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Lateglacial and Holocene climate and soil erosion in southeastern France: a case study from Etang du Pourra, Provence

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ABSTRACT: A synthesis of pollen evidence from Etang du Pourra, a small pond in Rhodanian Provence, France, complemented by new sedimentological, mineralogical and palynological data allow a reassessment of the Lateglacial–Holocene vegetation and climatic history of the area. The Etang du Pourra succession is shown to consist of two parts; the lower part dates from the Lateglacial and the upper reveals the Holocene pollen-stratigraphic succession typical of the region. In the Lateglacial, a humid and cooler phase is recorded before the Younger Dryas conditions progressively set in. In the Holocene succession, the consequences of human modifications on the environment are clearly visible in changes in mineralogy and pollen stratigraphy.

KEYWORDS: Pollen analyses, sedimentology, mineralogy, lacustrine sediments.

Introduction

In prospecting for a site suitable for the study of Quaternary vegetation history, the Provence region did not initially appear promising because the prevailing climate does not favour the accumulation of continuous continental sediments (Triat-Laval, 1979). However, recent pollen analysis of Late Quaternary sediments from Beauchamp Panières, Etang de Berre (Laval et al. 1991a, b) and the small Pourra pond (Fig. 1) demonstrate that fairly continuous sedimentary sequences do exist at a few locations. These provide valuable records of the environmental history of Provence during the last 13 000 yr. The ‘classic’ palaeoenvironmental sequence established for the area extending from south of Orange to the Mediterranean borders is briefly outlined, before we present the results obtained from the Etang du Pourra. This pond preserves an apparently continuous lacustrine succession from the Lateglacial to late Holocene. The unusual accumulation of Late Glacial sediments in this pond may be explained by a karstic downward migration of the basin floor (Mars, 1966). Comparison of sedimentological, mineralogical and palynological evidence from this site provides comprehensive information for piecing together the regional effects of Late Quaternary climatic changes.

The regional context

Evidence for precise climatic changes in the French Mediterranean region during the Upper Pleistocene are scarce (Eicher, 1987; Laval et al., 1991a). It is evident, of course, that temperatures had risen sharply by about 9000 yr BP following the cold Younger Dryas. Subsequently, only very minor climatic fluctuations occurred, as, for example, a humid phase (Table 1) that characterised the littoral zone from about 5000 to 3000 yr BP (Planchais and Parra Vergara, 1984; Laval and Médus, 1989). This phase is reflected in an extension of Abies, which is thought to have required a more oceanic rainfall regime.

The Lateglacial, including the Younger Dryas, is as evident at the various sites of Lower Provence (for example Courthezon, Beauchamp, Les Baux and Les Frignants (see Triat-Laval, 1979) as it is in many other regions. The Preboreal period for the entire French Mediterranean region is essentially characterised by a short extension of pine before the development of Quercus pubescens woodland. This is followed in the Boreal (ca. 8400 yr BP), by a strong but brief extension of Corylus accompanied by an expansion of Quercus pubescens. At Courthézon, Beauchamp, Mollèges and Meyranne, however, at ca. 8000 yr BP, Pinus percentages decline markedly. At the same time an increase in such taxa as Plantago and Ericaceae (Beauchamp, Cyperaceae
(Meyranne, Courthézon) and Juniperus, Quercus ilex, and Corylus can be observed.

The decrease in percentages of Pinus, and the increase of heliophytes and Cyperaceae pollen (Aurures, Barbegal, Beauchamp) persist into the Atlantic period. Evidence in the diagrams of human action is inferred from clear indications of deforestation and agriculture, which suggest widespread human action by ca. 7000 yr BP. At Courthézon, high percentages of Melampyrum found in a second diagram (Triat-Laval, 1979, Fig. D1) distinctly show clearing of the forest, and use of fire is revealed by a level of charred remains encountered above a date of 7350 ± 170 yr BP. Chicoraceae, Papilionaceae, Labiatae, Plantago (and Odontites in the diagram of Courthézon) have developed at numerous sites, suggesting the local application of agricultural methods. Moreover the cereals curve distinctly increases during this part of the succession.

In the Sub-boreal-Subatlantic the percentages of Quercus ilex type clearly replace those of Quercus pubescens along a N–S gradient in the Lower Rhône Valley. Depending on locality, these phenomena occur simultaneously (Barbegal, Les Baux), or successively (Beauchamp, Courthézon, Meyranne); that is to say, the rise of Quercus ilex type pollen occurs both before and after a steep decrease of Pinus pollen.

**Site description**

The Etang du Pourra (140 ha) is a shallow, seasonal sheet of water that occupies a trough which is only open to the north, and which lies within the hills bordering the Etang de Berre. Its bottom is at −6 m below sea-level in Begudian (Maastrichtian continental facies) sequence of impermeable marls and clays. Above this is the transgressive Miocene made up of alternating shelly calcarenites and sandy marls. The altitude of the surrounding plateaux (142 m), which seems to have ruled out any link with the sea during the Quaternary, and the imperviousness of the substratum, lead us to assume that the water regime of this lake is related only to the local hydroclimatic record.

The vegetation of the surrounding calcareous hills, outside the cultivated areas, where there are olive plantations on plots of Brachypodium phoenicoides, consists of garrigue (with Quercus coccifera, Ulex parviflorus and Rosmarinus officinalis), groups of Quercus ilex and thickets of Pinus halepensis in the valleys.
Table 1 Post-glacial and Holocene vegetation sequence

<table>
<thead>
<tr>
<th>$^14$C scale in years BP</th>
<th>Firbas zonation</th>
<th>Chronozones</th>
<th>West European vegetational history</th>
<th>Vegetational history in Provence (H. Triat-Laval, 1979)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>X</td>
<td>Subatlanticum</td>
<td>Anthropic action dominant</td>
<td>Quercus, Ulmus, Alnus, Betula, Fagus, Abies</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td>Carpinus decline almost completely</td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td>Sub-boreal</td>
<td>Alnus Coniferous woodland</td>
<td>Quercetum sclerophyllous (Quercus, Erica, Pistacia, Phyllirea) Abies regional</td>
</tr>
<tr>
<td>4000</td>
<td>VIII</td>
<td></td>
<td>Quercus, Fagus</td>
<td>Quercetum mixtum (with Quercus deciduous dominant)</td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td></td>
<td>Fagus</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>VII</td>
<td>Atlanticum</td>
<td>Ulmus decline</td>
<td>Quercetum mixtum Corylus (North Provence)</td>
</tr>
<tr>
<td>7000</td>
<td>VI</td>
<td></td>
<td>Quercetum mixtum</td>
<td></td>
</tr>
<tr>
<td>8000</td>
<td>Vb</td>
<td>Boreal</td>
<td>Corylus dominant, Pinus Betula decline</td>
<td>Quercetum mixtum Corylus (North Provence)</td>
</tr>
<tr>
<td>9000</td>
<td>Va</td>
<td></td>
<td>Betula, Pinus</td>
<td>Anthropogenic action (?). Quercus deciduous Abies, Fagus, Corylus (South France) Ephedra, Betula, Juniperus and steppe decline, short expansion of Pinus, Artemisia decline</td>
</tr>
<tr>
<td>10000</td>
<td>IV</td>
<td>Preboreal</td>
<td>Betula, Pinus</td>
<td>Steppe, light wood</td>
</tr>
<tr>
<td>11000</td>
<td>III</td>
<td>Younger Dryas</td>
<td>Tundra (Artemisia, Poaceae) with low shrubs</td>
<td>Pinus + few Quercus, Corylus, Alnus, Salix</td>
</tr>
<tr>
<td>12000</td>
<td>II</td>
<td>Allerød</td>
<td>Betula, Pinus</td>
<td>? Pinus, Betula, Ephedra, Artemisia Juniperus slight decline</td>
</tr>
<tr>
<td>13000</td>
<td>Ic</td>
<td>Older Dryas</td>
<td>Steppe</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ib</td>
<td>Bølling</td>
<td>Tundra with low shrubs</td>
<td>Steppe (Artemisia, Chenopodiaceae) Juniperus, Pinus</td>
</tr>
<tr>
<td></td>
<td>Ia</td>
<td>Pleniglacial</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Samples and methods**

A hole was made with an auger to a depth of 2.80 m, and below this to 5.03 m by a piston corer. For pollen analysis, 66 samples were taken at spacings of about 5 cm from the base to 2.80 m (samples 24) then at about every 12 cm. From 4.84 to 5.03 m, 10 of the samples proved to be non-polliniferous. The total number of palynomorphs counted for each level is variable (minimum 97, mean 136, maximum 216). This might result from poor preservation of pollen in some horizons.

Mineralogical analysis was carried out on 15 of these
samples distributed over the length of the core. The mineralogical composition of the bulk rock and the < 2 μm clay fraction was determined by X-ray diffraction, using a Philips 1729 diffractometer with a Co anticathode, operating at 40 mA and 50 Kv. In order to distinguish the different clay minerals, the oriented clay specimens were analysed in four different forms (see e.g. Holtzapfell, 1985): natural sample, treated with ethylene glycol, treated with hydrazine hydrate, and heated at 490°C for 4 h. Semi-quantitative estimates of the relative proportions of the minerals detected were calculated from measurements of the areas of selected diffraction peaks. Furthermore, two parameters were calculated from the diffraction spectrum of the clay minerals after treatment with ethylene glycol: the smectite : illite ratio and the crystallinity index (Vp) of smectite measured using Biscaye's method (1965).

A granulometric analysis was carried out on 35 samples taken every 10–12 cm using a laser diffractometer for the fraction below 80 μm; sand particles with a diameter greater than 80 μm, which were in any case absent or present in negligible amounts in all samples, could not be measured by the instrument.

Proportions of organic matter (OM) were determined using Walkley's method (in Brunel, 1948), and two 14C measurements were obtained from 10-cm-thick samples of the lower part (from 4.70 to 4.80 m and 3.42 to 3.55 m) where the OM curve peaked.

Statistical associations between the palynological taxa and organic matter content and different size grades were investigated, with a program of the AS (1986) software package, using factor analysis optimised by means of varimax rotation.

Pollen zonation

Two pollen assemblage zones (PAZ) have been distinguished on the basis of the major pollen percentage variations (Fig. 2): zone A from level 62 (480 cm) to 27 (296 cm), and zone B, from level 26 upwards.

Zone A

In this zone, the pollen from trees (AP) such as Pinus, Quercus (essentially Q. t. pubescens) and Corylus predominate. Herbaceous pollen types (NAP), which are few in number, are predominantly represented by Poaceae, Chenopodiaceae and Artemisia. This zone, which is characterised by high percentages of Corylus and Q. t. pubescens together with records for Cupressaceae, Betula, and other trees of Quercetum mixtum (deciduous oak) groves (e.g. Ulmus, Tilia, Fraxinus, Ligustrum, Vitis and Acer) suggests a vegetation cover typical of a humid climate. The zone is relatively homogeneous, although three subzones can be differentiated.

A1 From sample 62 (480 cm) to sample 53 (423–426 cm), corresponding to the immigration of the above-mentioned vegetation. It is characterised by a definite decrease in Pinus and an increase in Corylus.

A2 From sample 52 (417–419 cm) to sample 34 (324–326 cm), with rather high percentages of Q. t. pubescens and records of Carpinus, Oleaceae, Pistacia and Ericaceae. It reveals a diversification of the herbaceous component (e.g. Ranunculaceae, Sanguisorba, Fabaceae), which suggests a change to a milder and more humid climate. However, the rise in the number of holm-oak (Quercus t. ilex) indicates a slight drying, favouring a more typical Mediterranean flora (Molinier and Molinier, 1956; Wijmstra et al., 1990).

A3 From sample 33 (319–321 cm) to sample 27 (298 cm), recording the presence of Olea, the beginning of a slow decrease in Q. t. pubescens, Ulmus and Chara, oscillations in the curve for Corylus, the rarity of the Cupressaceae, the disappearance of Betula and the nearly complete absence of Carpinus, which taken together indicates a drier and probably cooler deforested period.

Zone B

This zone, from level 26 (287–289 cm) to the surface, is marked by a decrease in Corylus, oscillations in the curve for Q. t. pubescens, the appearance of Abies followed by Fagus and an increase of Q. t. ilex. In this upper part of the sequence, before the change in humidity reflected by the Abies curve, the increase of Chenopodiaceae marks dry local conditions. Three subzones can be differentiated.

B1 From sample 26 to 16, shows a fall in Corylus and a subsequent increase in Chenopodiaceae, which coincides with a decline in Q. t. pubescens and Ulmus pollen. These changes are considered to indicate significant environmental changes. Erica appears to have gained from these changes while Tilia disappears from level 15 onwards.

B2 From sample 15 to 6, shows a recovery of Q. t. pubescens while Abies slowly declines from level 18 onwards and eventually disappears in the upper part of the subzone. A second decline in Abies occurs after level 14. Next occur increases in Q. t. ilex, Fagus and Alnus. Chenopodiaceae pollen decrease, while Artemisia increase. The fact that Fagus and Q. t. ilex both appear at the same time from level 13 onwards, whereas in other diagrams from this region they are normally out of phase, may indicate a hiatus at this level.

B3 This subzone is characterised by a sharp rise in Olea accompanied by Chenopodiaceae, and a drop in Artemisia against a background of a general reduction of pollen of trees other than Pinus signals the establishment of a historical culture in a deforested landscape.

Sedimentological and mineralogical results

On the basis of macroscopic petrological characteristics (grain-size, colour) the core can be subdivided into four lithological units (Fig. 3A). From bottom to top we can distinguish 2.20 m of grey, fine-grained stratified sands with silty clay interlayers, 1.30 m of sandy silts where the colouring (grey, pink, greenish) is similar to that of the surrounding Begudian rocks, 0.50 m of dark grey silts with fine-grained sands with some charcoal at the bottom, then 1.00 m of beige grey silty clays. The last two facies are mottled with friable, knobby limestone and reddish traces of oxidation. The granulometric analysis (Fig. 3B) shows:
Figure 3  Lithological units (A) and grain-size distribution (B) in the Pourra core. Sample number references are particular to the grain-size study.

Figure 4  Mineralogical composition of the bulk rock (A), and of the clay-size fraction (B) in the Pourra core.
1. The importance of silts (2–20 μm) which make up more than 40% of each sample;

2. That grain size decreases with height. In the lower half of the core, fine-grained sands (48–80 μm) then coarse silts (20–48 μm) make up 25–40% of each sample. They are progressively replaced, in the upper half, by silts, then clays (<2 μm).

3. A significant granulometric variability in the lower two-thirds, characterised by more sandy peaks (samples 33, 30, 27, 25), then coarse silts (samples 20, 17, 14), in contrast to the regularity of the granulometric composition in the upper part.

X-ray diffraction studies of the bulk rock (Fig. 4A) reveal that quartz, calcite and clay minerals are predominant; dolomite and feldspars are found intermittently in trace amounts (<1.5%). There is an up-profile decrease of quartz percentages and a concomitant increase of calcite and clay minerals. This trend is interrupted twice: in the lower part, between 370 and 380 cm (level 45) and in the upper part at 120 cm (level 10), by significant declines in the amount of quartz and increases in clay minerals.
Figure 7. Simplified APNAP pollen diagrams of Etang de Berre core C3. Etang du Pourra and Beauchamp-Panieres. All curves represent the relative percentages, based on the overall continental flora. The chronozonation of the Beauchamp-Panieres diagram was inferred from the 87Sr/86Sr curve (Lava et al., 1991). PR = Precocial, DR = Dryas, Al = Allerod, Be = Bølling.
Figure 8 Results from the factor analysis for (A) the lower part and (B) the upper part of the Pourra core. Four factors account, in the two parts of the sequence, for 65 and 70%, respectively, of the variance of the system. Only the two major factors in each part of the sequence are represented. For the sake of clarity, factor loadings < 0.4 were omitted.

The clay fraction (Fig. 4B) is composed of smectite (always the major component) and illite; the amount of kaolinite and chlorite is significantly lower. The variations in clay composition fall into two parts, which correspond to the two pollen zones (A and B). In the lower part of the core (up to level 23 (272 cm); PAZ A) smectite is largely predominant and its proportion is relatively constant (80% on average, smectite : illite ratio = 5-7). Its crystallinity index (Fig. 5A) remains practically constant and high (Vp = 0.77 on average), indicating well-crystallised minerals. Kaolinite is present in small proportions, while chlorite is not detected. In the upper part of the core (above level 23; PAZ B) the variations are more irregular. On the whole, the percentage of smectite decreases up the profile while illite becomes more important and chlorite values are more significant. In detail (Fig. 5), starting from level 23, the percentage of smectite, the smectite : illite ratio and the crystallinity index of smectite decrease, reaching a minimum at level 11 (128 cm); above that, between levels 11 and 6 (76 cm), an inverse trend is observed. Finally, at the top of the core, between levels 6 and 1 (3 cm), there is a further decrease in the percentage and the crystallinity of smectite.

The organic (OM) content of the sediments shows two peaks at levels 37 and 10–11 (Fig. 5C). While the lower OM peak is not marked by any quantitative or qualitative change in clay minerals, the upper peak is found precisely at the level where smectite is less abundant and less crystallised, and where illite is most abundant. The same relationship is detected at the very top of the core (level 1). Overall, the crystallinity index of smectite and the OM content show a significant negative correlation in the upper part of the sequence (PAZ B) but no obvious relationship in the lower part (PAZ A) (Fig. 6).

Discussion

Pollen-stratigraphic correlations

We can correlate the Pourra sequence by reference to the biostratigraphic table suggested for Provence (Table 1).

Zone B shows a succession that clearly corresponds with the general Holocene history of vegetation established for Provence (Triat-Laval, 1979). The increase in Pinus and the occurrence of Corylus observed at the base are comparable with the forest recolonisation sequence typical of the region at ca. 10 000 yr BP. The increase of Abies, followed by rises in Alnus, Fagus and Juglans, have already been dated for this region (Triat-Laval, 1982), which allows subzones 83 and 82 to be ascribed to the Subatlantic and Sub-boreal and the upper part of B1 to the Atlantic. The lower parts of the succession (pre-Abies) are therefore of Preboreal and Boreal age.

Comparison of summary pollen diagrams from Berre (core C3), Beauchamp-Panières and Pourra (Fig. 7) reveals a number of similarities. First, the decline of Corylus and the long decrease of Arboreal Pollen (partly due to Pinus) which commence at the 3/4 Berre (core C3) boundary and the B1/B2 Pourra boundary, are similar to features dated to ca. 4200 yr BP in the Etang de Berre profile (Laval et al., 1991b). The presence in both diagrams of a Chenopodiaceae phase pre-dating the rise of Abies is also consistent. Further, although there are differences in detail, the decline in Pinus and in Corylus pollen in the Pourra PAZ A3 is comparable to that observed in Beauchamp and ascribed to the Younger Dryas (L3). However, the lower and middle part of zone A (PAZ A1 and A2) does not show the classic features of a Belling/Allerod subdivision. The 14C determinations from the lower part of the Pourra sequence indicate ages of 14 800 ± 290 yr BP (Ly5254) and 13 180 ± 260 yr BP (Ly5263) respectively. They are older than the accepted date for the opening of the Lateglacial (13 000 yr BP). Since the
Environmental history

The lower part of the Pourra profile (PAZ A), as indicated by the pollen evidence, suggests a forested vegetation cover indicative of a humid climate. This zone is differentiated by a relatively coarse granulometry, fluctuations in the granulometric parameters and a relatively homogeneous clay fraction, dominated by extremely well-crystallised smectite.

The coarse granulometric fractions (> 20 μm) are statistically related, using factor analysis (Fig. 8A), to the presence of Pistacia, characteristic of poor soil areas in the Mediterranean, and to hazel-wood (Corylus), usually found on the banks of streams feeding ponds. In contrast, the fine-grained fraction (2–20 μm) and the OM content are statistically associated with plants more clearly linked to enriched humic soils (Ulmus, Tilia, Q. pubescens) and to a high water table (Chara).

In order to elucidate the source of clay minerals in this lower part of the Pourra sequence, a comparative examination of X-ray diagrams of the clay-size fraction of typical samples of the surrounding geological substratum (Begudian and Miocene) was undertaken (Fig. 9). It reveals, through the predominant content and high crystallinity of smectite, a high degree of similarity between the clay fraction of the bedrock and the lower part of the Pourra sequence. Therefore, the palynological, sedimentological and mineralogical characteristics of PAZ A are consistent in suggesting a relatively humid climate during this period. This may have induced a relatively aggressive run-off which delivered material to the basin from freshly exposed bedrock.

The upper part of the profile (PAZ B) is characterised by an increase in fine granulometric fractions (< 20 μm) and by quantitative and qualitative variations of clay minerals in the < 2 μm fraction: that is to say a decrease in the smectite content and a definite degradation of the crystallinity of this clay mineral, which is significantly correlated with increases in the OM content. Thus, clay mineral associations appear to be clearly different from those characterising the lower part of the sequence and the geological substratum (Fig. 9). We conclude that the finest granulometric fractions of the Pourra PAZ B did not simply originate from the direct erosion of the surrounding geological substratum, as suggested for PAZ A. Statistical analysis (Fig. 8B) suggests an association of the finest granulometric fractions (< 20 μm) with cultivated vegetal species (Olea, Juglans, cereal), associated 'weeds' (Centaurea) and with water-margin species (Sparganiaceae).

Palynological, sedimentological and mineralogical characteristics of PAZ B are therefore consistent with the hypothesis that sediments accumulating during PAZ B were derived from disturbed soils on adjacent slopes, following extension of cultivated areas in forested lands. However, the effects of human activities, which are clearly obvious in this part of the sequence, appear to be complex. Thus, following the evidence for strong soil erosion (strongly degraded smectite correlated with high amounts of OM, which are at their highest at level 11), there is a progressive change in the granulometric and mineralogical parameters and the OM percentages up to level 6. These show characteristics closely similar to those of the lower part of the profile, which suggests renewed exposure of local bedrock following widespread removal of soils. This interpretation is supported by the increased percentages of reworked Cretaceous and Tertiary pollens, particularly in zone B3 (Fig. 2).

Conclusion

Sedimentological and mineralogical data in association with pollen-stratigraphic information has proved useful for reconstructing environmental changes, in particular hydrological
fluctuations, deforestation events and related soil erosion phases during the Late Quaternary.

The Holocene bioclimatic sequence formerly proposed for Provence has been confirmed. In particular, the Holocene is characterised by repeated impacts of anthropogenic activity on the landscape: it appears that Mediterranean vegetation provided but a weak protection against surface erosion.

The palynological succession shown in the Lateglacial of the Pourra pond and, particularly, the surprising weakness of the Younger Dryas signature help to illuminate previous research results in relation to the survival of mesothermic trees (e.g. Corylus and Quercus) and the rapid Preboreal forest recolonisation recognised in sites nearest the littoral zones (see Triat-Laval, 1979). For the Pourra site it is our opinion that the weakness of the changes recorded in the lower half of the pollen stratigraphic sequence is related to the exceptional geographical situation of the site and its geomorphological position in the small basin, but above all the lower part of the Pourra sequence is similar to the Pourra pond and, particularly, the surprising weakness of the Younger Dryas signature help to illuminate previous sequence (Lava1 et al. 1991). For the Pourra site it is our opinion that the weakness of the changes recorded in the lower half of the pollen stratigraphic sequence is related to the exceptional geographical situation of the site and its geomorphological position in the small basin, but above all the lower part of the pollen stratigraphic sequence is related to the

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