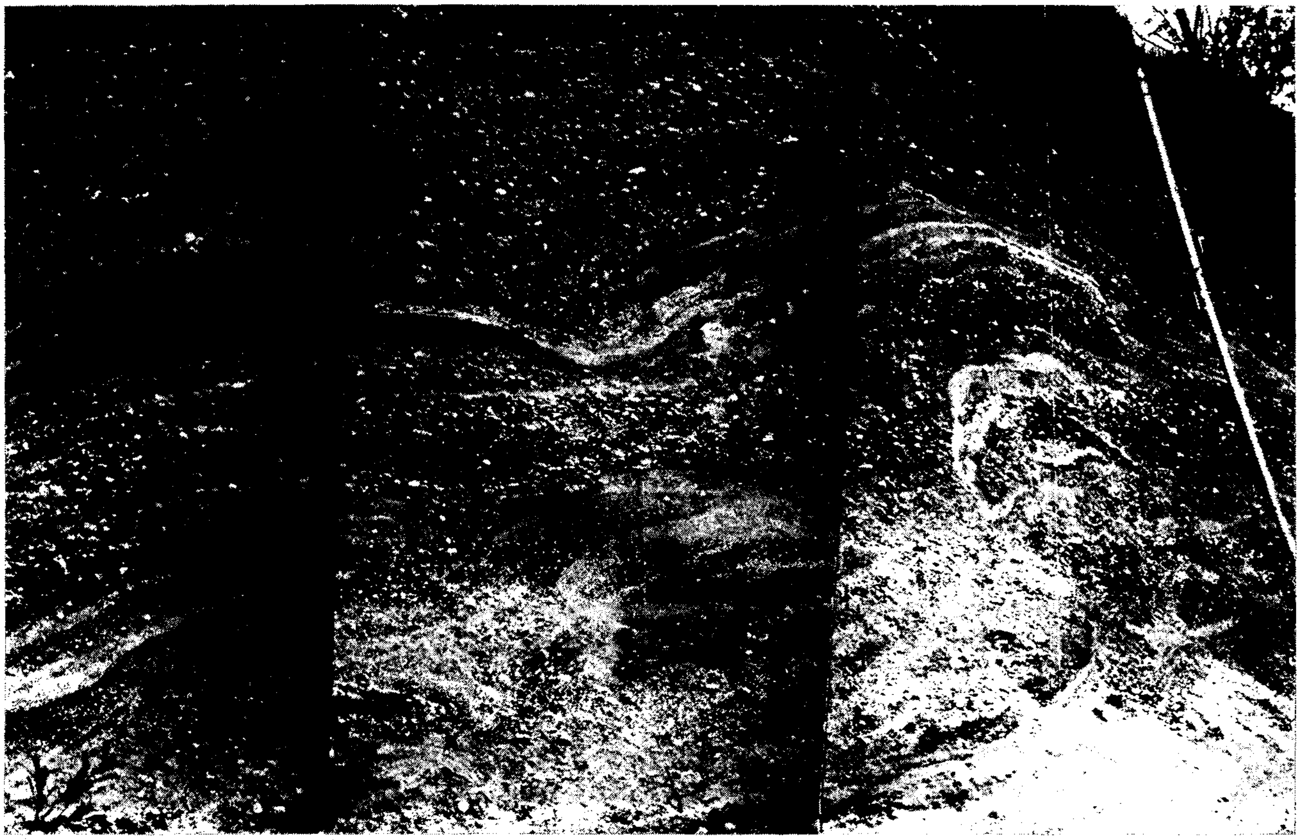

Figure 16. Collapsed structures in deltaic cone (scale 2,5 m).

of flora and fauna. The extraordinary discovery of a complete mammoth in the deltaic formations of the Joux valley (M. WEIDMAN, 1969) permitted a radio carbon dating. This date (12.270 B.P. ± 210) permits us to attribute this formation to the Tardiglacial period. But, as we will see later, the deltaic formation containing this fossil belongs to the last recess phase of the Jura glacier, while the Joux valley was invaded by a small relictual ice cap immediately before the complete deglaciation. It is then much posterior to the maximum glacial stage to which belong most of the deltaic formations we have studied on the west side of the Jura range.

2) Bottomset bed deposits

Varved silto-argillous formation.

They are very numerous in the Combe d'Ain where they are sometimes as far as 30 m thick.

–Definition of the lithological unit

The ground deposits can be considered as sandy-silty or silty-argillous laminites. The first characteritic is the regular disposition in centimetric beds alternately light (beige white) and dark (grey), horizontal or with a slight slope. Some synsedimentary (current figures) penecontemporary load casts "slump" or postsedimentary (collapsings and glaci-tectonics) deformations can locally affect them. Some gravels and some very little blunted isolated blocks are more or less abundant, but always numerous when the outcrop is important enough.

–Typical locality and typical profile

Among the numerous outcrops of the Combe d'Ain, the most important is the Ebaleves cut (x = 862; y = 193,2; Z = 460) at the flank of the concave bank of a meander of the Ain (Fig. 17).

–Lithological characteristics

The sedimentological study bore only on the

Figure 17a. Outcrop of "Les Ebalèves" in Chatillon on the right bank of the Ain river.

lower varved series which gives us the best proofs, the upper series being either affected by bulges, or much hidden by solifluction deposits.

a) Descriptive typology of the elementary units (varves). We could distinguish five main elementary "varve" types (Fig. 18) separated by major discontinuities.

Type 1: About 2 cm thick, this type presents a basal rough level topped by a thick light layer, in its turn covered by a dark layer about 3 to 4 mm thick.

Type 2: A little thicker than the previous one, this type presents a series of dark millimetric layers concentrated in the upper part of the light layer.

Type 3: Slightly thicker than the previous one, this type presents numerous dark millimetric layers more or less equally dispatched in the light layer.

Type 4: It is the replica of type 1, but much less thick, but beyond its thinness (5 to 7 mm), it differentiates itself by the lack of a basal rough level, and the varved type 4 ensembles show no major discontinuity (delamination zone) like the other types.

Type 5: It presents a middle thickness much more important, due to the large development of the basal rough level.

This descriptive and typological study brings about two fundamental questions:

– Does each elementary unity type represent a so called varve (that is, an annual cyclic deposit)?

– Does the ensemble of the inferior varved series previously studied and described represent a sedimentary cycle in relation with a glacial advance and recess?

We have tried to answer these two questions in a more precise sedimentary study.

b) Granulometric analysis. We have isolated the layers present in each type (basal rough level, light layer, dark layer) in order to do the granulometric analysis one by one.

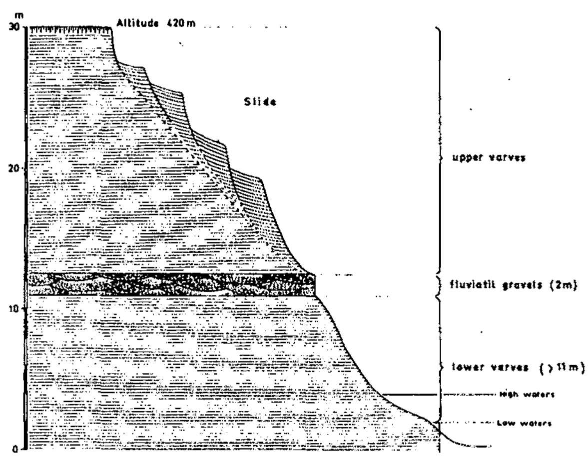

Figure 17b. Outcrop of "Les Ebalèves". Sketch.

The granulometric diagrams give a first idea of the texture of these various layers (Fig. 19):

- The basal layers have a relatively good granulometric sorting on the sandy-silty fractions (from the middle-size sands to the rough silts).
- The light layers have a much worse granulometric sorting on fractions ranging from the middle-size sands to the clays, the amplitude of the diagram spreading much more at the level of the fine fractions than at the level of the rough fractions.
- The dark layers have a good granulometric sorting on the silty-argillous fractions (from the middle-size silts to the clays).

We can notice:

- that the argillous fraction is always inferior to 10%, which excludes the usual name "varved clays" for these formations,
- that the aspect and mainly the colour (dark or light) of the layers is essentially linked to the texture: a fine, well sorted texture puts on dark colours while a rougher, badly sorted texture puts on lighter colours.

The calcimetric analysis of these formations gives calcium carbonate values between 85 and 98%.

An examination with a scanning microscope (Fig. 20) precises the structural organization of these formations: no laminar disposition is visible at this scale. The calcareous particles are piled one upon another without any visible order and are separated by holes. They are more or less anostomosed and, at the contact of two particles, a small calcitic bridge settles, giving cohesion to the ensemble. Locally, we can recognize calcite octahedrons, but most of the time, the particles do not show clear cyrstalline shapes: we consider that they are issued from Jura limestones and calcareous marls, ground and reducet to "glacial flour". Its compaction took place later at the deposit, by circulation in the interstitial capillaires.

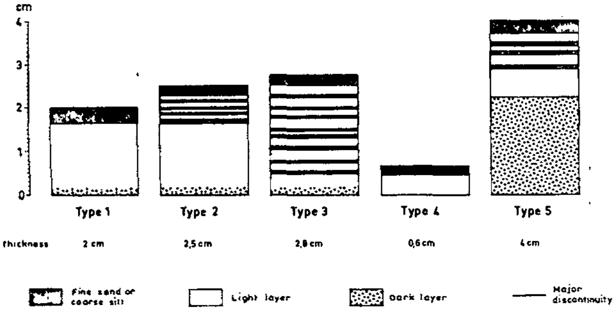

Figure 18. Typology of the elementary units of varves.

The study of the vertical evolution of the graphic mean value and of the typical deviation in two elementary units of type 2 permitted us to interpret these units as real varves, that is yearly varves. Fig. 21 shows this evolution. On 21 studied samples, carefully isolated vertically, we can ascertain the cyclic character of the texture. Each of the two cycles studied starts by a "basal" layer made of fine, well sorted sand. It is at this level that we find the major discontinuity permitting the physical delamination. The granulometric analysis of the light layer show an essentially silty, badly sorted sediments, as the alternating of light and dark layers at the summit results in a serrated evolution between the well sorted fine elements in the fine silts (dark layer) and much badly sorted samples in the middle-sized and rough silts. The cyclic character can be interpreted as the resultant of the annual cycle: basal rough deposits started during the spring thaw and continued by a badly sorted mixture of rough particles and of finer particles with a slower sedimentation. In our opinion, the top part represents a cycle of limited periods of flood and low waters characterizing the summer time. The last dark layer of the summit can show the low water level at the end of the summer, while a stop in the winter sedimentation permits the pilling up and the start of the diagenesis of the deposits (with which the deposits of the next cycle won't mix). So will be settled the major discontinuity that allows the delamination of the varves.

In comparison with the study of the elementary unit of type 2, we can propose an interpretation of the other types.

- Type 1, also considered as real varve, would represent a yearly cycle in which the alterning of the maximum summer floods and low waters would not be felt (greater distance from the glacial front?):
- Type 3 is but a variant of type 2, but is sudden spring flood would be immediately followed by an alterning of isolated floods and low waters (underfed glacier?).
- Type 4 is difficult: does it represent a real varve or a much shorter cyclic deposit? This is hard to say.
- Type 5 probably represents a real varve (yearly cycle) developed in an area relatively close to the glacial front.

c) Sedimentary figures. In the centre of the basin, the formations are regularly bedded and, apart form the steady presence of blocks (drop-stones) deposited after being transported of floating ice rafts,

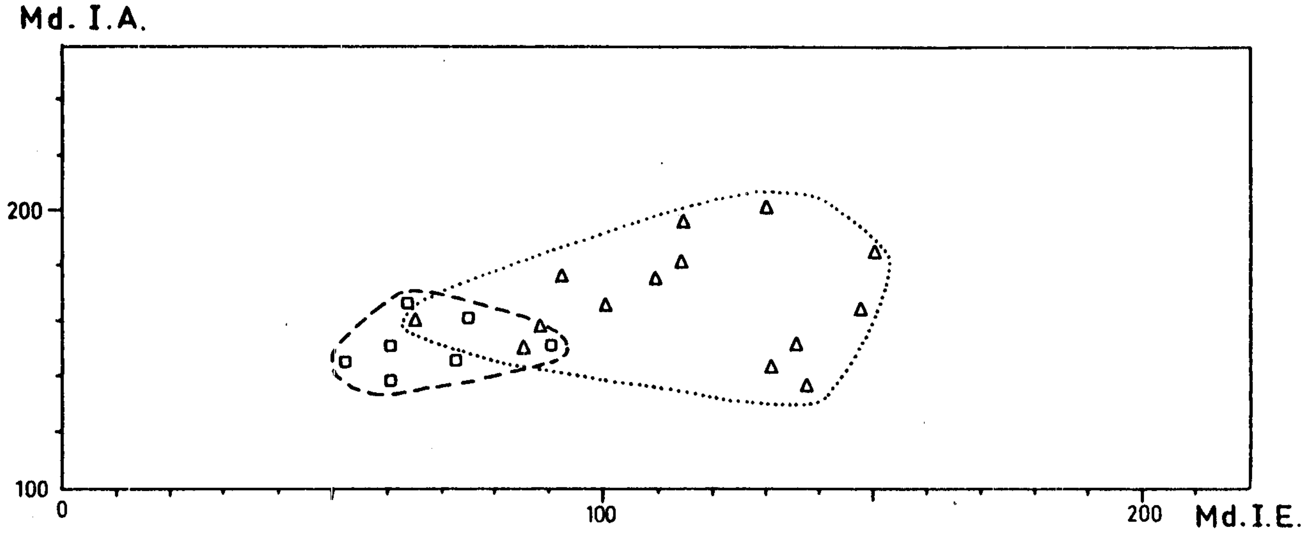

Figure 8. Relations between the degree of roundness (I.E.) and the degree of flatness (I.A.). Characteristics of the waterlain tills (N = 7) and ground moraines (N = 13).

two by two (Fig. 10). The same remarks can be made by looking at these diagrams: the ablation moraines give dispersed values opposed to the values grouped in relatively small areas of the ground moraines and subaqueous moraines. Nevertheless, the subaqueous moraines are included in a much smaller area and are spatially displaced in reference to the ground moraines. A certain overlapping between the two dispersion areas, always concerning the same samples, may occur in some cases. The interpretation of this overlapping can be made with the same arguments as before.

B) The proglacial deposits

The proglacial deposits of the glacial lake type can be grouped in two very distinct complexes:

- The rough deltas present on the lake margins, of the progradation deposit type, abundant in the Combe d'Ain, but also frequent all along the Jura glacial margin.
- The bottomset-bed deposits, fine, generally varved, always in association with the former and representing the sedimentological downstream expression of the lake margin deltas, sedimented after a period of suspension in still water.

1) The rough deltas

–Definition of the lithological unit

It is a rough detritic formation with well individualized beds rather regular in their longitudinal section (Fig. 11) and with abundant imbricated structures in their transverse section. Two ensembles are clearly individualized in the complete sections:

- The upper ensemble with a horizontal or very little inclined dip, about 2 m thick, unconformable on.
- The lower ensemble with an inclined dip, of a changing value (as far as 35°). At the bottom, this ensemble becomes finer on the whole and the sandy lenses dominate.

The texture of the bedded levels is very variable: heterometric levels with dispersed blocks in a sandy heterogeneous matrix often hardened, levels with blocks and rough gravels with an open work structure, sandy heterometric levels, finely bedded

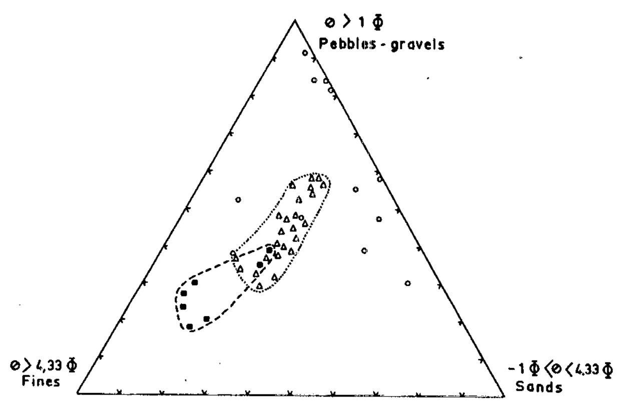

Figure 9. Triangular diagram and position of the waterlain tills (■), ablation tills (○) and ground moraines (▲).

Figure 20. Bottomset beds: photography with scanning microscope.

ection opposite to the major current developed mostly at the surface of the lake (after JOPLING, 1962, quoted by BLATT, MIDDLETON and MURRAY, 1980).

All these sedimentary figures are considered as contemporary of penecontemporary to the sedimentation.

Slump-slide: The most striking outcrop is situated in the Forges cut, at the confluence of the Drouvenant with the exsurgence of the big Clairvaux lake (Fig. 23).

These figures look like dissymetric folds with the up stream flank (NE) slightly ascending an the down stream flank (SW) much warped and affected by microfaults or even clearly thrust faults (right figure). The general slope shows a South-Westward translation with little rotation movement. This is why the English term "slide" would fit this figure better than the term "slump" reserved for the contemporanean dumping of the sedimentation with a rotating movement of the sliding. The abundance of microfaults in the overlapping zone also proves that the sliding happened as the deposit was showing a certain global compaction (case of the normal microfaults). The presence of inverse microfaults expresses piling phenomena probably immediately posterior to the sliding.

At the front of the overlappings, the deposits have undergone compressions affecting the sliding masses but also the upper less compacted masses, jammed between the flanks of the folds.

After the sliding, the bottom of the sedimentary

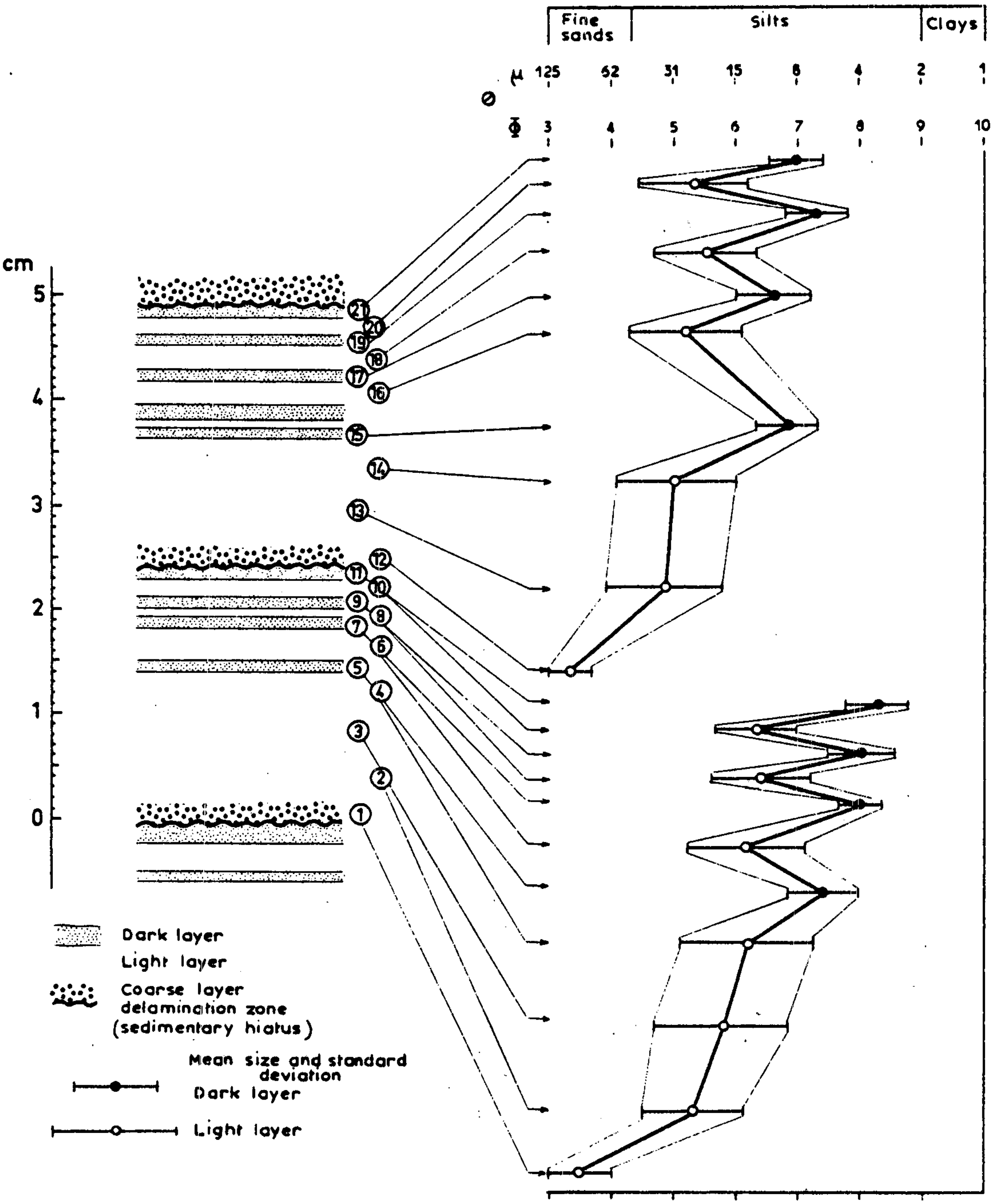

Figure 21. Vertical evolution of the graphic mean size and of the standard deviation in two elementary laminits.

basin showed undulations filled little by little by the deposits, which keep for a certain time a very soft cradle disposition. A sandy arrival finally filled the depressions and a regularly bedded sedimentation started progressively. Piling microfaults with very little thraw slightly fractured the upper ensemble later on.

–Biostratigraphic data and absolute chronology

The exclusively mineral composition of these formations has not permitted an absolute dating. We have tried to search microfossils (with C. CORNET from the University of Louvain for the diatoms and with H. RICHARD from the University of Besançon for the pollens). All these researches were in vain: these deposits are absolutely azoic and attest without doubt a strict glacial environment, without any vegetation.

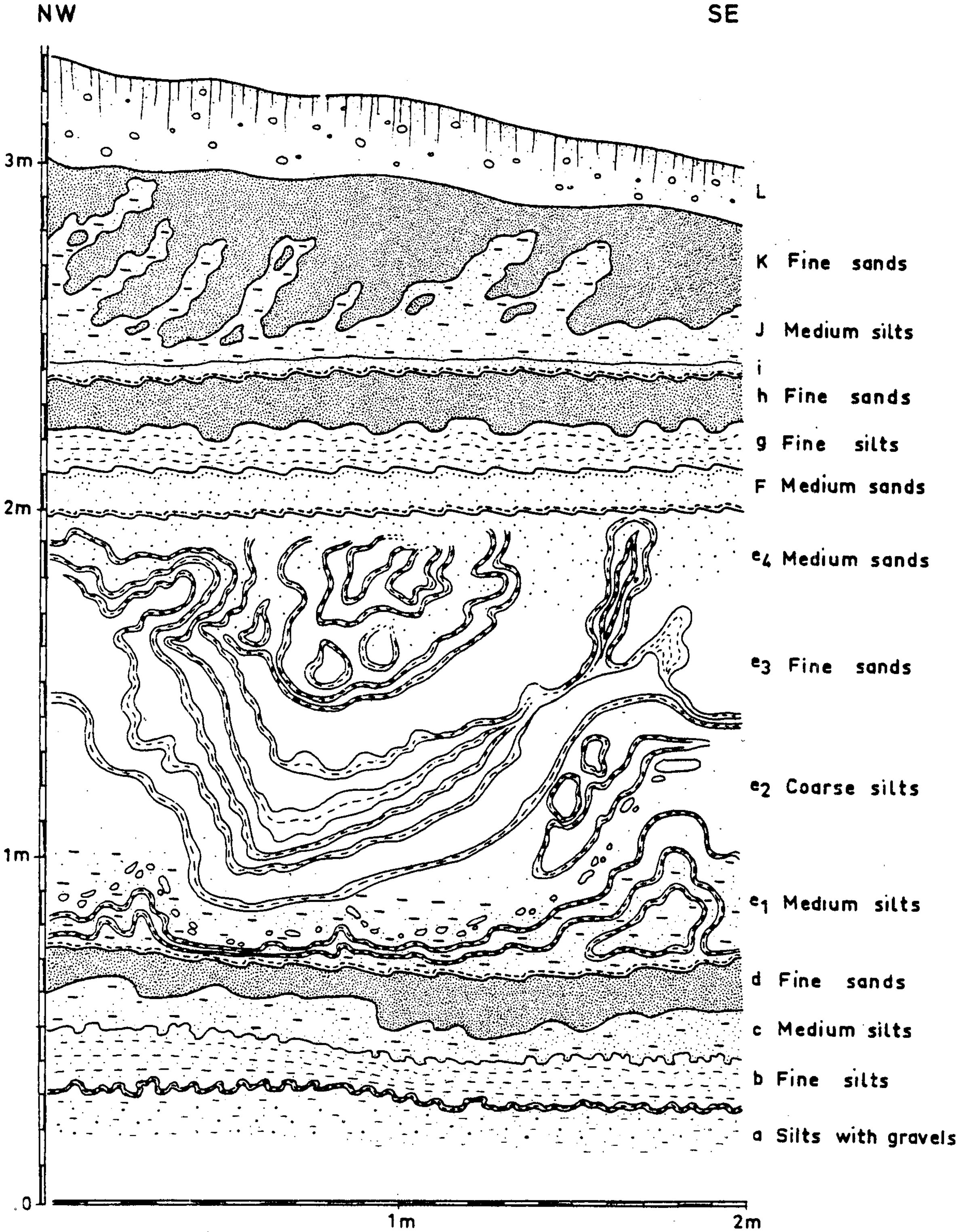

Figure 22. Sedimentary structures in contact of deltaic deposits and bottomset beds (legend in text outcrop of Combe Robert).

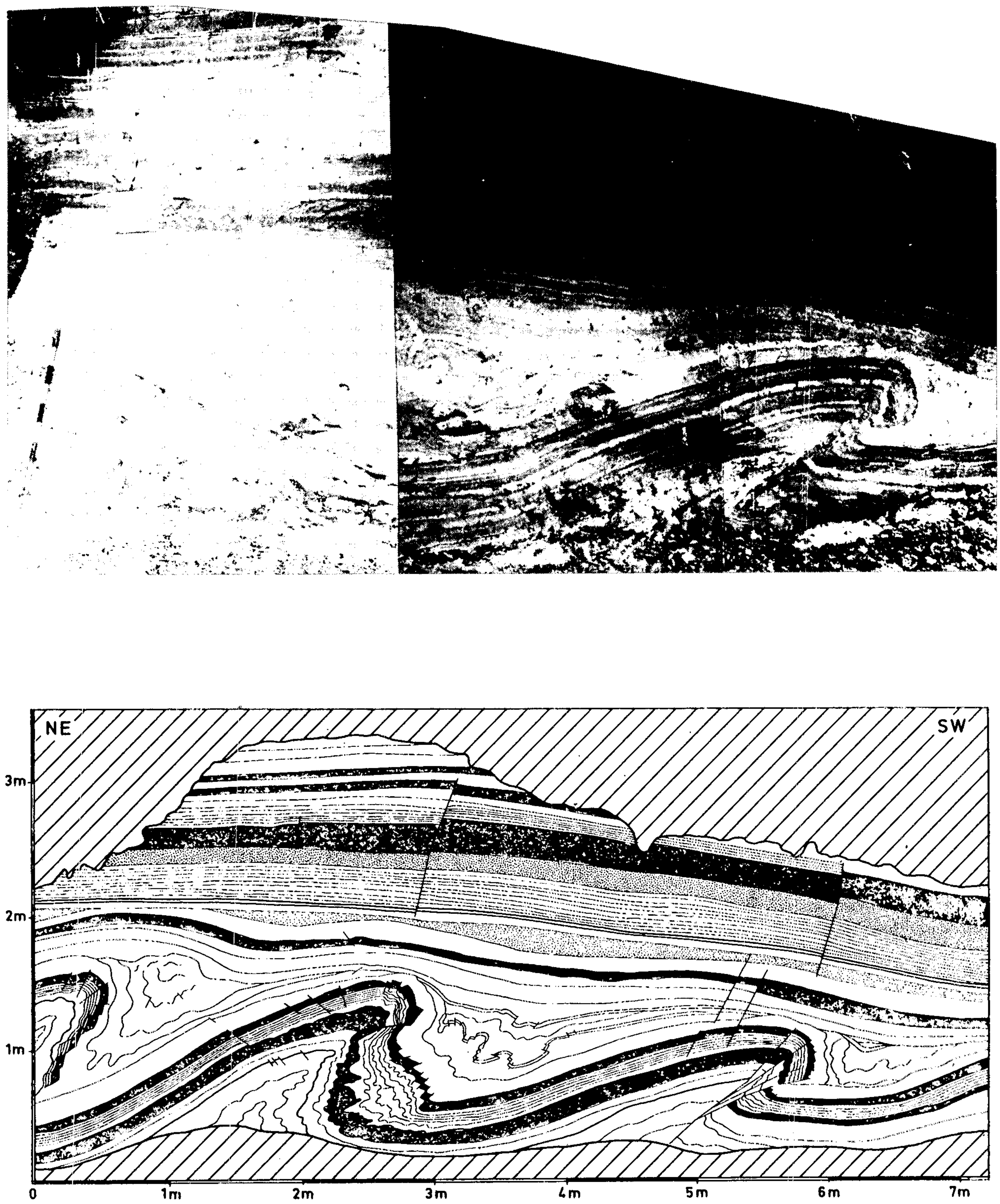

Figure 23. Penecontemporaneous deformation or slightly posterior to the sedimentation in silty lamination (outcrop of "Les Forges" in Clairvaux). a) photography, b) sketch.

THE SEDIMENTARY COMPLEX AT THE GLACIAL LAKE CONTACT IN THE COMBE D'AIN

Most of the observations done go into a dynamic sedimentary frame: the glacio-lacustrian margin. We possess, in our opinion, enough elements, isolated but genetically linked, to propose a sedimentary model proper to this type of environment (Fig. 24).

Let us examine, from up stream to down stream, that is roughly from East to West, the different contacts of the main sedimentary ensembles. The contact between bottom bed tills and ablation tills has rarely been observed. However, we have seen that the ablation tills existed in two distinct types according to their position and their morphology. Up stream, a metric level of the ablation moraine type lies on the bottom bed tills: these are the ablations tills in the strict meaning of FLINT. At the glacial front, the various maroinic ripples or ridges morphologically defined, show some ablation till facies: they constitute the "frontal tills". The facies of the bottom bed till type are at the level of the glacial front, covered by the morainic ripples under which they entd in wedge and it is possible to find isolated masses of bottom bed tills in the ablation tills.

The contact between ablation tills and proglacial deltas has been observed in several cuts. Some interstratifications of the two facies are possible, which proves that the glacier covered little by little the deltaic cone during its progress. The morphometric analysis have shown us that one or several deltaic material retakes have happened.

The so called delta is classically composed of tis two complementary series: the progradation slope (foreset bed), formed by the alterning of inclined layers of sandy pebbles, and the top layers slightly inclined down stream. We have exceptionally seen the passage of layers from one to the other, but most of the time, the top layers lie discordingly upon the inclined layers they are gullying. The sedimentary figures of the convolution and current ripple type are abundant in the silty-sandy top layers, and in some transversal cuts, numerous criss-crossed stratifications appear.

The progradation slope contains numerous gigantic blocks (dropstones) and we can observe in them collapsed layers-proving the collapsing, of the upper levels. The bottom of the progradation slope is marked by a thinner material that tends to be sandy and by a rectification of the layers, which become tangential. It is in the bottom part of the slope that numerous sedimentary figures are observed: more or less important slidings, large sized convolutions and current figures. These can show some directions contrary to the general flood, proving the existence of counter-currents coming from the bottom of the lake, towards the basis of the slope.

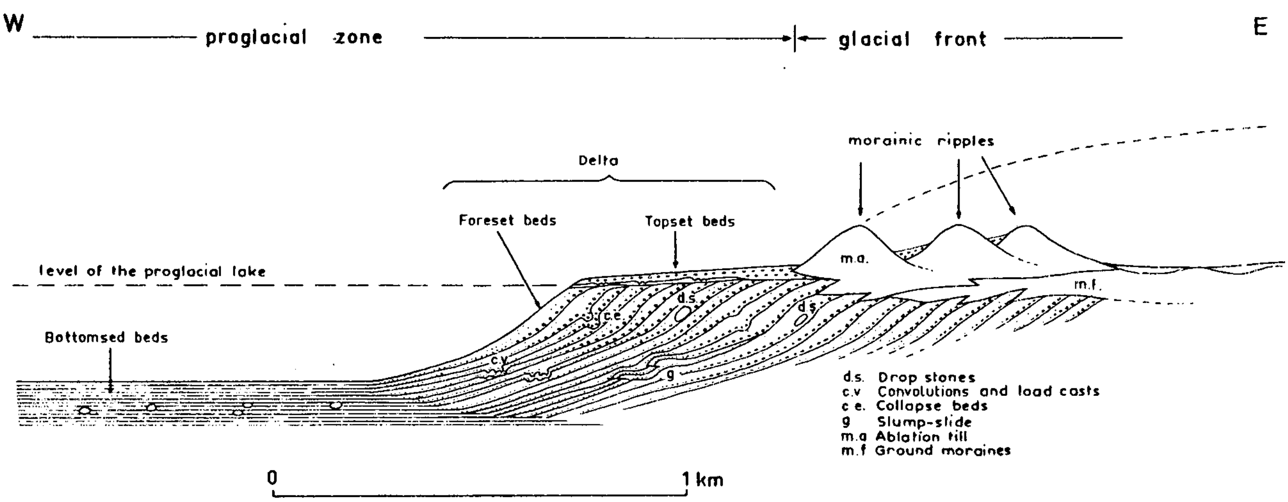

Figure 24. The sedimentary complex in the glacial lake contact.

The passage towards the bottom set beds is done progressively by a gradual slanting of the layers to the horizontal and by aquisition of the classical varved structure. Numerous huge blocks present in the varves prove the existence of many ice rafts floating at the surface of the lake and discharging their detritic burden when thawing.

This sedimentary complex was particularly well attested in the Combe d'Ain, which we used as a model for its rebuilding, but it exists in all the proglacial basins set forward in the western margin of the Jura range.

In each basin, some local particularities can happen, linked to the depth of the lake, to its longer or slower period of existence, to the proximity of the glacial front, but, roughly, each local type can be related to the sedimentary complex previously described. It constitutes one of the characteristics of the proglacial sedimentation of the Jura area.

We have also noted the possibility of a direct discharge of the glacial margin in a frank lacustrian environment. It is in this context that is developed the facies of the subaqueous tills attested in the southern part of the Combe d'Ain and in the area of Douncier-Villard on Ain. In this case, the proglacial cones exist only on the margin of the glacial neck, while the morainic facies become directly some varved facies, then containing a much more important proportion of drop-stones.

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