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Late Glacial and Holocene development of semi-closed depressions (thaw lakes?) in the Limagne Rift Valley, French Central Massif

S.B. Kroonenberg, R.M. van den Berg van Saparoea & A.T.J. Jonker
Agricultural University, Department of Soil Science and Geology, P.O. Box 37, 6700 AA Wageningen, the Netherlands

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Abstract

Palynological, micromorphological, tephrochronological and sedimentological studies of the deposits in semi-closed depressions in the Limagne Rift Valley in France testify to development in five stages: (1) an erosional, probably interglacial stage, with differential fluvial erosion of soft Oligocene marls not protected by overlying terrace gravels; (2) a fluvial-periglacial stage, with deposition of fluvio-periglacial sediments, partly involuted subsequently; (3) a lacustrine stage, possibly related to thermokarst, with deposition of calcareous mud and volcanic ash layers in the Late Glacial; (4) peat growth and deposition of black clays in the Preboreal, Boreal and Atlantic, and (5), depending upon local conditions, fluvial deposition, soil formation, or lacustrine deposition until recent times.

Introduction

The semi-closed depressions of the Limagne Rift Valley in the French Massif Central have for a long time attracted the attention especially of soil scientists, as here the famous 'terres noires de Limagne' are found, black soils which figure among the richest agricultural lands of France (Gachon, 1963; Bornand et al., 1968, 1975). Nevertheless, since the theses of Derruau (1949) and Gachon (1963) comparatively little attention has been paid to the origin and the Quaternary geological history of these basins. In this paper a first synthesis is presented of data gathered from 1949 onward by French scientists, and of field work and laboratory analyses by the Agricultural University of Wageningen. Special attention will be given to possible effects of thermokarst in the origin of the basins.

The Limagne graben is a north-south trending, 40 km wide rift valley which formed in the Eocene-Oligocene by updoming and rifting in the surrounding Hercynian crystalline basement (Fig. 1). It has been filled with up to 2500 m of Oligocene and Miocene sediments, mainly limestones and marls in the western part of the rift valley, and predominantly (non-calcareous) arkoses and clays in the eastern part. Abundant alkalibasaltic to rhyolitic volcanism started about 25 Ma ago, and continued at least until the Early Holocene. Renewed uplift at the end of the Tertiary resulted in the development of the present drainage system consisting of the Allier River and its main tributary the Dore. The Tertiary deposites were strongly dissected and a flight of at least nine alluvial terraces developed, the highest of which is situated at about 140 m above the present river level. The terraces are numbered following French usage from Fz (present flood plain) to Fs (highest terrace level). A synthesis of the geological development of the Massif Central is given by Autran & Peter-

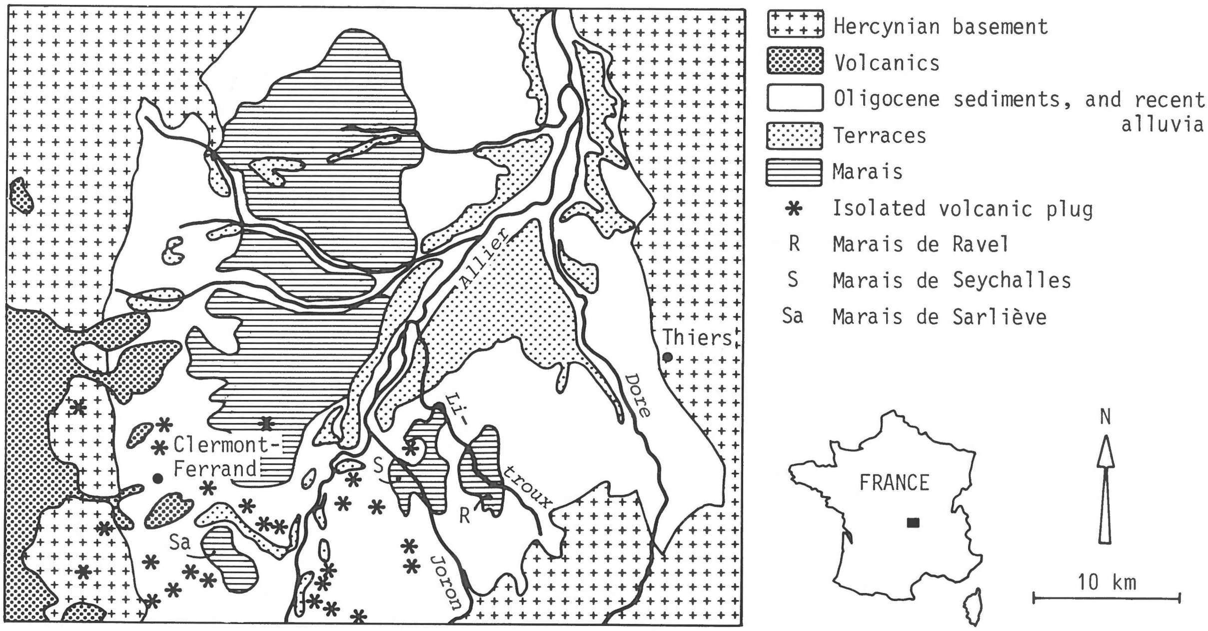

Fig. 1. Geological sketch map of the Limagne Rift Valley.

longo (1980), and of the geomorphic history by Derruau (1949). Geological maps at scale 1 : 50.000 have been published by BRGM (e.g. Jeambrun et al., 1976).

Oval shaped semi-closed depressions (locally called 'marais'), several kilometres in diameter, occur in the lower parts of the rift valley, at an altitude of 315–320 m, about 15 m above main river level. This corresponds with the altitude of the Low Terrace (Fx) of the Allier river, which reportedly is of Würm age (Rudel, 1953). However, the marais are typically separated from the Fx terrace and the lower Fy and Fz levels by elongated barriers parallel to the river, mainly consisting of terrace gravels of the Fw and Fv levels, and locally of Oligocene sedimentary rocks (Fig. 1). The basins are drained via small streams that breach the barriers through narrow gaps. The bottom of the basins is generally flat, though locally undulations are found where outcrops of Oligocene marls occur at shallow depths. The slopes that grade into the surrounding highs are typically concave. In the southern part of the rift valley, well-stratified fluvial and lacustrine deposits have been found in such depressions, which record part of the fluvial and periglacial history during the Last Glacial and the Holocene.

The Marais de Ravel

The Marais de Ravel (Figs. 2 and 3) is an oval N-S elongated depression measuring 5 to 2.5 km, and situated at 320 m above sea level at its deepest point. It is contained between a prominent ridge of Oligocene arkose of 474 m altitude in the east, and a lower ridge of limestones and marls 335 m high to the west. The axes of the ridges parallel the longest axis of the basin. The basin is drained by the Litroux river, a tributary to the Allier. This stream emerges from a gap in the arkose ridge in the southeast, forming a very flat type of alluvial fan (Derruau, 1949). The Litroux is bordered by natural levees protruding at most 6 m above the deepest point of the basin. The central part of the basin is artificially drained by ditches. The topsoil of the basin consists mainly of heavy non-calcareous clays, and is largely in use as rough pasture lands.

The stratigraphy of the deposites in the Marais de Ravel has been established in two sections of closely spaced augerings with a peat gouge, reaching a maximum depth of 6.60 m. Part of one core has been studied microscopically, in thin sections made after impregnation of the core with polyester resin. The following lithological units have been

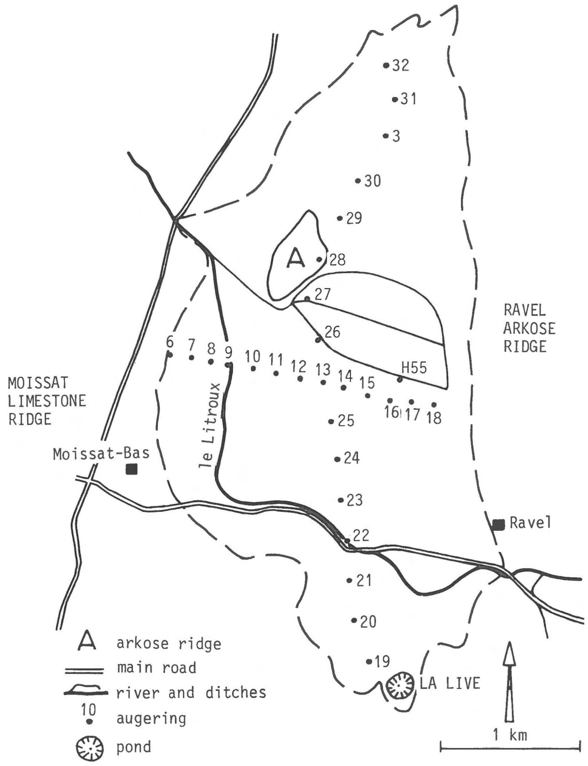

Fig. 2. The Marais de Ravel.

distinguished from top to bottom (Figs. 3 and 4):

Unit 1.
Light-coloured mottled fluvial clays and fine gravelly sands, to a depth of 1.50 m in the backswamps in the deepest parts of the basin, and at least 4 m deep at the natural levees of the Litroux river. This unit has not been studied microscopically.

Unit 2.
Below an abrupt transition black smeary clays 1-2 metres in thickness occur. They are essentially non-calcareous, but locally there are some carbonate nodules. Microscopically they are seen to consist of very fine, strongly oriented clay virtually without any silt- or sand- sized mineral grains. Only at two levels low amounts of silt - and fine sand sized volcanic minerals have been found (see below). Thin peaty laminae and light-coloured diatom-rich laminae occur occasionally. The calcareous nodules by their radial structure testify to in situ development.

Unit 3.
The black clays of Unit 2 gradually pass into an alternation of peaty layers and black clays with low amounts of sand and silt that are partly of volcanic origin. The peat seams locally contain recognizable plant remains. This unit is generally 0.50 to 1 m thick. Locally, near the base, thin light-greenish gyttja laminae of a few cm thick occur, which under the microscope are seen to mainly consist of diatoms. At the very base locally a thin layer of varying thickness (1–10 cm) of very fine sandy dark-coloured volcanic ash has been found (see below for description).

Unit 4.
At the base of unit 3 there is an abrupt transition to bluish grey calcareous lacustrine muds, with occasionally shells of mm-sized fresh-water snails. This unit is usually not more than 0.5 to 1 m thick, and becomes increasingly sandy towards the base. Under the microscope the muds are seen to consist of finely laminated micrite with locally shell fragments and abundant diatom skeletons, with in the upper part abundant volcanic minerals, but towards the base increasing amounts of quartz, feldspar and muscovite grains.

Unit 5.
The lowermost unit consists of non-calcareous fine-to coarsely laminated, often highly micaceous, light grey sands. Its heavy mineral composition indicates a local origin for these sediments. The transition to unit 4 is gradual. The contact with the underlying Oligocene rocks had not yet been reached at the depth of 7.00 m. In the southernmost part of the Marais de Ravel, in a small circular pond about 200 m in diameter, a deviating stratigraphy has been observed, consisting of an upper layer of fluvial clay and sand comparable to unit 1, followed by 3 m of pure peat, and below that again fluvial or colluvial light coloured loamy sand (La Live profile, Fig. 4).

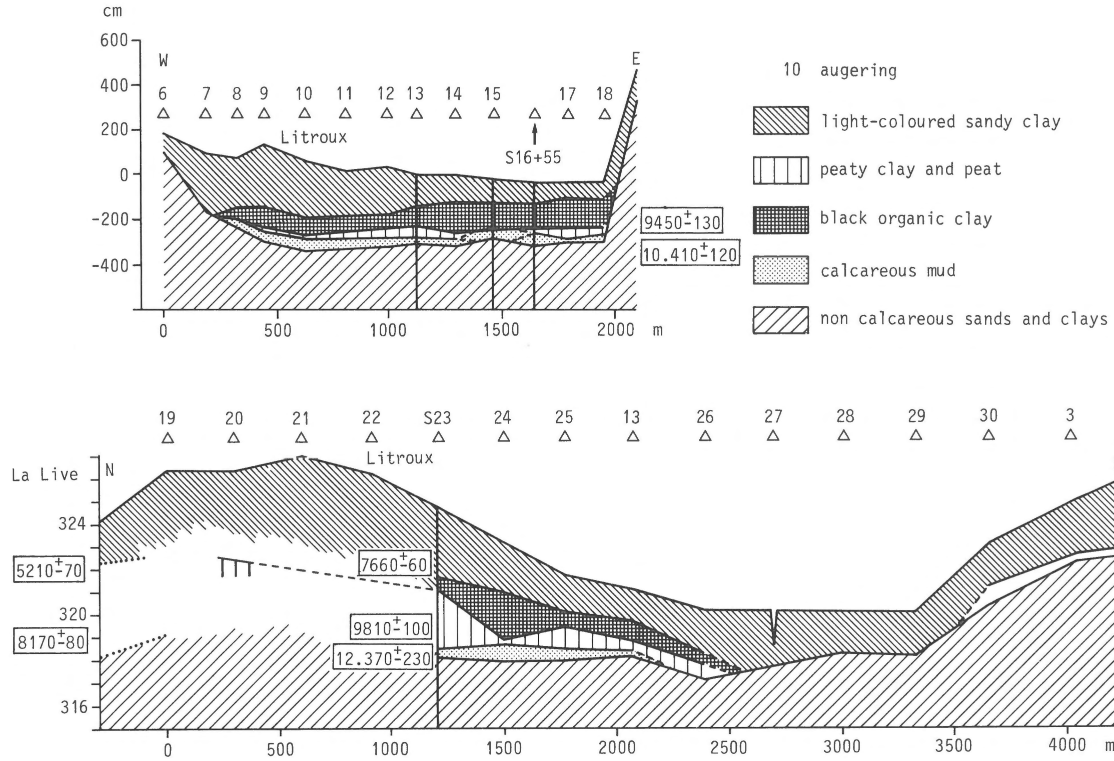

Fig. 3. Cross-sections of the Marais de Ravel.

Palynology and age

Three sections have been analysed palynologically, two of them were calibrated with ^{14}C datings (Fig. 5). Only sediments of the lowermost four units have been studied, as the upper Unit 1 proved to be sterile. Pollen conservation in the other units is also generally poor. Samples have been taken at intervals of 5 cm, but not all samples were counted, so the resulting diagrams give a very generalized picture only. In two diagrams five pollen zones could be distinguished from bottom to top. By comparison with much more detailed sections by De Beaulieu et al. (1982, 1984, 1985) and Reille et al. (1985) from areas further south in the Massif Central our data can be fit to some extent into a regional paleoenvironmental scheme.

Zone E.

In this zone non-arboreal pollen, especially *Artemisia* and Gramineae, largely predominate, and, to a lesser extent, Cyperaceae. There is a small percentage of *Pinus* and *Betula.* This zone largely coincides with lithological unit 5 as far as can be concluded from the small amount of samples. The predominance of non-arboreal pollen in these fluvial sediments suggest that at the time of their deposition an open steppe- or tundra vegetation prevailed. The presence of appreciable amounts of *Pediastrum* and *Myriophyllum* indicates wet local conditions. De Beaulieu et al. (1984, 1985) defined the lower boundary of their so-called Dryas ancien (ca. 15,000 – 13,000 BP) as the crossing between the increasing *Artemisia* curve and the decreasing *Pinus* curve. In view of the predominance of *Artemisia* over *Pinus* in this zone, and the Late Glacial age of the overlying horizons, these sediments indeed may be ‘Dryas ancien’ (Late Pleniglacial) in age. In S23 this is in harmony with the ^{14}C ages obtained for the overlying unit (see below). Sedi-

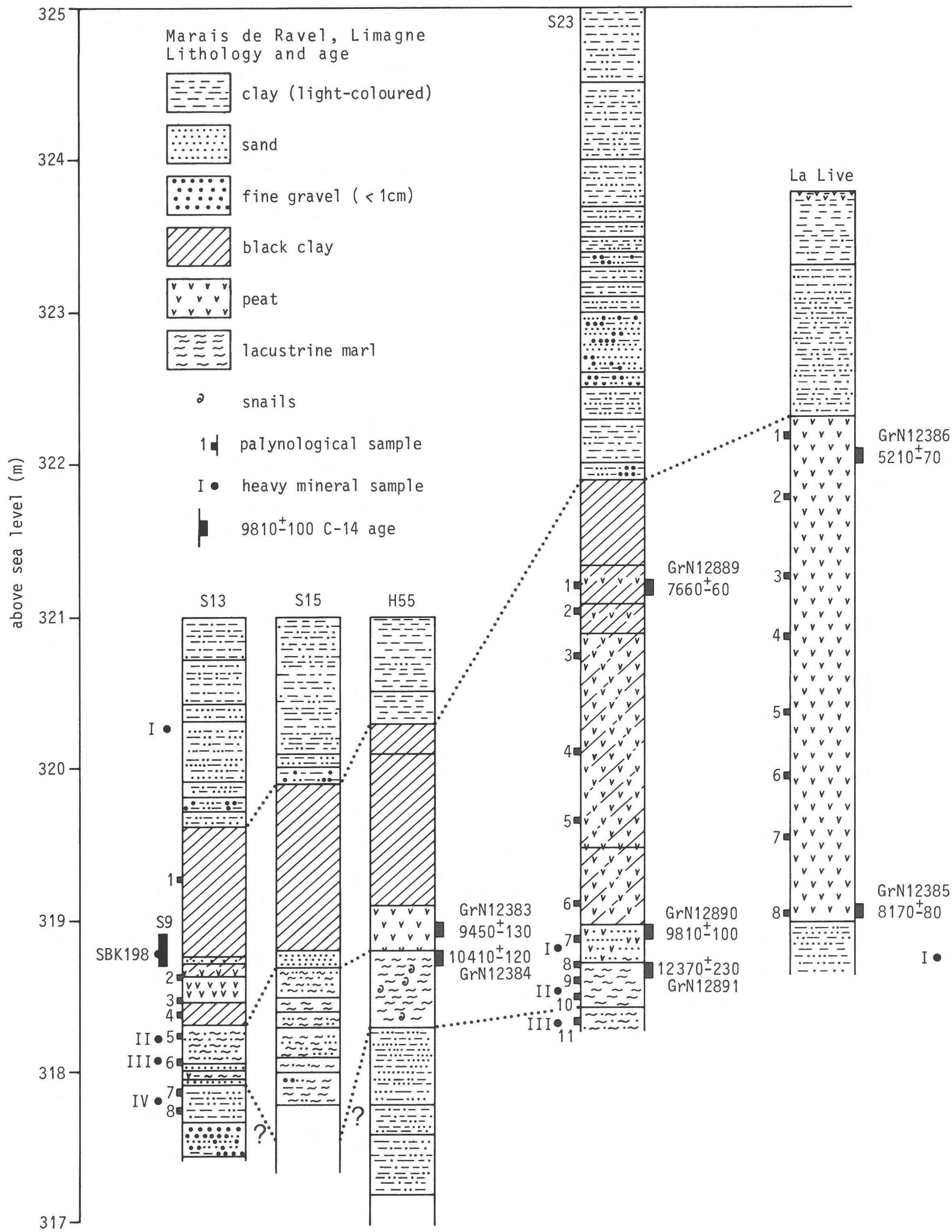

Fig. 4. Lithology of the main cores studied in the Marais de Ravel.

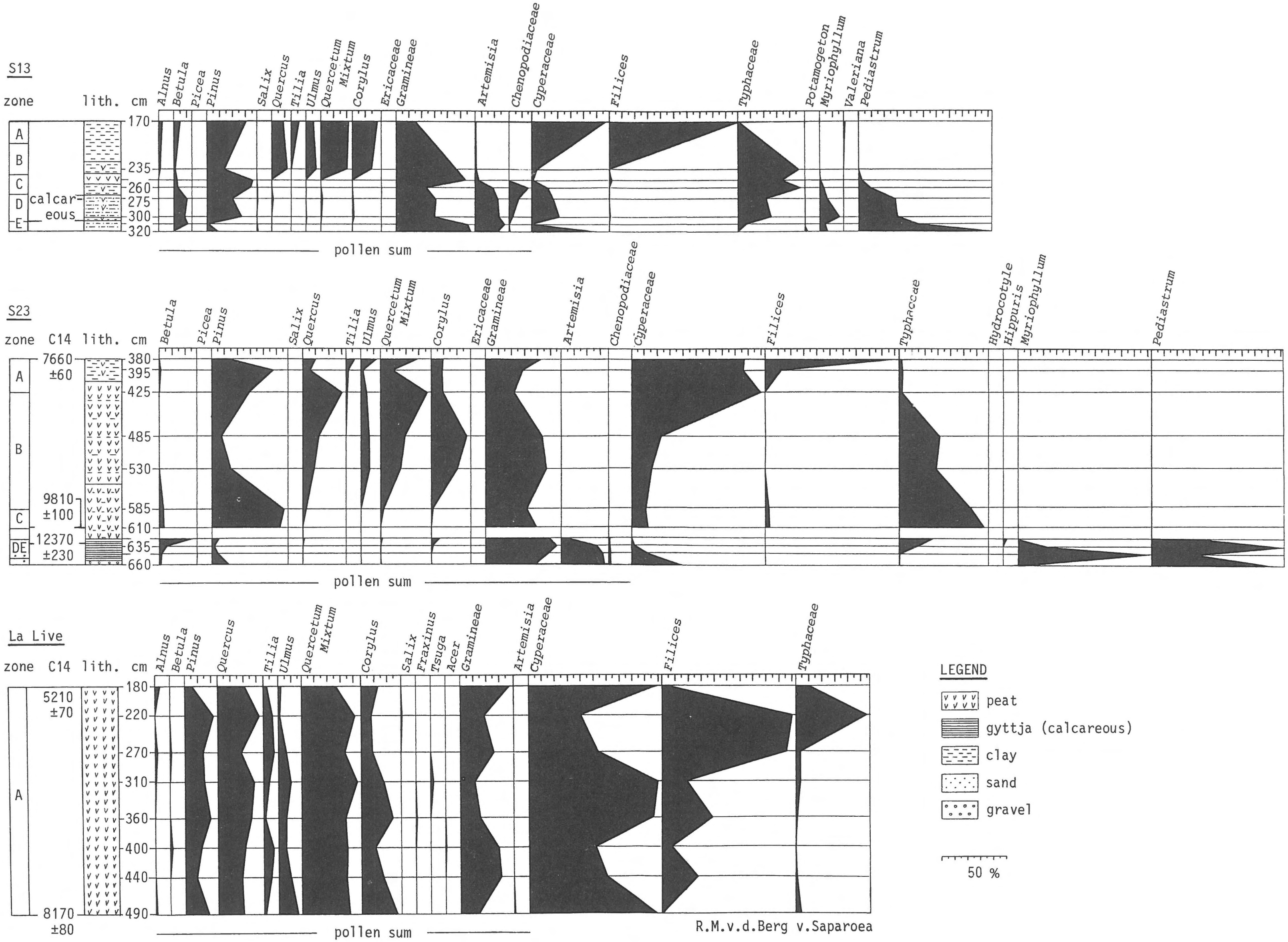

Fig. 5. Palynology of cores S13, S23 and La Live in the Marais de Ravel.

mentation probably took place in a fluvio-periglacial environment (see also section on Marais de Seychalles).

Zone D.
Zone D largely consisting of lacustrine marls, shows still a predominance of non-arboreal pollen (*Artemisia*, Gramineae), but there is a notable increase in *Betula*, whereas *Pinus* remains low in core S23 and shows an increase in S13. The increase in *Betula* points to a climatic amelioration, as has been noted for the Bølling and Allerød interstadials in the Cantal, the Aubrac and the Velay (De Beaulieu et al., 1982, 1984, 1985). The 12.370 ± 230 BP age obtained for this zone in core S23 (GrN 12891), might indicate a Bølling age. In that case the overlying ash bed, palynologically sterile, would indicate the presence of a hiatus between Bølling and Preboreal. Zone D in S13, on account of its higher *Pinus* content, might be of Allerød age. A 10.410 ± 120 BP age was obtained for lacustrine marls at the same level in core H 55 (GrN 12384). Both reported datings were made on the shell-bearing calcareous mud itself. However, the sampling interval applied in our study, as well as the complicating presence of fairly thick and sterile volcanic ash horizons, preclude as yet a detailed reconstruction of the climatic oscillations of the Late Glacial. The fact that Zone D largely coincides with the only true lacustrine and the only calcareous sediments in the sequence at least supports an interstadial rather than a stadial age.

The occurrence of calcareous muds is not restricted to the sections reported here. From the Marais de Lempdes, near the Marmilhat School, both Rudel & Lemee (1955) and Gachon (1963) described similar sediments, that are palynologically comparable. There is, just as in our sections, a low amount of pollen of thermophilous trees in their sections, which led Gachon (1963) to suppose a Boreal age for them. However, it has been shown by De Beaulieu et al. (1984, 1985) that the occurrence of pollen of thermophilous trees is by no means an uncommon phenomenon in sediments of unambiguous Late Glacial age. It has been even encountered in Late Glacial peats at altitudes over 1000 m by these authors. Therefore, an interstadial Late Glacial age is accepted for the calcareous muds.

Zone C.
The transition from zone D to zone C occurs in the same interval where calcareous muds give way to peaty clays. The sharpness of the transition may be due to the presence of a hiatus in S23. In this core there is a strong increase of *Pinus* pollen, while Betula and non-arboreal pollen are on the retreat especially *Artemisia*. In S13 the increase in *Pinus* is less well marked. There is a small percentage of pollen of thermophilous trees (*Quercus, Ulmus, Corylus*) to be seen in S23. A ^{14}C age of 9810 ± 100 BP (GrN 12890) was obtained for a peaty clay in S23 (see Fig. 5), and a second one of 9450 ± 130 BP from H55 (GrN 12383). No palynological data are available for this core. Palynological, lithological and radiocarbon data concur in a Preboreal age of this pollen zone (possibly still partly Younger Dryas in the lowermost part), in which an appreciable climatic amelioration is reflected. Birch forest was replaced by coniferous forest, and the decline of *Pediastrum* and simultaneous increase of Typhaceae reflect the transition of open water lacustrine conditions to peat growth in the basins.

Zone B.
This zone shows an increase of thermophilous tree pollen, notably *Quercus, Ulmus* and *Corylus*, indicating a further warming of the climate. *Pinus* decreases and *Betula* has largely disappeared. In the upper part of this zone Cyperaceae show an increase. No ^{14}C datings are available for this zone. Assuming a constant sedimentation rate of the (peaty) clays of 1 mm/year on account of the ^{14}C age of 9810 ± 100 BP at 6.05 m depth and of 7660 ± 60 BP at 3.80 m depth (zone A, see below) in core S23, the Preboreal/Boreal and Boreal/Atlantic boundaries would be located at 5.20 m and 4.20 m, respectively. From the diagrams themselves these boundaries would be located at 5.85 and 4.25 m respectively. However, a hiatus between the Preboreal and Boreal cannot be excluded, according to De Beaulieu (pers. comm.) because of the low *Corylus* contents. In S13 the palynologically established boundaries occur at 2.40 and ca. 2.00 m.

Zone A.
The uppermost part of the S13 and S23 cores (apart from the sterile overlying fluvial clays), show persistent domination of arboreal pollen, although with a considerable fall especially of *Corylus* pollen at the transition from zone B to zone A in core S23. Furthermore *Tilia* makes her first appearance. The high values of Cyperaceae and Filices and the complete disappearance of Typhaceae indicates progressive shallowing of the depression. A ^{14}C age of 7660 ± 60 BP (GrN 12889) was obtained from S23 for this zone, confirming the palynologically most probable Atlantic age of this zone.

The whole section of 3 m of peat at the La Live pond was assigned palynologically to this same zone. A ^{14}C date for the base of this section is still in the upper Boreal (8170 ± 80 BP; GrN 12385), whereas the top is in the upper part of the Atlantic (5210 ± 70 BP; GrN 12386). The upper boundary of this zone is formed by the palynologically sterile fluvial clays and sands of the Litroux river. If sedimentation continued at a rate of 1 mm/year at S23, the top of the black clays would have an age of 7500 BP, indicating that either fluvial sedimentation has started earlier at these sites than at La Live, or alternatively that the upper part of the black clays has been eroded away.

Tephrochronology

The French Massif Central has been the site of considerable volcanic activity already since the Miocene. Late Pleistocene and Holocene volcanism took place mainly from the N-S stretching range of small volcanoes on the western uplifted border of the rift valley, the Chaîne des Puys. They are mainly basaltic scoria cones, tuff rings and maars, which emitted lava flows that locally reached the rift valley itself, e.g. near Clermont Ferrand. Details about the chronology, composition and emplacement of these volcanoes are given by Brousse et al. (1969), Rudel (1974) and Camus et al. (1983). It was thought that because of prevailing western winds in the area, ash clouds must also have reached the Limagne rift. Therefore, special attention was paid to the occurrence of ash layers.

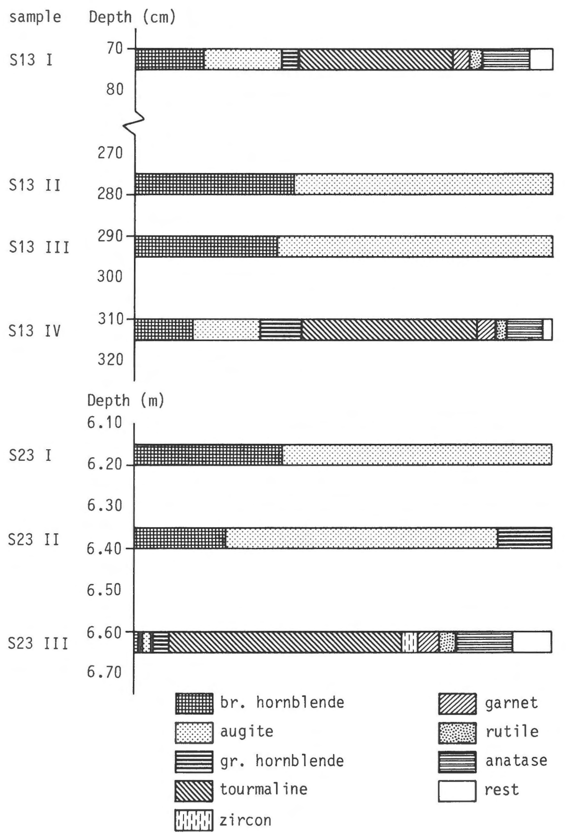

Fig. 6. Heavy mineral diagrams of the cores S13 and S23 in the Marais de Ravel.

The Litroux river upstream from the Marais de Ravel drains an area underlain essentially by granites and arkoses, with only a small basaltic plug in the extreme south of its watershed. Thus high concentrations of volcanic minerals must derive from ash clouds blown over the basin. This does not exclude, however, that some sediment derives from superficial deposits containing volcanic minerals from eruptions previous to the filling of the Marais de Ravel.

Inspection of the thin sections of core S13 showed the presence of a pronounced concentration of volcanic rock fragments and minerals in the calcareous mud between 270 and 260 cm depth. This layer has been found back in all layers studied mineralogically in the same stratigraphical position (Fig. 6). In thin section it is seen to consist for the overwhelming part of rounded fragments up to 0.5 mm in size of trachyandesitic composition, with microphenocrysts of plagioclase and minute crystallites of augite and opaque minerals, and somewhat larger phenocrysts of plagioclase, greenish augite and brown, kaersutitic amphibole. Some fragments contain appreciable amounts of volcanic glass. Loose crystal fragments are mainly plagioclase and minor amounts of augite and brown amphibole. In this interval no non-volcanic minerals were noted in thin section, apart from the surrounding micritic mud. This is in sharp contrast with the underlying laminae, in which quartz and muscovite are preponderant, and hardly any volcanic minerals are to be seen. In the horizons that cover the ash layer a mixture of volcanic and non-volcanic components is present.

Heavy mineral analyses (Fig. 6) of this lithological unit in all three sections (except La Live) show a near complete dominance of augite and brown amphibole, in which augite generally occupies about 60–70% of the total amount of volcanic minerals. The purest sample at 615–620 cm depth in core S23 was analysed in several size fractions without separation in light and heavy minerals. Its composition in the size fraction 105–210 μm (87% rock fragments, 10% plagioclase, 1% augite 1% brown amphibole and 1% opaques), confirms the impression gathered from the thin sections. Similar results are obtained for the 50–105 and 210–420 mm size fractions. The sample is non-calcareous.

A bulk chemical analysis gave the following composition: SiO_2 52.53; TiO_2 1.87; Al_2O_3 18.90; Fe_2O_3 8.02; MgO 2.43; MnO 0.14; CaO 7.22; K_2O 2.09; Na_2O 6.00; P_2O_5 0.80; H_2O+ 1.47; Total 101.48. Its chemical composition is in harmony with the trachyandesitic petrography (cf. Camus et al., 1983). Analysis of similar ash layers by Gachon (1963) from other Marais gave comparable results. Fragments of volcanic rocks are also abundant in the alluvial sands of the Allier river (Larue, 1979; Kroonenberg et al., 1987 and in prep.), but these are of (alkali)basaltic composition and are concentrated in the heavy fraction. No such fragments have been found in any of the heavy fractions of the Marais de Ravel, and therefore any direct influence of the Allier River can be excluded.

The analysed ash layer forms the boundary between the peaty clays dated at 9810 ± 100 BP, palynologically belonging to zone C, and the calcareous mud dated at 12.370 BP and palynologically belonging to the Late Glacial (see above). The ash itself is palynologically sterile. Below the calcareous muds the content of volcanic minerals is still high, suggesting that various eruptions may have taken place at short intervals. Because of the obvious incompleteness of the Late Glacial record in this section and the uncertainty of the exact age of the calcareous mud, the details of the Late Glacial volcanism cannot yet be unraveled.

Trachyandesitic magmas are comparably rare in the Chaîne des Puys, only 3% of the available analyses show this composition (Camus et al., 1983). They have been emitted mainly by the Puy de Pariou and the Puy de la Nugère in the northern part of the Chaîne des Puys. These volcanoes are known to have had explosive phases (Rudel, 1974, Camus, 1974), and therefore are possible sources for the ashes reported here (cf. Brousse et al., 1969).

In the thin section of S13 a second ash layer of similar composition but much less well developed is encountered just above the peaty layers dated in S23 at 9810 BP, at 10 cm above the base of Unit 3. It is seen to consist of trachyandesitic rock fragments, plagioclase and brown amphibole mainly, though in concentrations much lower than in the preceding layer. This ash layer is immediately followed by a diatomaceous gyttja, possibly indicating a temporary increase in the silica concentration of the lake water due to ash falls. A still more dubious concentration of volcanic material occurs at 160 cm in the same core; assuming a constant sedimentation rate of 1 mm/year these ashes would be about 9700 and 9000 year old.

Summarizing, there is ample evidence for a major period of trachyandesitic explosive volcanism in the Late Glacial, possibly from the Puy de la Nugère or the Puy de Pariou. Unambiguous evidence for younger volcanic events such as reported from elsewhere in the Massif Central (Camus et al., 1983, Juvigné, 1983a, b), has not been encountered in the present sections.

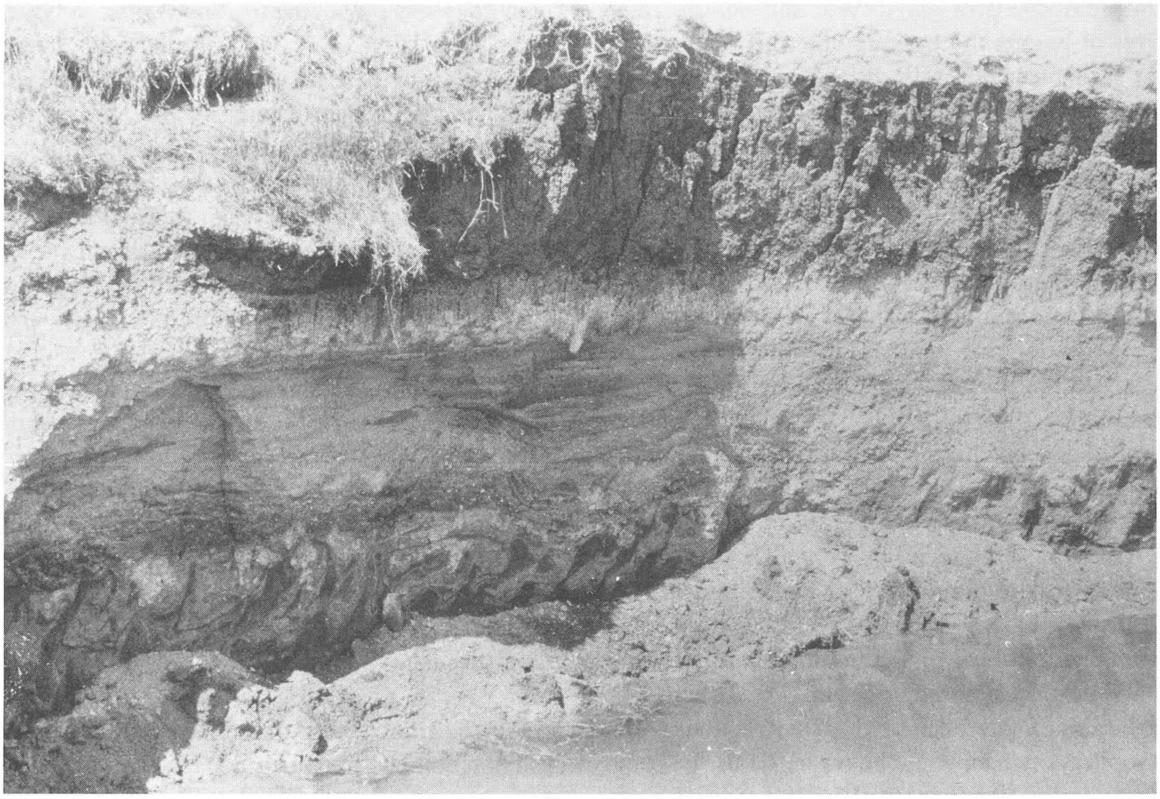

Fig. 7a. The Marais de Seychalles section.

The Marais de Seychalles

The Marais de Seychalles (Fig. 1), an elongated semi-closed basin W of the Marais de Ravel, has not been studied in such detail as the latter one, but an exposure near the farm La Touraille shows an interesting sedimentary sequence which sheds more light upon the origin of the marais as a whole and on the environmental conditions in the Weichselian (Fig. 7a, b).

The La Touraille exposure shows in its lowermost part a sandy and a clayey layer with strong involutions up to almost a metre in length. It is truncated by an erosional surface, which in turn is overlain by a sequence of horizontally laminated poorly sorted sands and fine angular gravel. The heavy mineral composition of these sediments indicates a local origin, unrelated to the Allier river. On top of these sediments a thin band of bluish white calcareous mud is found, which resembles the one in the Marais de Ravel sections. Small, cm-sized involutions are present in this layer as well. After a short interval of greenish gyttja and grey clay, another layer of coarse sands and fine gravel occurs, equally of local origin, and topped by the black clays familiar from the Ravel sections. The topsoil, though slightly colluviated, is developed essentially in this black clay. All sediments are calcareous in this section.

Large involutions such as present in the lowermost part of the La Touraille section are interpreted as due to loadcasting of water-saturated sediments on melting permafrost (see e.g. Vandenberghe & Van den Broek, 1982 for details). They do not only have paleo-environmental significance, but they can also be used as a stratigraphical tool (Van der Hammen et al., 1967, Maarleveld, 1981, Vandenberghe, 1983). It has been shown that the last main period for the formation of involutions in the southern Netherlands was after the cold period,

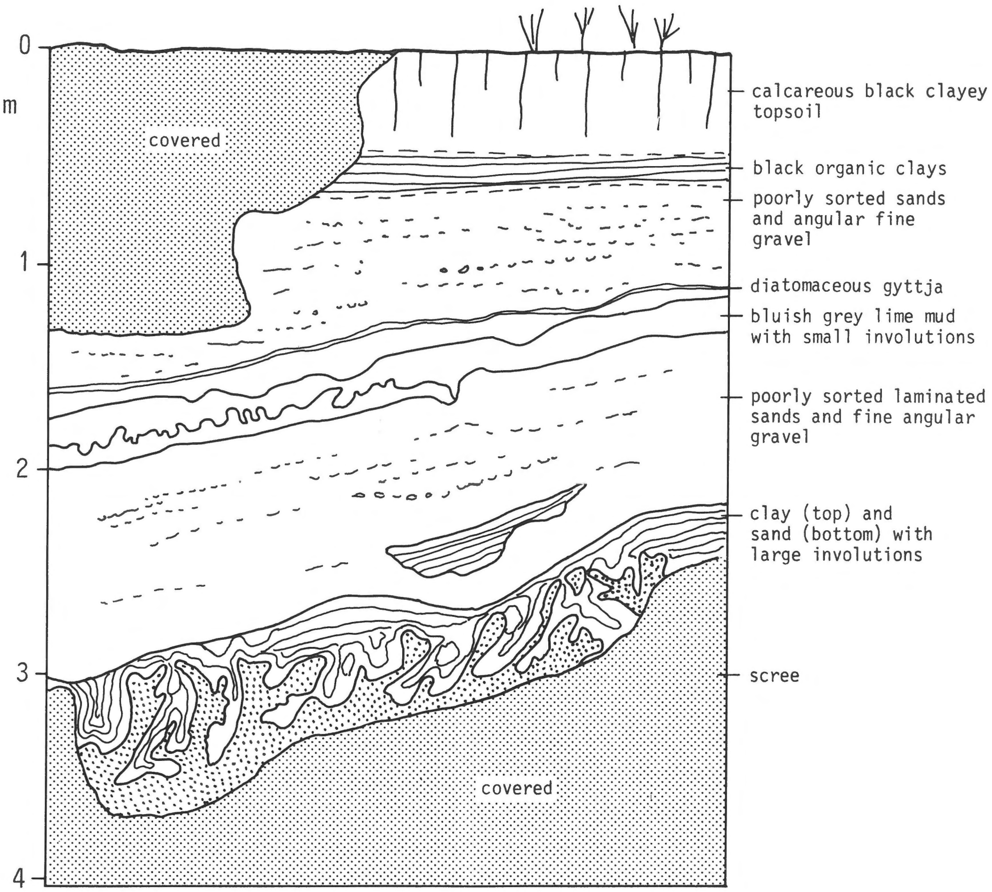

Fig. 7b. Interpreted Marais the Seychalles section.

the maximum of which occurred later than 26,000 BP and probably before 20,000 BP (Vandenberghe, 1983). The sediments which truncate the involutions may testify by their poorly sorted, angular character to deposition by sheetwash under sparse vegetation cover and relatively dry climatic conditions. This may correspond to the drier interval between 20,000 and 13,000 BP, if the Late Glacial age of the overlying calcareous muds is accepted. This would fit with the 'Dryas ancien' age assumed for the lowermost fluvial sediments in the Marais de Ravel section (see above).

The development of the semi-closed depressions

Erosion of the basins (Eemian?)

Derruau (1949) discussed various possible origins for the semi- closed basins in the Limagne rift. An origin by dissolution of the underlying marls is thought to be unlikely because of the impermeable nature of the rocks. A purely tectonic origin has to be excluded as well, since the alluvial terraces which separate many marais from the main rivers do not show evidence of post-depositional deformation. The Marais de Sarliève, SW of Clermont-Ferrand, was allegedly formed by blocking of an older stream by the alluvial fan of the Artière river, but for other marais such an origin was thought unlikely because most alluvial deposits are older than the marais. It can be added that a glacial origin is ruled out as well, as the terminal moraines of the nearest glaciers of the Mont-Dore and Cantal did not extend below 600 m.

Derruau (1949) attached great importance to the irregularities of the bottom topography especially of the greater marais, which would represent an erosional fluvial relief, masked by later colluviation. Differential erosion affected especially the soft marls which because of their position away from the river, never were covered with a protecting terrace gravel. This erosion would have taken place during a more humid period within the Last Glacial. The Low Terrace, now at 15 m above the Allier river bed, and at the same altitude as the top of the marais fillings, would have acted as a base level.

The morphological and sediment characteristics of the marais studied here enable to amend this picture in several ways. In the first place, it is evident that some marais are filled to a considerable depth with fluvial and lacustrine sediments. It is thought unlikely that the present upper level of the terraces which corresponds in altitude to the uppermost part of the marais, can have acted as a base level for the streams that shaped the present bottom topography of the basins. Rather, the base of the corresponding terrace level, determined by hydrogeological studies (BRGM, 1975) to be locally at more than 20 m below the top of the terraces, should correspond to the base level when the marais basins were eroded. This implies that evacuation of sediment from the basins took place in a period when dissection was also preponderant in the river bed. It is logical to suppose that this is the interglacial period immediately preceding the deposition of the Low (Fx) Terrace of the Allier river, hence the Eemien, if the Würm dating of that terrace (Rudel 1953) is accepted.

Fluvial deposition and permafrost development (Pleniglacial)

Accepting interglacial erosion to have formed the basin floors implies that the fluvio-periglacial filling of the basins occurred simultaneously with the deposition of alluvial sediments in the main course (now Fx terrace) of the Allier river during the Würm. The mineralogical differences indicate, however, that the basins were filled from local sources, not from the Allier. The deepest sediments exposed sofar, the involuted sands and clays in the Marais de Seychalles, have been deeply frozen after their deposition. Evidence for permafrost conditions during at least part of the Würm is widespread in the Limagne. Involutions such as encountered in the Marais de Seychalles have been described from other sites as well, e.g. north of the Marais de Sarliève (Rudel & Lemée, 1955), and in the Joze quarry (Bornand et al., 1968). Frost weathering of Oligocene limestone is evident also on that site. As argued above, the development of the involutions probably reflects permafrost degradation, a result of slightly warmer conditions during the Upper Pleniglacial.

There is little direct evidence for renewed permafrost development after that period. The fluvial sediments that overlie the truncated involutions are largely undeformed, and the involutions in the lacustrine marls themselves are an order of magnitude smaller than those in the lower part of the section. Larger-sized deformations are visible in the trenches along the new highway north of Clermont-Ferrand (Collis & Loison, pers. comm.), but nowhere they attain the intensity of those in the Marais de Seychalles.

The Late Glacial lacustrine phase: thaw lake origin?

Whereas the evacuation of sediment from the basins must have taken place by fluvial erosion, it is rather difficult to see how fluvial erosion alone can give rise to the very characteristic oval outlines of most marais. The sedimentary sequence in the Marais de Ravel shows that Pleniglacial fluvial deposition was followed by a Late Glacial lacustrine phase. Therefore, the basins may have acquired their present shape by coastal erosion along a lake shore at the transition of the Pleniglacial to the Late Glacial, a period marked by an appreciable climatic amelioration.

Two hypotheses can be put forward to explain the origin of the present shape of the marais:

1. *Formation in a Late Glacial backswamp environment to the same fluvial system that also deposited the Upper Pleniglacial sediments.*
However, this is thought to be unlikely for the following reasons. The microscopic studies of the sediments of the Marais de Ravel indicate that the lacustrine marls are remarkably pure. Apparently no clastic sedimentation at all occurred during the Late Glacial lacustrine phases. Even in the Early Holocene the deposition of clastic material is restricted to extremely fine grained peaty clays and peat clays. The only discernible coarser materials are volcanic ashes. This implies that the Marais de Ravel was essentially a closed basin during the Late Glacial and Early Holocene. In the Marais de Ravel, the Litroux river is demonstrably active only from 7500 BP, or even 5100 BP onward, leading to the deposition of the top layer of light-coloured, palynologically sterile back swamp clays. There is more evidence for temporary fluvial action in the Marais de Seychalles after the deposition of the lacustrine marls, but no datings are available up to now.

2. *Formation as thaw lakes by the degradation of permafrost.*
The degradation of permafrost in actual periglacial areas gives rise to widespread disruption of drainage patterns due to a great number of phenomena collectively designated as thermokarst (e.g. Czudek & Demek, 1970; Washburn, 1979). Among the most conspicuous features is the development of thaw lakes, usually of elliptical shape, and often several kilometres in diameter. They are much larger than the depressions formed by melting of pingos. Indeed, pingos may develop within such thaw lakes. Well-known examples are the oriented lakes of the Arctic coastal plain of Alaska (Washburn, 1979). The alassy (thaw lakes) of northeastern Siberia, characterized by steep sides and flat floors, may reach 15 km in diameter. Alassy occupied by water produce strong thermo-erosion along the shores, as the banks are quickly undermined by rapid thawing of the permafrost at the waterline, causing extensive slumping. Thaw lakes may form by a variety of processes, such as the melting of a larger body of ground ice or by melting of ice wedges (Czudek & Demek, 1970). Present-day alassy in wooded areas may also form as a result of forest fires and ensuing degradation of underlying permafrost bodies.

There is a great similarity in morphological characteristics between the marais in the Limagne and thaw lakes in actual periglacial areas. This applies not only to the steep sides and flat bottoms, but also to minor features, as shallow slump scars visible everywhere along the former shores. The circular La Live bog is comparable in size and shape to pingo remnants, though it lacks the characteristic ramparts found in other areas around them.

It can be objected that there is little evidence of permafrost in the period immediately preceding the Late Glacial lacustrine phase in the Marais of the Limagne. Nevertheless, there is a remarkable lack of involuted structures in actual thermokarst areas as well. Absence of involutions, therefore, not necessarily proves absence of permafrost. It is conceivable, that in the dry period between 20,000 and 13,000 BP permafrost with much lower ice content originated than in the preceding, moister period, so that at a climatic amelioration load casting was less likely to occur. Therefore, a thermokarst origin for the present aspect of the basins is tentatively accepted.

The Late Glacial interstadials were not only special in giving the final touch to the present shape of the basins, but also in the calcareous nature of the sediments deposited in the Marais de Ravel in this interval, in sharp contrast to the non-calcareous nature of both underlying and overlying sediments. A possible explanation may reside in the sudden increase of the pCO_2 in the soil as a result of the expansion of the vegetation cover, thus favouring increased $CaCO_3$ dissolution in the calcareous ridges in the west. The subsequent peat development and concomitant acidification brought an end to deposition of $CaCO_3$ in the Early Holocene. It thus appears that the Late Glacial, as in many other places, was a period of very rapid environmental change.

Conclusions

The semi-closed basins in the Limagne rift offer an example of fossil thermokarst lakes in which at least five stages of development can be discerned.

1. During an interglacial stage following the deposition of the Fv and Fw terraces, differential erosion by tributaries of the entrenching Allier River lowered the soft Oligocene marl surfaces beyond those terraces. This stage probably corresponds with the Eemian.

2. During a, probably complex, fluvial-periglacial stage these lower areas experienced alternating fluvio-periglacial deposition and erosion, permafrost formation and degradation and formation of involutions, spanning the period from at least the Middle Würm to about 13,000 BP.

3. During the Late Glacial interstadials large thaw lakes were formed in which calcareous muds were deposited, while thermo-erosion took place along the shores. Possibly pingoes were also formed, in an environment of oscillating but generally ameliorating climate, coincident with a climax in volcanic activity in the Chaîne des Puys.

4. In the Early Holocene peat growth and deposition of black clays started, under a closing vegetation cover. Locally, as in the Marais de Seychalles, fluvial deposits may have accumulated in this interval as well.

5. In the Late Holocene, conditions diverged greatly between different basins: In the Marais de Ravel peat growth and sedimentation come to an abrupt end in the Atlantic (between 7500 and 5200 BP). Probably the lake drained and light-coloured sediments were deposited on top of the older sequences. In the Marais de Seychalles soil formed on the black clays, as in many other marais, complicated by subsequent deforestation and ensuing anthropogene colluviation (Gachon, 1963). In the Marais de Sarliève, an open lake until its reclamation in 1655, a complete sequence of Holocene sediments was deposited (Gachon, 1963).

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