PLEISTOCENE VARVES AND RELATED SEDIMENTS

LAC DU TRIEVES, DRAC VALLEY, SOUTHEASTERN FRANCE

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ABSTRACT

A thick Wurm ll lacustrine section is preserved in the Drac Valley in the subalpine range approximately 50 km south of Grenoble. The sediments were formed during ice maximum, rather than minimum, by the simultaneous ponding of both the Bonne and Drac Rivers. A total of 170 m of lacustrine sediments are exposed overlying gravel terraces of two pre-Wurm valleys, which have been described by Lambert and Monjuvent (1968). Decomposition commenced with rapide accumulation of coarse and fine gravels, sands and silts constituting the lower 40 m of the section. Bedding features indicates deposition was predominantly by traction transport from moderate-energy currents. Sand deposition is succeeded by 130 m of varved clays which record at least 10.000 years of contineous sedimentation. Simple, complex, and drainage varves are described which indicate periodic variations of the rate of ice melt, and periodic spillower from adjacent lakes at higher elevations. Varve deposition was controlled by temperature and density variations throughout the lake which give rise to changes in varve character with increasing distance from the source area.

SOMMAIRE

VARVES PLEISTOCENES ET SEDIMENTS CONJOINTS
DU LAC DU TRIEVES, VALLEE DU DRAC,
SUD-EST DE LA FRANCE

Une épaisse formation lacustre Würm II subsiste dans la vallée du Drac, au sein des chaînes subalpines, 50 km environ au Sud de Grenoble. Les sédiments se sont formés au maximum de la glaciation, plutôt qu'au minimum, par le barrage glaciaire simultané des vallées de la Bonne et du Drac. Un total de 170 m de sédiments lacustres affleure au-dessus des terrasses caillouteuses de deux vallées prewürmiennes décrites par LAMBERT & MONJUVENT (1968). Le dépôt commence par une rapide accumulation de graviers grossiers et fins, sables et silts constituant les 40 m inférieurs de la séquence. Les figures de litage indiquent un transport et un dépôt essentiellement par des courants de traction d'énergie modérée. Le dépôt sableux est suivi par 130 m d'argiles varvées qui représentent au moins 10000 ans de sédimentation continue. Des varves simples, complexes et de drainage sont décrites, qui indiquent des variations périodiques du rythme de fusion de la glace et des déversements périodiques en provenance de lacs adjacents de niveau supérieur. Le dépôt et les caractéristiques des varves ont été contrôlés par les variations de température et de densité dans l'ensemble du lac, ainsi que par la distance des sources d'apport.

Les types de varves comprennent: (1) des paires de lamines claires et sombres typiques des varves classiques, d'une épaisseur moyenne del,5 cm; (2) des varves de drainage normalement épaisses (19,5 cm maximum); et (3) des varves complexes pouvant compter jusqu'à 15 couplets argiles-silts représentant le dépôt d'une seule année. La tendance attendue d'un amincissement des couches d'été vers l'aval du lac ne se fait apparemment pas jour. Les varves distales montrent une couche d'été plutôt plus épaisse, mais avec une plus grande proportion d'argile. Ce fait est interprété comme l'indication d'une stratification thermique directe dans la partie distale du lac, dont le résultat est un dépôt accru d'argiles pendant les mois d'été. De même une stratification inverse proche de la partie distale accroît les chances d'un courant profond intéressant l'ensemble du flux sédimentaire avec pour conséquence un dépôt rapide de l'argile.

INTRODUCTION

The Drac River occupies a valley in the Franch Alps between the Subalpine chains on the west (Vercors, Dévoluy) and the external crystalline massifs on the east (Belledonne, Taillefer, Quaro, Beaumont). Its course is cut into an area underlain by Jurassic and Cretaceous limestones and calcareous shales (marnes) in its lower reaches, but drains an area of Hercynian igneous and metamorphic rocks near its headwaters.

The valley of the Drac rests partly on bedrock and partly on terrace gravels which belong to two ancient, pre-Würm erosion cycles as described originally by Lory (1931) and later by Crosnier-Lecompte et al. (1953) and Lambert and Monjuvent (1968). These earlier valleys are labeled the Drac de Cros for the younger trace and Drac de Sinard for the older. They can be identified by outcrops of terrace gravels and bed load deposits encountered in drill holes near Sinard and La Motte d'Aveillans (Haudour, 1961).

The gravels are overlain by a considerable thickness of lacustrine clays and sands in the region between Monteynard and Corps (Fig.1) and, in turn, by a thin, discontinuous layer of Wurm till. The earliest descriptions of Pleistocene stratigraphy (e.g. Penk and Bruckner, 1907) labeled the entire section as till of Wurm age and this interpretation has persisted until fairly recently on published maps of the region. However, studies by Lambert and Monjuvent (1968), Monjuvent (1969, 1973) and Huff (1974) have shown the existence of a thick section of lacustrine clays with some interbedded sands overlying the terrace gravels and in turn partly overlain by till and have suggested that an age of Wurm II be assigned to it. Stratigraphic evidence indicates the lake existed as one of three large glacial maximum lakes whose locations

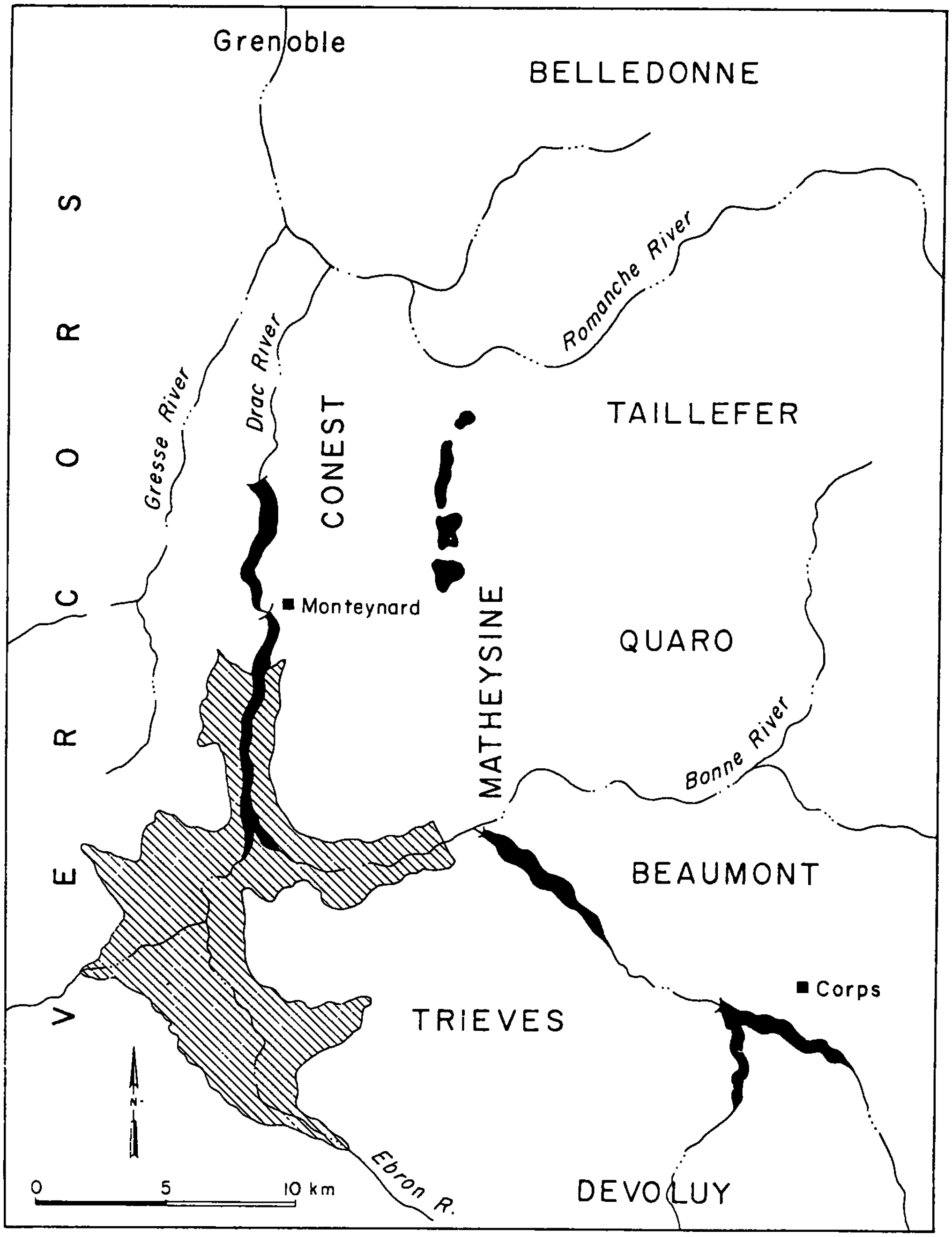

Figure 1 Location map of the study area. Areas in black représent presnt-day reservoirs. Shadded area shows the outline of Lac du Trièves during Wurm II maximum.

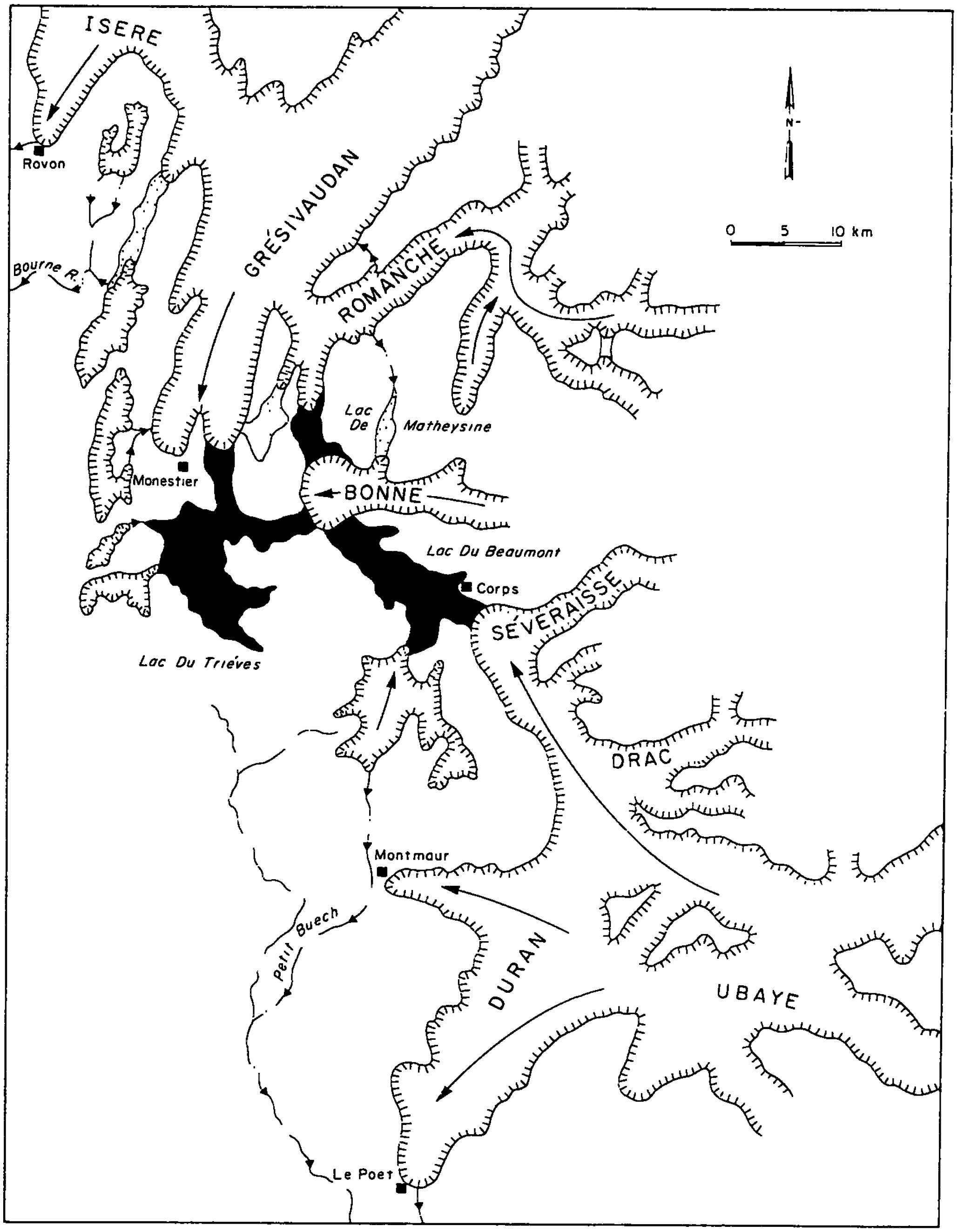

Figure 2 Positions of the Severaisse, Bonne and Gresivaudan ice tongues during the Wurm II maximum. Present towns and drainage are shown for references. Three lakes thought to have been ponded simultaneously at separate elevations are shown in black (after Monjuvent, 1973)

were determined by blocking of preexisting drainage. North-flowing drainage by the Drac and its tributaries was interrupted by the southward moving Gresivaudan ice tongue which followed the present course of Isere River, and the Romanche and Bonne ice tongues from the crystalline massifs to the east (Fig.2).

The sediments in these lakes represent conditions existing during glacial maximum time rather than during periods of glacial retreat or during interglacial intervals. Following withdrawal of Wurm ice the lakes draining and the present course of the Drac and its tributaries was established. Recently several reservoirs have been constructed along the Drac to provide hydroelectric power as well as recreation facilities. The consequent elevation of the water table has caused numerous slides in the glacial clays and has greatly increased the number of exposures. Of the three lakes shown in Fig.2, lac du Trièves, Lac du Beaumont and Lac de la Matheysine, the first, Lac du Trièves, affords the best exposures because of the recent landsliding along that portion of the Drac valley and consequently will be considered in detail in this report.

METHODS

Studies of the mechanism of clay deposition were made by measuring vertical sections of laminated clays on a layer-by-layer scale to first determine the degree to which varves had developed, and then making comparisons between laminated sections exposed in different parts of the drained lake bottom. Selected grain size' analyses of several clay-silt laminae pairs were made as well as carbonate composition and clay mineral content. Coarse silt and fine sand laminae occasionally displayed cross-bedding which was measured and plotted in an effort to show sediment dispersal patterns.

BASAL SANDS AND GRAVELS

The basal 40 m of lacustrine sediments are composed of coarse and fine gravels with interbedded layers of well-sorted, cross bedded sands (Fig.3). These sediments are best exposed at Savel where they unconformably overlie Wurm II till just above road level at an elevation of 520 m, and continue up to the first prominent sand bed at 560 m. Between 560-600 m the section consists of well sorted, massive (1-2 m thick) fine sand layers interbedded with laminated clays and silts. Above 600 m there are few sands and the section consists almost entirely of varved clays.

Cross bedding measurements in the sands (Fig.4) indicate axially oriented transport directions with one and perhaps two point sources of sand dispersal. The sequence is typical of glacio-lacustrine basin-fill sediments which are characterized by the onset of fluvio-deltaïc sands and silts in the early stage and give way to more quiet-water deposits as the lake level continues to rise (Atwater, 1986).

There are eleven major (0, 3-2 m thick) sand beds between 560-600 m elevation. Some portions of several beds are graded, but for the most part internal structures consist dominantly of cross-bedding and ripple-drift cross-lamination. Typically, these are small scale bed forms about 2-7 cm in amplitude which have been eroded on the stoss side and interfinger with clay-rich trough deposits on the lee side (Fig.5). These would be classified as Type 1 cross-laminations according to Walker (1963). He interprets the similitary in thickness of individual sets, the thickness of individual laminae and the angles of climbing of one ripple onto the next as indicating a constant supply of sediment directly from suspension in addition to heavy bed load movement. Mud fillings in the trough are due to periodic slackening of the current during hydrodynamic fluctuation of the environment. However, flow rates were not reduced enough to preserve stoss side laminae and the beds are considered to be the result of rapid and fairly constant traction or bed-load transport, rather than turbidity currents. Further evidence of bed-load transport is provided by the sharp basal contacts of the sand beds and the well preserved ripple bed forms on top (Figs. 6 and 7). Both cross-sectional and perpendicular views of distal ripple-draft laminae similarly indicate traction deposition (Figs 8 and 9).

Basal load forms and internal deformation in the sand layers are common and indicate deposition on unconsolidated clay surfaces in the former case and penecontemporaneous deformation associated with dewatering and/or slumping in the latter. The syndepositional timing of deformation is indicated by the undisturbed clays overlying convoluted.layers.

DESCRIPTION OF THE CLAYS

The first recognition of glacial lacustrine clays in the Drac Valley was made be Lory (1931) who interpreted them as a morainic facies of Wurm maximum glaciation. THe view was repeated by Gignoux and Moret (1952) and Bourdier (1962), although Gignoux and Moret suggested that the lacustrine aspect of the clays might indicate some form of subglacial deposition during stagnant intervals. Moret (1934) reported a carbon 14 age from a pine tree fragment found in the so-called Eybens clays, a very similar appearing clayey section near Grenoble which has been quarried for years for the manufacture of roofing tiles. He found they were at least 37.000 years old and hence labeled them Riss-Wurm interglacial deposits. They were described as "probably varved", that is, seasonal but not quite in the same sense as the classic Scandinavian varves.

The widespread clays of the Drac valley were studied in some detail by Lambert and Monjuvent (1968) during regional mapping of the area and are described as lacustrine clays of Wurm II age. Their reconstruction of late Pleistocene events in the Drac valley, beginning with the oldest, is as fallows:

1- Pre-Wurmian glaciation (probably Riss) evidenced by a few, large crystalline boulders and occasional, well-leached till beneath the oldest alluvial deposits.

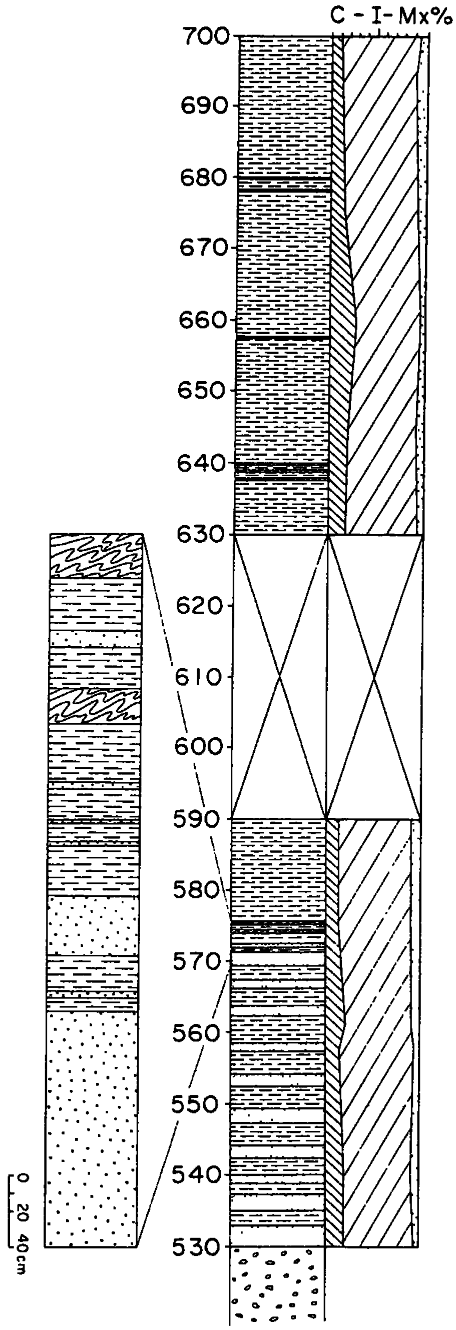

Figure 3 Composite stratigraphic section of lacustrine sediments as exposed near Villarnet. The vertical scale is in meters while the expanded portion between 570-580 m illustrates some details of the sand and clay interbedding. The section between 590-630 m is covered by vegetation. Relative abundances of chlorite, illite and mixed-layer clays is shown schematically on the right (from HUFF, 1974).

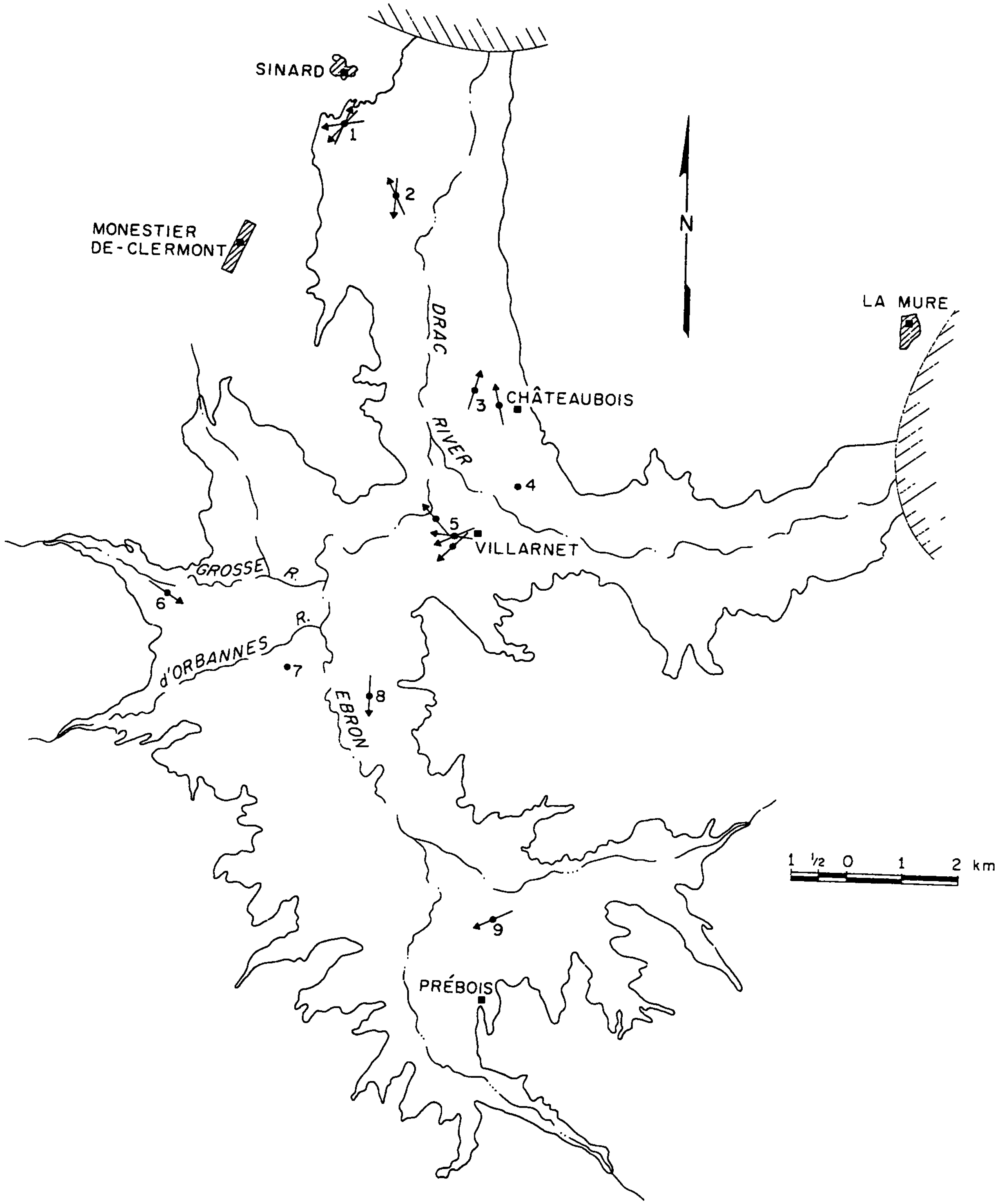

Figure 4 Distribution of detailled sampling localities described in text. Arrows represent mean transport direction of sands and silts as determined by cross-bedding measurements.

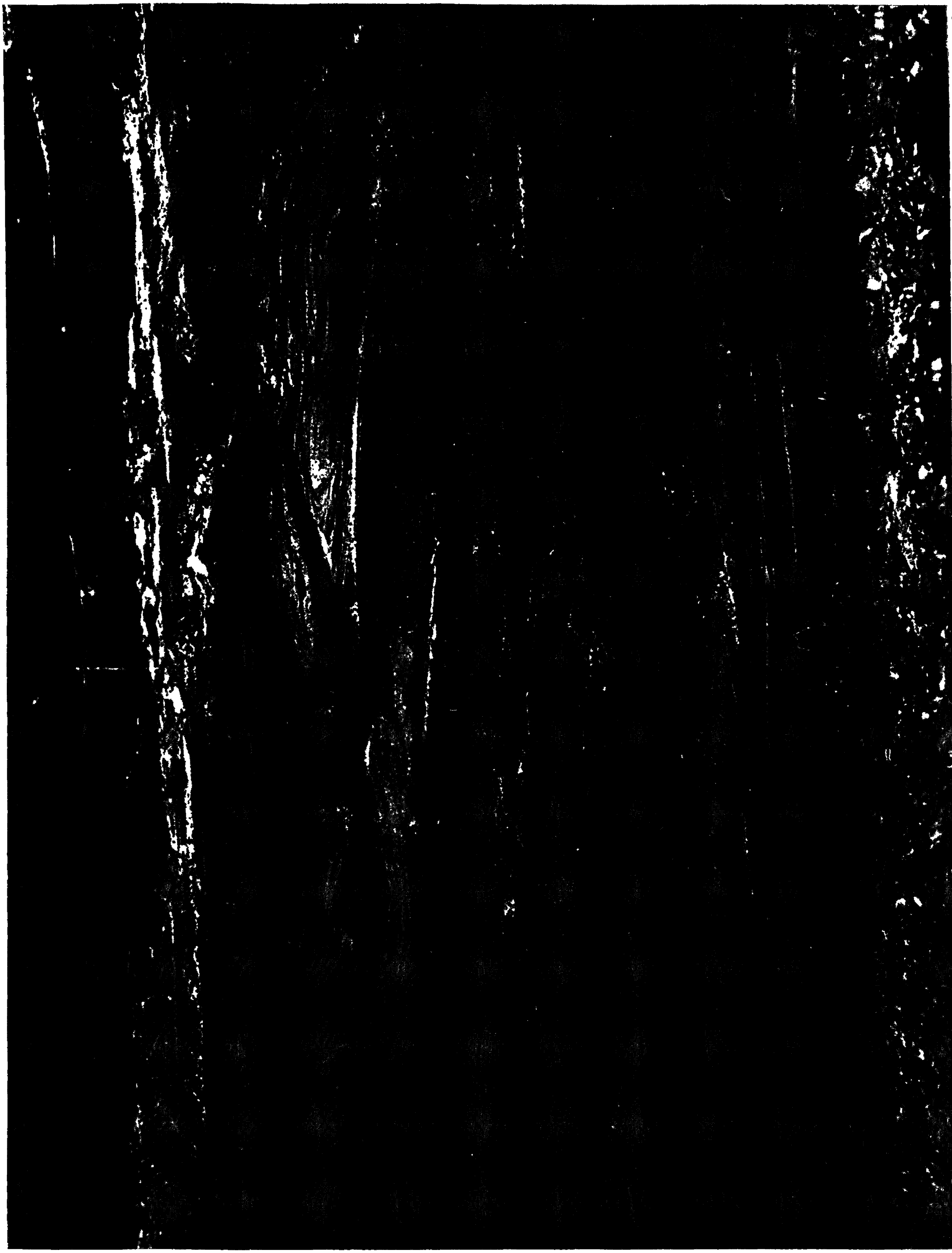

Figure 5 A 26 cm sand bed near the base of the section at Combe de la Poya. Ripple-drift cross-lamination indicates current from the right with truncation of laminae on the stoss side. The top of the unit has been deformed by penecontemporaneous slumping.

Figure 6 A 4 cm sand bed with well-preserved internal cross-stratification from the upper part of the section at Vıllarnet. Preserved bed-forms on the upper surface and a sharp basal contact with the underlying clay indicate relatıvely low-energy, traction flow-deposition.

Figure 7 The same bed shown in Fig.5 at a smaller scale. The final pulse of sand transport is preserved by asymmetrical bedforms. Succeeding clay deposition occured under low energy conditions.

Figure 8 Feathe-edge sand rıpples represent final deposıtıon at the distal end of a traction-load lamina. These layers often merge with the sılt bands in varve couplets and may represent the mechanism by which all summer layers are deposited.

Figure 9 View perpendicular to the bedding surface showing the scalloped arrangement of ripple-drift cross-laminae. Transport was from the left. Camera lens cap for scale is 4 cm in diameter.

Figure 10 A 2 cm fine sand layer overlying a discontinuous, lobate silt bed which has been deformed downward into the underlying clay by compaction and/or remobilization of the unconsolidated sediment. Preservation of cross stratification in individual lobes indicates they remained largely intact during deformation.

Figure 11 Penecontemporaneous deformation of a silty-clay bed 30 cm thick near the base of the section at Combe de la Pouya. Underlying sediments were disturbed only slightly and the overlying beds occur in sharp contact.

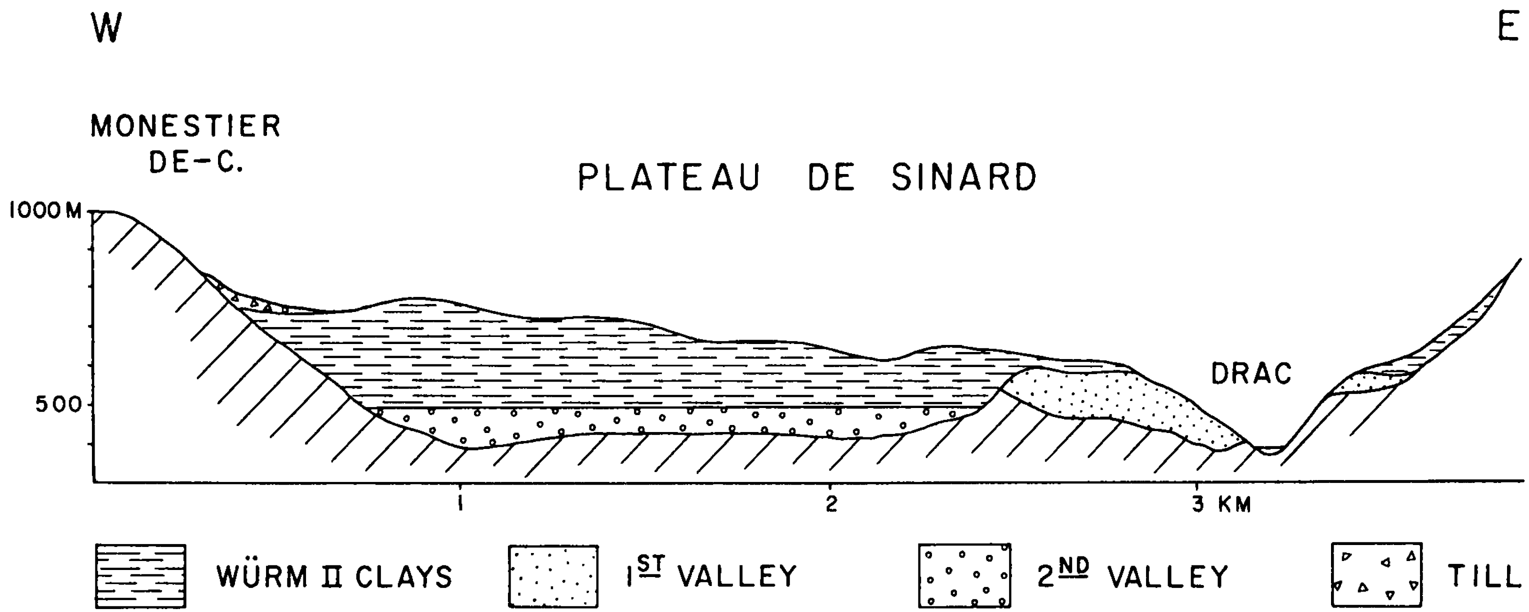

Figure 12 Cross section of the Plateau de Sinard showing preserved portion of both prelacustrine valleys (Lambert and Monjuvent, 1968).

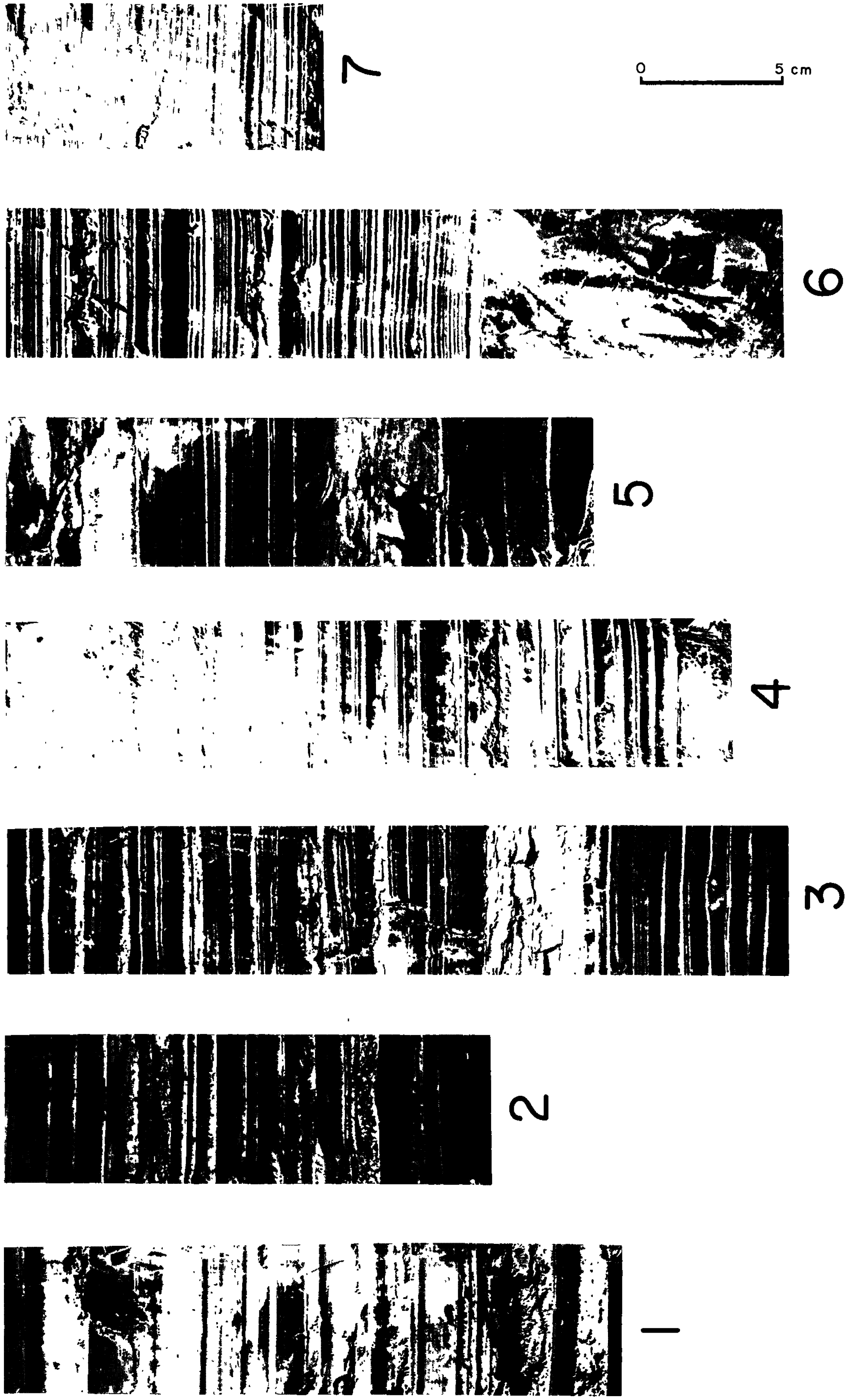

Figure 13 Examples of the various types of simple, complex and drainage varves described in the text. Localities are, 1/ Sinard, 2-3/ Villarnet, 4-5/ Chateaubois, 6-7/ D'Orbannes River.

2. Excavation of the older valley, Drac de Sinard, with the formation of terrace gravels at an elevation of 610 m near Sinard (Fig.12).

3- Excavation of the younger valley, Drac de Cros and the formation of terrace gravels at an elevation of 520 m near Sinard.

4- Ponding of Drac valley drainage between the downstream movement of the Drac and Severaisse ice tongues and the upstream extension of the much larger Gresivaudan tongue to the North (Fig.2). The level of water in this lake can be judged by the height of deltaïc sands and gravels in the vicinity of Corps where they are found at 850 meters. These sediments interfinger upstream with till and downstream with lacustrine clays and silts.

5- Final advance of Wurm ice leaving a surficial cover of till over lacustrine sediments at Sinard and cutting the through of Gresivaudan even deeper.

6- Retreat of Wurm ice with the formation of additional small lakes trapped behind recessional moraines upstream from Corps.

Reexamination of sediments deposited during the maximum development of Drac valley ponding demonstrates an even greater impotance of the intervention of the Bonne glacial tongue. Glacial clays and deltaïc silts are found at 850 m near Corps, indicating water level near that elevation. But below the confluence of the Bonne and Drac rivers, south of La Mure, lacustrine clays reach an elevation of only 760 m and interfinger with deltaïc sands which extend up to about 780 m. So it is probable that water level below the Bonne glacier was not higher than 800 m while above, toward Corps, it was at least 850 m. This apparently created two lakes in close proximaty with considerable difference in elevation between them. It will be shown later that periodic spill over from the higher Lac Beaumont to the lower Lac du Trieves was fairly common.

Close inspection of the Drac Valley clays leaves no doubt of their lacustrine origin. They are thinly laminated and varved, dark bluishgray, plastic clays interbedded with fine silts, silty clays, and occasionally fine sands. Figure 3 shows a composite section from several outcrops near Villaret. The lower contact with terrace gravels is in places transitional and in others fairly abrupt, suggesting a logical incorporation of fluvial sediments in the earliest stages of lacustrine sedimentation.

Periodic horizons of convoluted clays and silty clays are found throughout the section and in all parts of the study area. They range from slightly disturbed laminated clays and silts which have been thrown into a series od asymmetric folds whose axes are inclined generally toward the center of the lake basin, to completely distorted zones in which all original sense of bedding and lamination has been destroyed. In all cases these distorted zones are immediately overlain again by laminated clays and silts which have not been involved in the disturbance indicating and in many cases actually truncating folded horizons below. This indicates the disturbance was a contemporaneous phenomenon which occured at the sediment water interface, probably involving slumping due to sediment overloading or thixotropy due to differential rates of dewatering of silt and clay layers, or both.

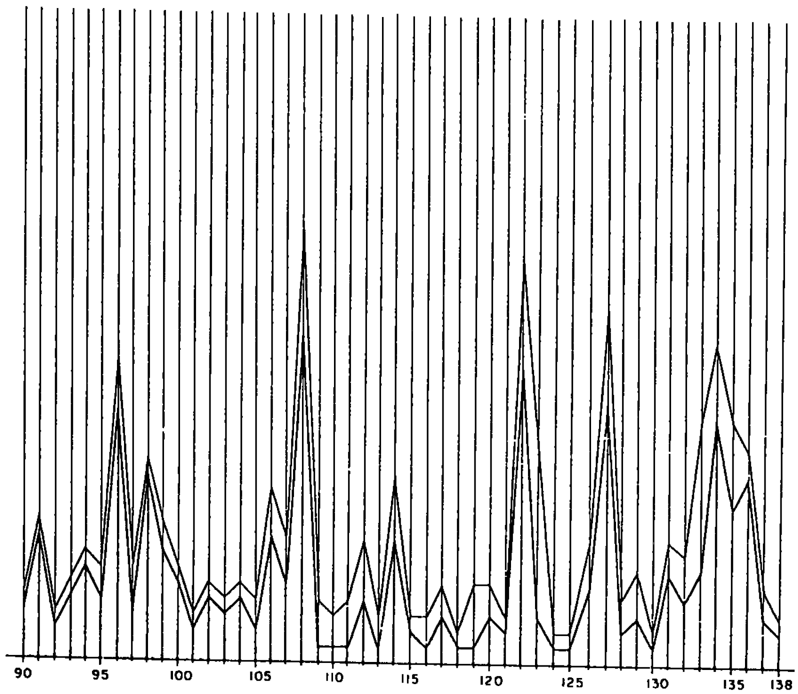

Figure 14 Varve plot of summer-dominated varves at Sinard. The numerical scale is in centimeters, recording successive varves downward as numbers increase. The vertical scale is exaggerated five time and records summer (shaded) and winter (unshaded) varve thickness at each cm interval.

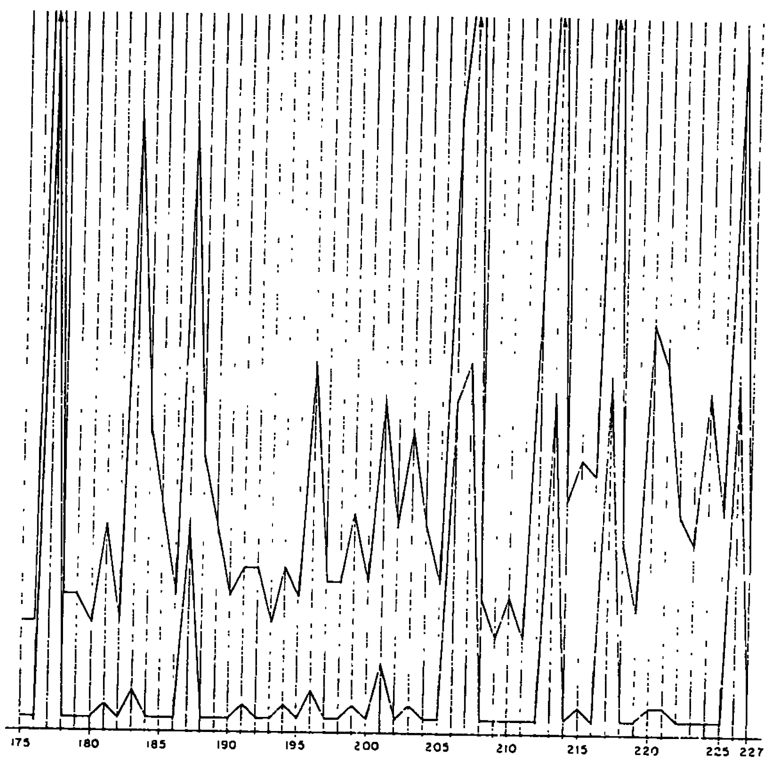

Figure 15 Varve plot showing well-developed drainage varves at Chateaubois. Sea text for discussion.

Similar features have been described previously in the literature on Quaternary lacustrine sedimentation (e.g. Legget and Bartley, 1953; Mathews, 1956; Smith, 1959; Hyne, 1972).

The nature of lamination within the clays varies from what might be called simple annual varves to complex varves containing laminae representing depositional periodicities of less than one year (Agterberg and Banerjee, 1969). For the most part individual laminae are remarkably uniform in the distal portions of the deposit, but less so nearer the upstream margin of ice contact and presumed sediment source.

Continuous exposures are not available that might allow correlation of individual laminae for more than a few tens of meters. However, some idea of the lateral variation in the character of varves can be obtained by descriptions of particular localities where good exposures do exist.

Sinard - locality 1 in Figure 4 - is a commerical clay pit located at the nothernmost part of the former lake near the downstream contact with the Gresivaudan ice tongue. It is located at an elevation of 750 meters which places it at the highest point of any preserved sediments in this segment.

Three hundred fifty varve pairs were counted at this locality averaging 1, 2 cm in thickness with the maximum being 4,1 cm (table 1). They appear to be of both the simple, Scandinavian type, as well as complex, with the incorporation of very thin silty layers within the winter clay sediment (Fig.13). Occasionally these silty intercalations appear at the base of the darker, clay portion, but more commonly they occur near the top. Contacts, for the most part, between summer and winter segments are sharp rather than gradational, and the lighter-colored summer layers tend to be thicker. The average sumer thickness is 0,7 cm and the average winter thickness is 0,5, giving a summer/winter ratio Of 1,4 (table 1). Figure 14 illustrates a portion of these varves measured at Sinard, specifically, numbers 90 through 138. They are plotted with the vertical scale five times the horizotal to bring out differences in varves thickness. The shaded area represents the thickness of light-colored, silty layers, generally considered to represent sediments deposited during intervals of melting in the spring or early summer of the year, and the open area indicates the thickness of the dark layers which are taken to represent the much slower accumulation of fine clays during period of freezing. The varves are dominated by the summer layer, probably as a consequence of their proximity to the northernmost source.

Chateaubois - locality 3 in figure 4 - lies along a deep ravine eroded into the thick clays. As in most cases the exposed clays have been covered with a thick layer of debris carried by sheet-wash and require considerable excavation in order to reveal undisturbed material.

Varved clays were exposed and measured at two stations, one at 660 meters and the other at 600 meters. The upper section was given the most attention because of the variability of varves types and thickness. Six hundred forty-four individual pairs were measured averaging 1,7 cm in thickness (table 1). Columns 4 and 5 in Figure 13 are from this section and figure 15 illustrates thickness variability between varves 175 and 227. Particulary noticeable in this section are two aspects of the Drac valley deposits: the appearance of multiple groups of extraordinarily thick varves and the tendency for many varves to have numerous small silt clay couplets interbedded in them. A typical, complete rhythmic unit here begins with a 1mm silt at the base followed by 0,5 - 1,0 cm maroon or bluish-gray clay, followed in turn by 1 to 3 couplets of silt and green clay averaging 1mm in thickness. Seldom are there no couplets in this 10 meter section, and some varves have as many as 15. Individual couplets probably represent short-term climatic fluctuations during the course of one year.

Thick varves, reaching a maximum of 19,5 cm appear for the most part to have unusually thick silt and clay layers together, and only occasionally show increased clay thickness accompanied by very thin silts. These have been interpreted by earlier workers (Waitt, 1964; Atwater, 1986) as drainage varves representing periodic overflow from basins at higher elevations. These units tend to be grouped within a range of 100 or so varves and to be separated from similar groups by varve series of fairly low amplitude, such as the series 90-138 shown in Figure 16.

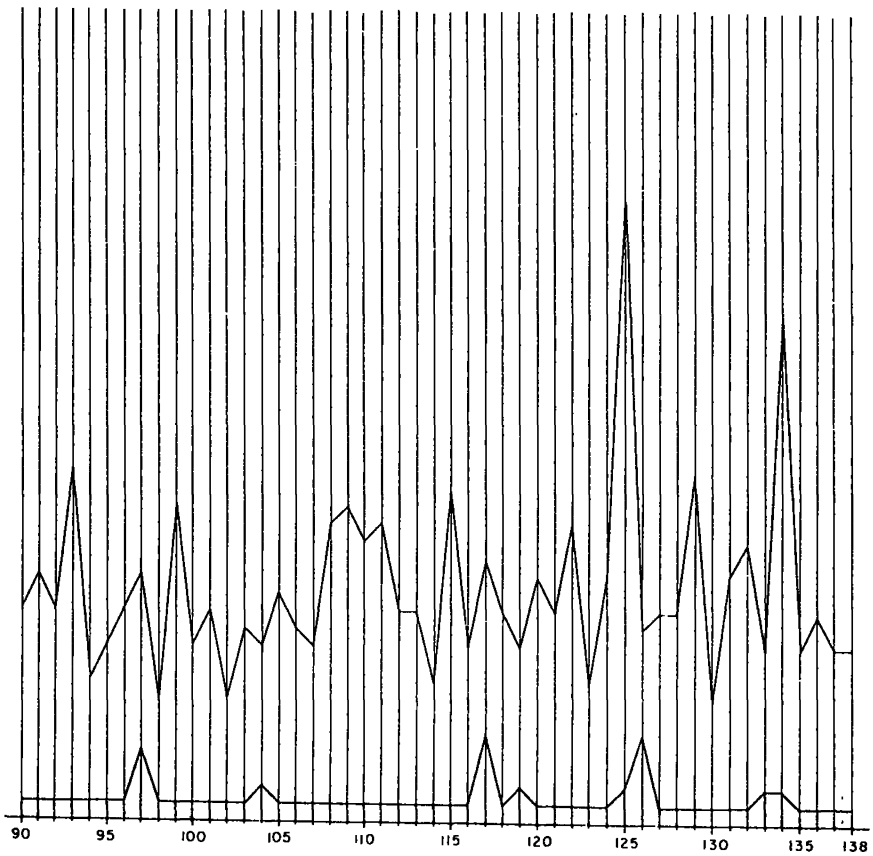

Figure 16 Winter-dominated distal varves along the d'Orbannes River. Summer (shaded) and winter (unshaded) beds are dominant.

Villarnet - This section at location 5 in Figure 4 is one of the most complete exposures in the entire basin due to recent landsliding. The total vertical exposure is 170 meters of which the basal 40 meters are dominated by massive sand layers as much as 2 meters thick. Ninety varves were counted at the 670 m level. Their average thickness (table 1) is 1,5 cm with the maximum thickness being 12,2 cm and the ratio of summer to winter layers 0,33. Varve types are illustrated in columns 2 and 3 of Figure 13. They include simple and complex diatactic varves with an average of 2 couplets and a maximum of 5 in the latter. Many individual layers contain small pebbles and fragments of sandy till which were apparently rafted into the lake during periods of melting.

D'Orbannes River - This locality is number 7 in Figure 4 and includes only a few meters of varved clays overlying high fluvial gravels. Individual laminae are for the most part quite thin averaging 0,4 cm with a maximum out of 126 varves measured of 1,3 cm (table 1). The summer-winter ratio has the highest value of any of the sections measured, however 1,5. Columns 6 and 7 in Figure 13 illustrate this particular section. It becomes increasingly difficult to distinguish between very thin, complete varves and what have been referred to earlier as couplets incorporated within varves in this kind of situation. The best guide seems to be the regularity or periodicity of repeat units based on a slightly thicker winter clay with thin silt zones near the top. Also for many varves there is a slight amount of gradation from silt to clay in the main part of the varves whereas individual couplets have sharp contact above and below.

Pompe Chaude - This locality is number 9 in Figure 4 and is located in one of the most distal parts of the basin. Varves development is very irregular here with a poor distinction between true varves and simply laminated clays. Fifty nine varves were counted in a section which seemed to display the best development at an elevation of 700 m. These varves are, for the most part, complex with an average of 3 silt-clays couplets per varve and a maximum of 6. Cross bedding measurements weakly developed in a few drainage varves provide some data on current directions as shown in Figure 4.

DISCUSSION OF VARVE DEPOSITION

The nature of varve formation in sediments is mainly based on the periodicity of single units, and in this case with a repeat interval of on year. When the therm "varve" is used, therefore, it carries definite genetic connotations with rather precise meanings. And these meanings are always subject to the closest scrutiny as regards any real evidence that they are justified.

Excellent summaries of the development of thinking about seasonal banding in glacial sediments have been published beginning with Sayles (1919) and including De Geer (1912), Sauramo (1923), Anderson (1928) and Antevs (1925). Specific, detailed studies have expanded these ideas further such as those by Rittenhouse (1934), Fraser (1929), Antevs (1951), Legget and Bartley (1953) and Agterberg and Banerjee (1969).

The amount of ice melting is perhaps the most obvious factor in determining the silt clay ratio. A high melting rate produces large quantities of mud and a wide zone of cold water which may, during summer months, occupy the upper levels of on alpine lake, producing inverse stratification. This aspect can be very important if it is responsible for keeping large quantities od suspended clay from reaching the bottom. Subsequent winter deposits would be depleted in clay and enriched in the coarser silts which are carried in traction close to the bottom in a manner similar to that described by Houbolt and Jonker (1968) for sediments in Lake Leman.

A second factor related to this is the nature of thermal stratification in the lake. Antevs (1951) points out for example, the mud transport in glacial lake Jonhson occured in semistratified water near the ice contact. Much clay was carried down to lower depths and sorted for winter deposition in the central, isothermal portion of the lake. In the distal, stratified zone clay was transported in the upper water strata and stored in the lower.

A third factor is the distance between the terminus of the melting ice and the lake margin, and a fourth is the extent of retainment or trapping of mud in nearby basins. In the case of upstream basins periodic overflow into a lower basin may result in the formation of extraordinarily thick varves referred to as drainage varves. These many occur due to the breaching of an ice barrier or the failure of an earth barrier separating two adjacent lake basins.

A comparison of the particle size distribution curves of several Drac Valley varves with data from other sources (Fig.17) shows curves for three samples, two from Chateaubois and on from Sinard, plotted against data from Ballivy et al. (1971) and Legget and Bartley (1953). The curves are in general agreement with those of other workers showing slightly coarser texture in the summer or silty horizon compared to the winter one. For must of the Drac Valley varves the term diatactic seems to fit better than symmict, at least insofar as these terms were defined by Sauramo (1923). Contacts between light and dark layers are sharp with no evidence of gradation. Some of the Sinard varves do appear to contain more clay in the light layers than is found in the upstream direction near Chateaubois or Villarnet.

Carbonate analyses of the two Chateaubois specimens plotted in Figure 17 indicate higher proportions occur in the light layers than in the dark. For sample DC 13 the light layer has 26,4 percent and the dark layer 14,2 percent. For sample DC 14 the light layer has 27,4 percent and the dark layer 22,4 percent. This is in agreement with the observations of some early workers who felt that increased carbonate content in alpine lake waters during warmer periods of the summer could aid in flocculation of fine suspended particles thereby increasing summer layer thicknesses (Burwash, 1938).

As far as distance from ice front to lake margin may be concerned, the section at Villarnet (Fig. 3) suggests a close proximity to ice during the time of deposition of the basal 40 meters of sediment. The abundance of thick, cross-bedded sands separated by intervals of varved and laminated clays interbedded with thin sands having sharp contact both above and below is quite similar to lacustrine deltaic sediments described elsewhere by Houbolt and Jonker (1968) and Coleman (1966). The cessation of this pattern above the 570 m level suggests either a retreat of the ice to a more distant point or the intervention of some sort of sedimenation barrier, or both.

Detailed mapping of Wurm deposits in the vicinity of La Mure by Monjuvent (1973) indicates a tongue of ice occupying the Bonne River valley reached the confluence with the Drac River drainage sometime after the initiation of deposition in Lac du Trièves. Its immediate effect was it interrupt direct flow from the main Drac and Severaisse ice tongues (Fig. 2) and cause a second, higher level ponding known as the Lac du Beaumont. A third, smaller lake (Lac de Matheysine) was also formed at this time. This interpretation most reasonably explains the appearance of a substantiel number of unusually thick varves such as those diagrammed in Figure 15 from the section at Chateaubois. These are interpreted as drainage varves in the same sense as those described by Antevs (1951). That is, deposits representing sudden breaching oroverflow from proximal basins during single seasonal intervals. They are paired layers and in most respects resemble the normal varves of 1-3cm in thickness.

Some drainage varves contain faint laminations within the clayey interval indicating they were probably deposited in a series of heavy mud flow rather than by a process of continuous sedimentation. The deposition of mud in alpine lakes has not been thoroughly studied , but available evidence indicates the thermal characteristics of the lake water are particulary important, as is the rate of release of mud from melting ice. In the latter case, Rainwater and Guy (1961) cite an example of variable clay release in their studies of the Chamberlin Glacier in Alaska. They note that during a single 24 hour period the concentration of suspended clay ranges from approximately 305 ppm at 4:00 pm to 14 ppm at 6:00 am. Silt release is also highest at 4:00 pm and lowest at 6:00 am. Such diurnal variations may or may not be preserved that can exist in this type of sedimentary environment.

Varves which Antevs (1951) and others refer to as complex varves are quite common. Usually, it is the clayey portion of a single varve which contains numerous small silt-clay couplets referred to earlier. Occasionally clay laminae appear within silty layers also. Such couplets record intervals of temporary weather fluctuation in which melting may accelerate momentarily, then receded, such as an early spring thaw or a sudden storm. A maximum of 15 couplets was recorded for a single varve at Chateaubois, but evidence is lacking as to whether the time intervals represented are days, weeks, or months.

Thermal characteristics of lake water determine density and viscosity value and thus are important in controlling the rate of clay sedimentation. Data on this aspect of glacial lakes is scanty though some attempt has been made to compile existing information by previous authors. The earliest studies of French alpine lakes were made by Forel (1892, 1895) and Delebecque (1898), and established, in the case of Lake Leman, a correlation between the density of sediment laden water entering from the Rhône and the level of their distribution according to the thermally dependent density of lake water. Houbolt and Jonker (1968)

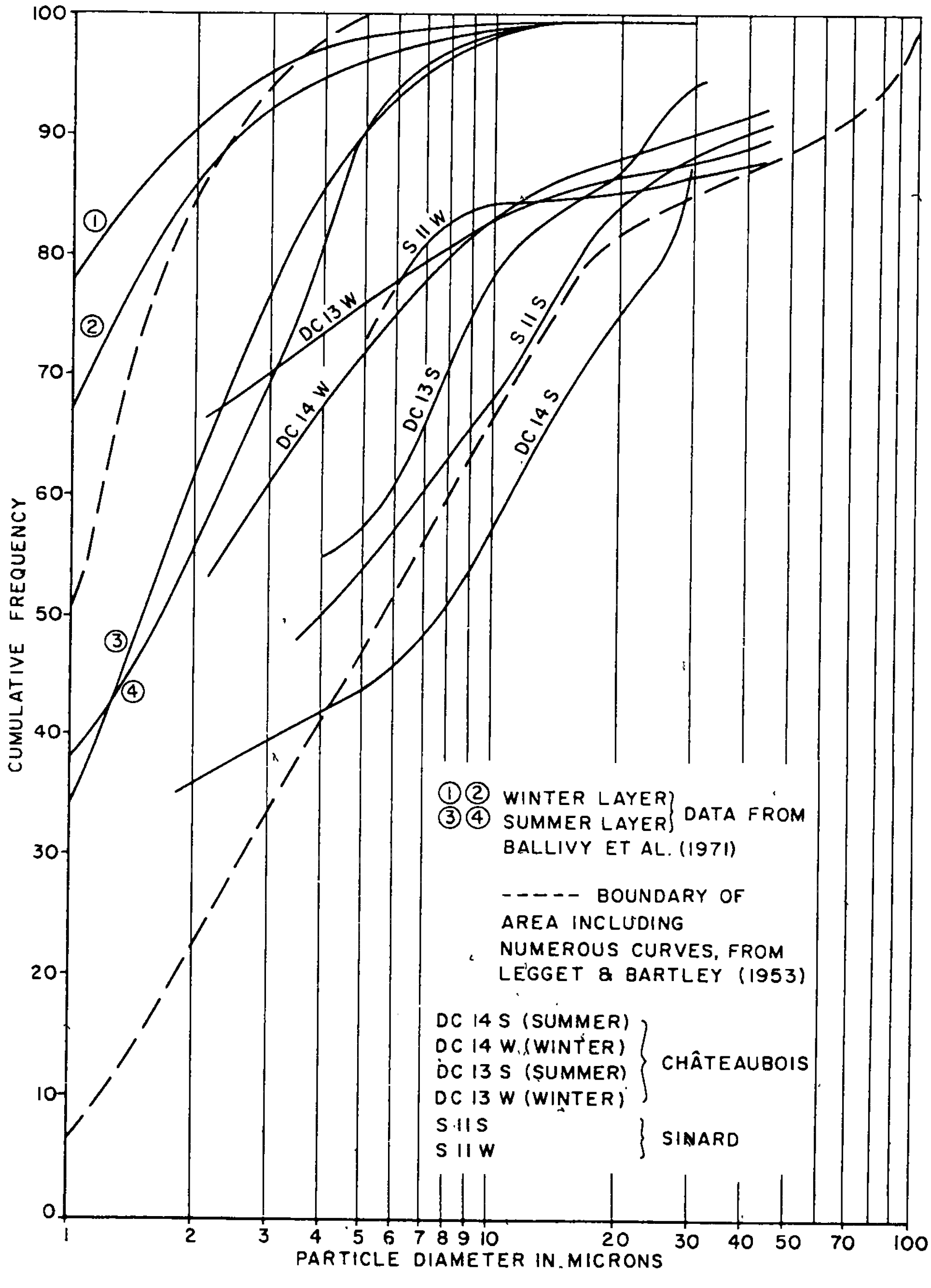

Figure 17 Particle-size distribution curves for summer and winter layers compared with similar date reported by Vallivy et al. (1971) and Legget and Bartley (1953).

add more detail to that information by distinguishing between traction transport of sand along the lake bottom and density transport of clay along the thermocline. They report recognizable turbidite characteristics.

Hutchison (1957) distinguished between dimictic lakes, those circulating twice a year being inversely stratified in winter and directly stratified in summer; monomictic lakes in which winter circulation occurs when insolation causes surface temperatures to rise above 4°C; and cold monomictic lakes in which surface temperatures remain below 4°C the year around and circulation occurs only at the height of the summer. Some of the large subalpine lakes are monomictic such as Lake Lucerne and Lake Lugano, while others such as Lake Constance and Lake Leman are dimictic. The effects of altitude on water temperature are essentially the same as those related to latitude. Hutchison reports that in the Central European Alps between 44°N and 48°N some small lakes between 2100 and 2900 m elevation are cold monomictic. These are associated with glacier margins or snowfields. Other lakes in the same region but not associated with glacial meltwater have surface temperatures up to 16°C. Other, scattered studies by Kindle (1930), Mathews (1956), Hattersley-Smith and Serson (1964), and Gilbert (1971) tend to confirm that glacial lakes are cold monomictic.

Fine clay particles spread over the surface of proglacial lake will probably take much more than a single season to reach bottom, whereas clay-rich density currents traveling close to the lake bottom may deposit large amounts of clay in relatively short periods of time.

Cross-bedding indicates the dominant sediment source was from the upstream direction, and only lesser amounts were contributed from local tributary streams or from the Gresivaudan ice tongue moving upstream from the direction of the Isere Valley. Comparison of silt and sand layers from different portions of the lake basin show that only the very finest silts were carried as far as Sinard and that most coarse sand and silt layers merge into zones of cross-bedded lenses. In three dimensions these appear as dunes, some developes in succession on the same level and others expressed as ripple-drift cross-lamination. Such lenticular bedding was interpreted by Reyneck and Wunderlich (1969)and by Jopling and Walker (1968) as related to fluctuations in current velocity and variations in concentration and composition of suspended sediment. In marine environments such bedding is produced by alternation of wave action and slack water, whereas in lakes and lagoons it is the result of sediment and current pulses issuing from a source area, frequently a delta front. Kuenen (1951) suggested varve formation may be dominantly a turbidity current process, with surface spreading of fine clays responsible for only the ultra distal deposits. In this study there is little evidence to suggest varves formed by this mechanism, altough distal varves such as those at Sinard do appear to have more clay-rich summer layers giving rise to apparent thickening of summer deposits (Fig.8) compared with varves formed nearer the proximal end. It would seem more reasonable that the process, while definitely related to seasonal variation, depends upon sand silt and clay separation from cold meltwater by the development of a thermocline in a cold monomictic lake thereby allowing for traction transport of sand-silt and diffusion transport of suspended clay. Some surface spreading of clay also occured, much of which may have by-passed the basin completely through drainage outlets at the distal end, and the remainder which sttled slowly enough to be incorporated with the fine summer silts as well as forming winter clays at the distal end.

AGE AND DURATION OD DEPOSITION

Table 1 presents mean thicknesses of varves measured at six separate locations within the lake basin. Thicknesses vary with distance from the source areas but nevertheless are fairly consistent throughout the area and average 1,3 cm. A first approximation of depositional duration can be obtained by simply dividing total clay thickness by the average number of varves. The basal 40m of the section consists of sands and gravels which undoubtedly accumulated at a much higher rate than the rest of the section. So if that portion is removed from the maximum of 170 m and the remainder divided by 1,3 the deposition is 10.000 yr. Some clays occur in the basal 40 m along with the coarser clastics so this figure might be considered a minimum estimate. If the underlying terrace gravels are Wurm II maximum as suggested by Lambert and Monjuvent (1968), then the base of the lacustrine section is dated between 40,000 - 50,000 yr. and the top between 30,000 - 40,000 yr.

SUMMARY

1. Varved clay, silt and sand was deposited in the ice-dammed drainage of the Drac River during Wurm II maximum glaciation. Type of varves includes (1) pairs of light and dark laminae typical of classical varves and averaging about 1,5 cm in thickness; (2) abnormally thick drainage varves (max. 19,5 cm); and (3) complex varves with as many as 15 clay-silt couplets included within a single, annual deposit.

2. The expected tendency for thinning of summer layers toward the distal end of the lake apparently does not occur. Rather, distal varves have thicker summer components but containing greater amounts of clay. This is interpreted as an indication of direct thermal stratification at the distal end resulting in greater clay deposition during summer months. Inverse stratification near the distal end increased the chance of under-flow of the total incoming sediment load the consequent rapide deposition of clay.

3. Maximum thickness of the sediment was about 170m and extrapolation of varve-count indicates a probables maximum life span for the lake of about 10,000 yr.

TABLE J. Varve Thicknesses at Selected Sites in Lac du Trieves

Location (elevation)	total varves counted	maximum thickness for single varve (cm)	mean thickness for single varve (cm)	maximum summer thickness (cm)	mean summer thickness (cm)	maximum winter thickness (cm)	mean winter thickness (cm)	summer-winter ratio	distance from source (km)
Sinard (750 m)	350	4.1	1.2	2.6	0.7	3.1	0.5	1.4	18.0
Chateaubois (660 m)	644	19.5	1.7	12.5	0.2	16.0	1.3	0.23	12.0
Chateaubois (600 m)	79	4.9	1.5	1.5	0.5	3.9	1.0	0.5	
Villarnet (670 m)	90	12.2	1.5	6.0	0.4	6.2	1.1	0.33	9.0
d'Orbannes River (700 m)	126	1.3	0.4	0.9	0.24	0.5	0.16	1.0	13.00
Pompe Chaude (700 m)	59	6.0	1.6	1.7	0.6	4.9	1.0	0.6	18.00

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