

Surface Geosciences (Palaeoenvironment)

Holocene hydrological and vegetation changes in southern France inferred by the study of an alluvial travertine system (Saint-Guilhem-le-Désert, Hérault)

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Abstract

A geobotanical study of the travertine system of Saint-Guilhem-le-Désert (southern France) was carried out in order to reconstruct the local Holocene environment in a region where the postglacial vegetation history is poorly documented. The travertine system has started at ca. 8500 cal. BP, in a landscape dominated by *Pinus sylvestris* type (probably *Pinus nigra* sub sp. *salzmannii*). Around 7000 cal. BP, the travertine system recorded torrential events not evidenced at the regional scale, showing the particularity of the Verdus hydrological regime. More recently, ca. 5100 cal. BP, a lake or a marsh was filled within the Verdus plain, as attested to by sand and silt particles accumulated in the sequence. The present-day vegetation dominated by *Quercus ilex*, on south facing slopes, was most likely established between the Bronze Age and the Gallo-Roman period correlatively to the decline of *Pinus nigra* and deciduous *Quercus*, most probably under human influence. **To cite this article:** A.A. Ali et al., C. R. Geoscience 340 (2008).

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Résumé

Changements hydrologiques et dynamiques de végétation durant l'Holocène dans la région de Saint-Guilhem-le-Désert (Hérault, France) à travers l'étude géobotanique d'un système travertineux alluvial. L'étude géobotanique d'un système travertineux localisé dans la région de Saint-Guilhem-le-Désert (Hérault, France) a permis de distinguer les changements hydrologiques et de végétation qui se sont succédé durant l'Holocène dans la vallée du Verdus. Le processus de travertinisation s'est amorcé aux alentours de 8500 ans BP, dans un paysage dominé par les pins (probablement *Pinus nigra* subsp. *salzmannii*). Aux alentours de 7000 ans BP, des épisodes torrentiels sont enregistrés dans le système travertineux, consécutifs aux crues du Verdus, dans un contexte régional de faible dynamique hydrique des rivières. Il y a 5100 ans, un marais ou un lac s'est formé dans la plaine du Verdus, comme le montre le dépôt dans la séquence travertineuse de matériels sableux et limoneux. La végétation actuelle, caractérisée par des boisements de *Quercus ilex* sur les versants sud, s'est probablement établie au détriment du Pin noir et de chênes

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caducifoliés, vraisemblablement sous contrainte anthropique à partir de l'âge du bronze. *Pour citer cet article* : A.A. Ali et al., C. R. Geoscience 340 (2008).

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Mots clés : Travertin ; Sud de la France ; Empreintes foliaires ; Charbons de bois ; ^{14}C ; Dynamique de végétation ; Holocène

1. Introduction

The causes of the major Holocene environmental changes in the Mediterranean area constitute a basic issue in order to apprehend future ecosystem dynamics, in regard to the current global climate change [20]. Holocene hydrological recording is mostly inferred from river dynamics [24,30,45]. The beginning of the Holocene is characterized by high river discharge. After 7000 cal. BP, the mid-Holocene is characterized by low infilling in the valleys and incision processes. However, in this general hydrological scheme, there is a high spatial variability, with torrential events recorded during the Middle and Late Holocene [31,32].

Holocene vegetation history is mainly displayed by palynological [25,35,38,42,52], archaeobotanical [10,11,49,54] investigations, and morphosedimental and palaeobotanical studies carried out on travertine deposits [1]. Palaeoecological results underline the role of pine and juniper species during the Late Glacial/Holocene transition, followed by the development of deciduous oak forests, which dominate the landscape up to the Middle Holocene [26,34,35,51]. This palaeovegetation scheme is linked to the establishment of temperate climatic conditions [12,17,18,20,21,29,37,48]. Since 5000–4000 cal. BP, the development of agro-pastoral activities induced the regression of deciduous oak forests and the expansion of evergreen oaks (*Quercus ilex* and *Quercus coccifera*) [10,36,43,54]. This dynamics occurs asynchronously at a regional scale, related to human settlements [11,54]. The intensification of anthropogenic pressures occurring after the Bronze Age favoured the opening of the landscape and consecutively the development of matorral and, particularly, of communities dominated by *Pinus halepensis* [6–8,11,38,43,49].

In order to improve our understanding of the magnitude of the transformation of the Mediterranean ecosystems and ecological factors involved, it is essential to provide data at different chronological and geographical scales. Special attention must be paid to regions weakly documented, as the Mediterranean foothills of the Massif Central, where our study was

carried out. The Mediterranean lowlands are poor in wetlands suitable for pollen analyses, but rich in travertine systems enclosing plant macroremains (charcoal and plant imprints). They offer the opportunity to apprehend both hydrological and landscape dynamics with high spatial resolution [1]. These natural limestone formations result from the saturation of water in soluble bicarbonate [27]. The deposit of homogenous travertine facies (calcareous deposit) requires steady environmental conditions such as regular flow and forested environments, while detrital facies indicate erosion processes, induced either by climate or human agency [27]. Charcoal fragments mostly preserved in detrital levels could result from local fire events (climatic or human induced) or from firewood used in archaeological sites. Their deposition in travertine sequences mostly occur during erosion processes affecting the surrounding slopes. Plant imprints enclosed in calcareous facies (leaves, needles, twigs, trunks, seeds and cones) result from vegetation growing on the river banks.

This paper deals with the study of the Verduis travertine system Gué des Gours (Saint-Guilhem-le-Désert, southern France), rich in plant macroremains and presenting distinct morphosedimentary facies. Data obtained allow us to recognize local Holocene palaeoenvironmental changes and to discuss the main ecological forcing involved. This site presents a relic forest dominated by *Pinus nigra* subsp. *salzmannii*, an endemic pine species growing in southern France and Spain [39]. This pine species has a restricted area in France and is genetically in danger due to hybridation with *Pinus nigra* subsp. *austriaca*, a pine species abundantly planted during the last century for soil restoration purposes [40]. The palaeoecological investigation presented in this paper allows us to retrace the dynamics of *Pinus nigra* subsp. *salzmannii* since the Early Holocene in regard to natural and/or anthropogenic disturbances.

2. Study area

The village of Saint-Guilhem-le-Désert (Hérault) is located in southern France, 40 km northwest of

Montpellier (43°43' N, °3°33'E) (Fig. 1). During the Middle Ages (804 AD), a Benedictine monastery was established in the village. Part of the material used for its construction came from travertine blocks. During this period, monks cultivated the terraces; at the bottom of the valley, traces of an irrigation system dating back to this period are still preserved. Leaning against the Séranne massif, the 'comb of the Verdus', where the travertine system is located (200 m a.s.l.), is partly protected from fierce northern winds. The present-day vegetation in the comb is of the Mediterranean type,

with *Pinus nigra* subsp. *salzmannii* spreading on the north-facing slopes and on screens. On the south-facing slopes, *Quercus ilex* is dominant along with *Juniperus oxycedrus*, *Pistacia terebinthus*, *Viburnum tinus* and *Spartium junceum*. Above 400 m, *Pinus nigra* subsp. *salzmannii* dominates both on the north- and south facing slopes, in association with *Buxus sempervirens*, *Sorbus aria*, *Amelanchier ovalis*, *Quercus pubescens*, and *Acer monspessulanum*. The present-day climate in the area is characterized by strong seasonal contrasts, with dry and hot summers, rainy during the other

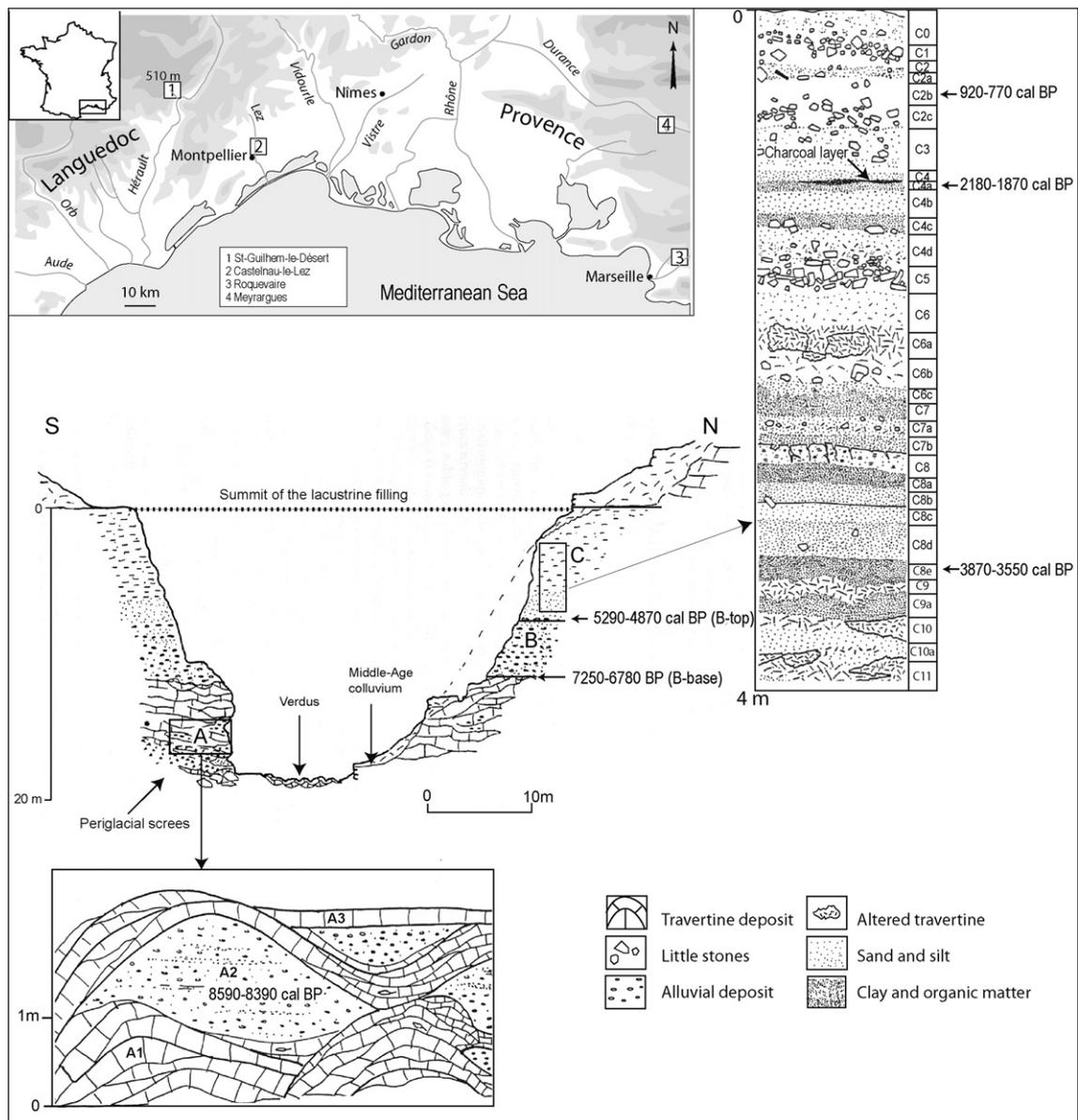


Fig. 1. Location of the Saint-Guilhem-le-Désert area, in southern France, and stratigraphic sequence of the Gué des Gours.

Fig. 1. Localisation de la zone d'étude et stratigraphie de la séquence travertineuse du Gué des Gours.

seasons (800 mm yr^{-1}). The mean annual temperature is 11°C .

3. Stratigraphy and sedimentation

The substratum around the village and on the surrounding elevations is composed mainly of Bathonian dolomite lithofacies. The catchment area corresponds to the plateau of Lavagne, located between Saint-Guilhem and the Seranne massif (Fig. 2). Three distinct travertine series were recognized along the Verdus River, from upstream downwards: Infernet, Abbaye, and Fonzes [4]. Two independent travertine domes, situated 200 m apart, form the Infernet system: Gué des Gours (upstream) and Arrière (downstream). The Arrière dome was built from a structural irregularity of the substratum and formed a barrage against the Verdus [4]. The Gué des Gours travertine, rich in plant remains, corresponds to the deposit where our study has been carried out. This outcrop deposited on periglacial and alluvial materials presents three distinct units (A, B, and C; Fig. 1). Unit A, where plant imprints were sampled, is composed of both detrital and travertinous facies. Unit B corresponds to the deposit of torrential materials. Unit C is composed of sand, silt (at the base) and colluvium elements (at the top).

4. Materials and methods

Palaeobotanical investigations (identification of charcoal and plant imprints) and ^{14}C dating were carried out in the different units.

4.1. Plant imprints

In Unit A, plant imprints from the travertine blocks were extracted using hammer and chisel and drawn using a stereomicroscope coupled with a *camera lucida*. Two levels were sampled (A1 and A3). The identification is based on comparison of morphology features with samples from reference collections (UMR 5059 and herbarium of Montpellier). Generally, the morphological features preserved in fossils allow specific identifications, which are particularly important to recognize woody-vegetation diversity. However, the reduced amount of material collected here prevents interpretation based on relative frequencies of taxa identified. Consequently, presence/absence of taxa only is used to interpret imprint assemblages.

4.2. Charcoal fragments

Charcoal fragments were sampled in all units (A, B and C) by water sieving of sediments (5- and 2-mm

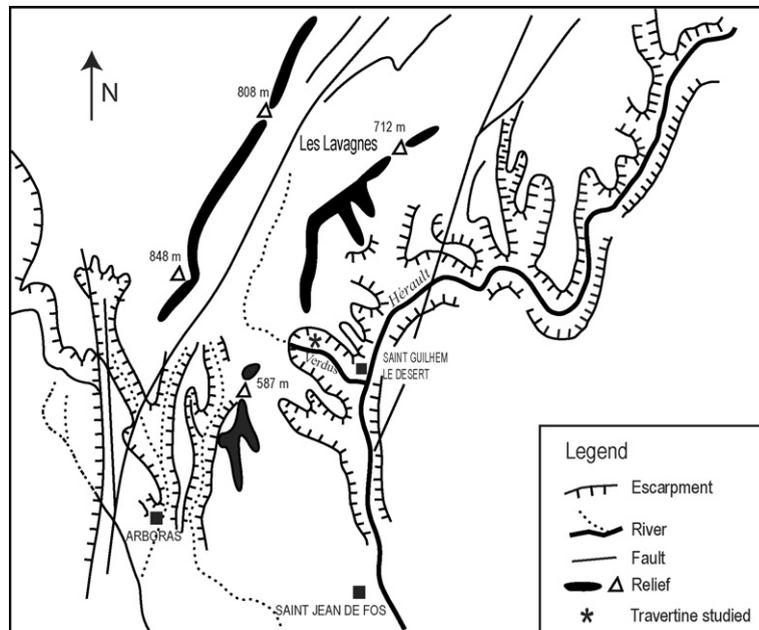


Fig. 2. Geomorphological setting of the study area.

Fig. 2. Carte géomorphologique de la zone d'étude.

mesh). Specimens recovered may result from forest fires, except those from level C8e, which could come from fuel of archaeological sites, as testified to by the presence of artefacts (pottery fragments). The wood anatomical structure is preserved during charring, allowing taxonomic identification. Charcoal fragments were fractured manually according to the three anatomical planes of the wood and observed using a reflected-light microscope. One hundred to 300 fragments by level were studied. Identification was achieved by comparison with a reference collection of modern charred wood species as well as wood anatomy atlases [16,22,23,46]. The palaeoenvironmental interpretation of the successive charcoal assemblages is based on both qualitative (presence/absence) and quantitative (absolute and relative frequencies) approaches [2,3].

4.3. ^{14}C dating

Carbon-14 dating was carried out on charcoal fragments collected in six levels, using conventional and accelerator mass spectrometry (AMS) techniques. All dates were calibrated using the CALIB REV 4.4.2 program and the calibration dataset INTCAL98 [47]. Calibrated ages are rounded to the nearest 10 years.

5. Results

5.1. Dating and geochronology

The Gué des Gours travertine is an alluvial system presenting 20 m of vertical development. Table 1 shows results from ^{14}C dating carried out in this system. The date obtained at the base of the outcrop (A2) reveals that the travertinisation process had already started at ca. 8600–8400 cal. BP (Table 1). It was interrupted at ca. 7250–6780 cal. BP (base of unit B) by the deposition of torrential materials, composed of mixed dolomite and calcareous fragments (Fig. 1). Around 5290–4870 cal. BP, this torrential period came to a stop (top of unit B)

and was followed by the deposition of fine materials composed of sand and silt, corresponding likely to the establishment of a lake or a marsh (unit C) [4]. This lacustrine phase is also recorded in malacofauna analyses, allowing one to clarify the sedimentation process [5]. Five main phases have been recognized in that unit C:

- 11 to 10: this phase is characterized by the abundance of *Bithynella viridis*, aquatic gastropod revealing the establishment of wetland areas (paludal);
- 9a to 7a: the beginning of this phase is characterized by running water (paludal) and after by stagnant water (lacustrine, 8e to 7a). Aquatic species are still abundant;
- 7: short paludal phase, characterizing the beginning of the incision of the Arriège barrage;
- 6c and 6b: lacustrine phase with both aquatic and terrestrial species;
- 6a to 0: these levels are characterized by terrestrial species such as *Pomatias elegans* and *Cecilioides acicula*.

Ceramic and millstone archaeological materials were found in level C9, characteristic of the Chalcolithic period (Fontbousse culture). Late Bronze age pottery remains were also found in level C8e, confirmed by ^{14}C dates effectuated on charcoal (3550–3870 cal. BP). The relative abundance of various archaeological materials suggests the existence, during this period, of human occupation near the travertine system [4]. The top of the deposit with colluviums elements and dated ca 920–770 cal. BP pinpoints from the dismantling of the travertine system.

5.2. Palaeovegetation

Plant imprints collected in unit A allowed the identification of 16 species belonging to the local vegetation (Fig. 3). Most specimens come from level

Table 1
 ^{14}C dating from the Gué des Gours sequence (charcoal)

Tableau 1
Datations ^{14}C obtenues sur les charbons bois interstratifiés dans la séquence travertineuse

Levels	Material	Dating technique	^{14}C (BP)	Calibrated (BP) 2 δ	Lab. code
A2	charcoal	Conventional	7710 \pm 60	8590 – 8390	LV-1766
B-base	charcoal	Conventional	6130 \pm 100	7250 – 6780	LV-2181
B-top	charcoal	Conventional	4430 \pm 60	5290 – 4870	LV-2182
C8e	charcoal	Conventional	3440 \pm 80	3870 – 3550	MC-2163
C4a	charcoal	Conventional	2070 \pm 80	2180 – 1870	LY-4546
C2b	charcoal	AMS	925 \pm 30	920 – 770	Poz-10472

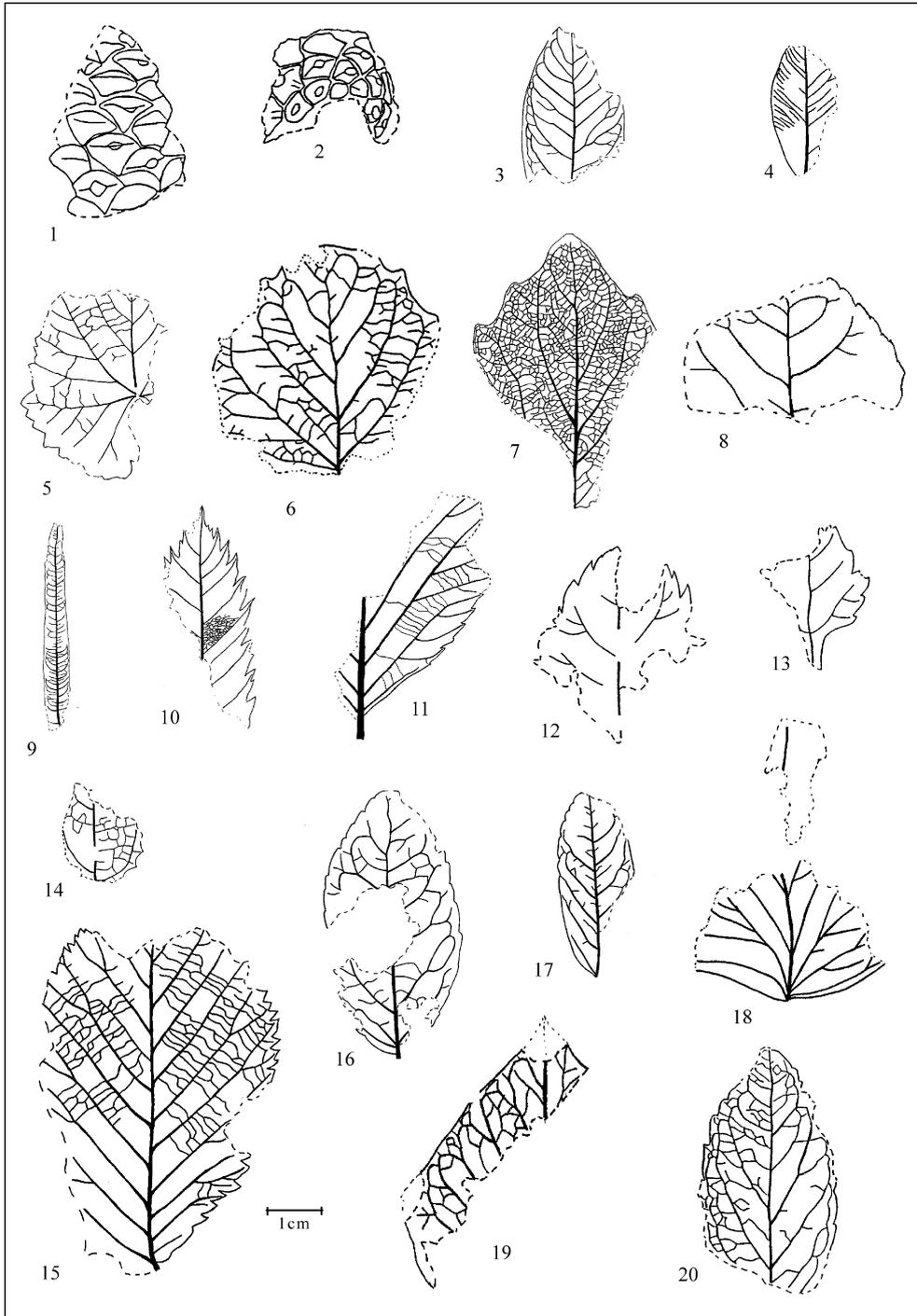


Fig. 3. Plant imprints identified in the travertine sequence. 1–2: *Pinus nigra* subsp. *salzmannii* (cones) 3: *Laurus nobilis*; 4: *Buxus sempervirens*; 5: *Vitis vinifera* subsp. *sylvestris* 6: *Populus tremula*; 7: *Populus alba*; 8: *Populus nigra*; 9: *Salix viminalis*; 10: *Sorbus aucuparia*; 11: *Sorbus aria*; 12–13: cf. *Crataegus*; 14: *Rhamnus alaternus*; 15: *Ulmus minor*; 16–17: *Phillyrea media*; 18–19: *Hedera helix*; 20: *Sambucus nigra*.

Fig. 3. Empreintes fossiles identifiées dans le dépôt travertineux.

A1. Mesohygrophilous (*Salix viminalis*, *Populus alba*, *Populus nigra*) and mesophilous species (*Sambucus nigra*, *Ulmus minor*, *Hedera helix*, *Sorbus aucuparia*, and *Vitis vinifera* subsp. *sylvestris*) dominate the plant

assemblage. More xerophilous species such as *Buxus sempervirens*, *Phillyrea media* and *Rhamnus alaternus* were also identified [41]. Two cones, identified as *Pinus nigra* subsp. *salzmannii*, were found in A3 level.

The taxonomic list obtained by charcoal analysis displays 4 to 12 taxa/sample, including species absent from the leaf assemblage, such as a deciduous *Quercus*, *Quercus ilex/coccifera* (evergreen oak), *Taxus baccata*, *Olea europaea*, and *Juglans regia*. As seen in Fig. 4, *Pinus sylvestris* type is present in all levels. The nomenclature used here concerning the pine fragments identified results from the absence of reliable qualitative anatomical criteria to distinguish pine species belonging to section *sylvestris* (*Pinus sylvestris*, *P. uncinata*, *P. mugo*, and *P. nigra*) growing in the western Mediterranean Basin, even if some authors think that this distinction is possible [57].

Our results show that *Pinus sylvestris* type was the dominant taxon in the vicinity of the travertine system, since at least the Early Neolithic (8590–8390 cal. BP) and up to the Middle Ages. During the torrential period of the Verdus River and up to the Late Neolithic (5290–4870 cal. BP), *Pinus sylvestris* type was mostly associated with species of the Mediterranean oak forest such as deciduous *Quercus*, *Buxus sempervirens*, *Juniperus* and *Rhamnus/Phillyrea*. However, it is only during the Late Neolithic that deciduous *Quercus* reaches relative high frequencies (30%). During the lacustrine period, mesophilous taxa such as *Taxus baccata*, *Juglans regia*, *Corylus avellana*, *Laurus nobilis*, *Ulmus minor*, *Fraxinus*, *Acer campestre/monspessulanum*, *Cornus* sp., are recorded. These may have developed near the travertine sequence thanks to the new edaphic conditions. During this period, the deciduous oak forest was still present. From the Middle Bronze Age (3870–3550 cal. BP) to the Middle Ages (920–770 cal. BP), frequencies of *Quercus ilex/coccifera* and *Rhamnus/Phillyrea* increase, while deciduous *Quercus* declines. At the end of the sequence, *Quercus ilex/coccifera* developed, along with *Prunoi-deae* and *Olea europaea*, around the travertine system, in a regional context of increasing landscape exploitation [10,19].

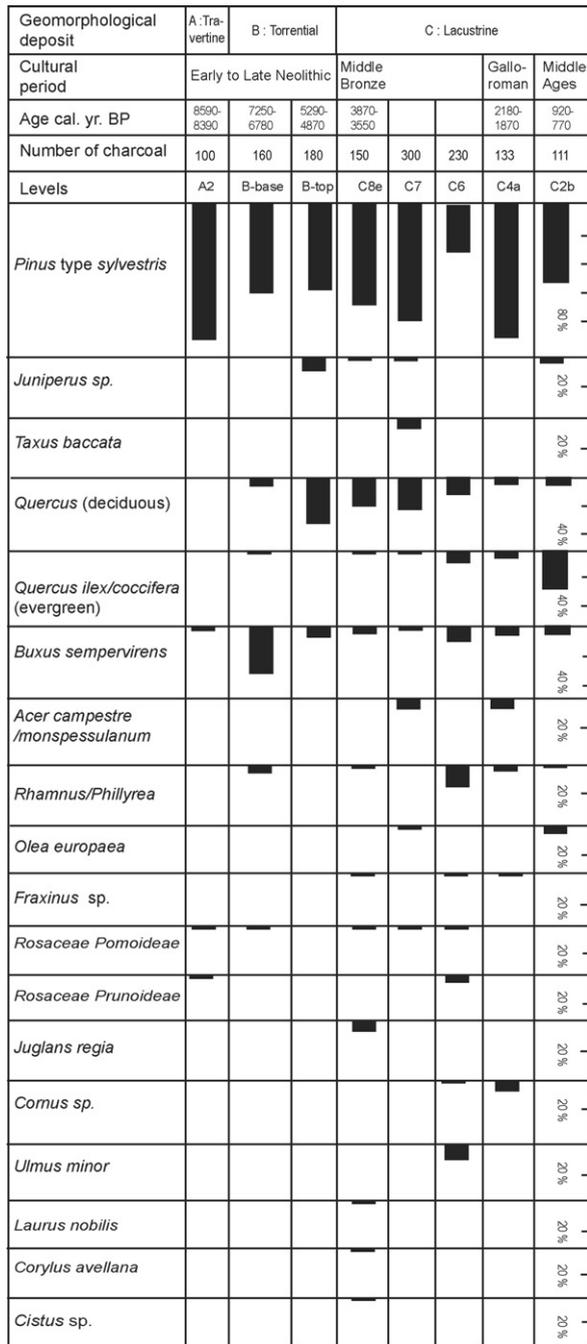


Fig. 4. Vegetation features of the study area based on charcoal analysis.

Fig. 4. Caractéristiques de la végétation locale d’après l’analyse anthracologique.

6. Discussion

6.1. The hydrological dynamics of the Verdus River

The establishment and development of the travertine system of Saint-Guilhem-le-Désert is in agreement with information already obtained concerning travertine processes in the Mediterranean region, which

started at the beginning of the Holocene [53,56]. Most of the Mediterranean travertines of southern France were formed during the Preboreal-Atlantic periods, but some travertinous formations of the Provençal Luberon Mountain began earlier, during the Tardiglacial [31].

The travertine system clearly recorded the hydrological dynamics of the Verdus River. At the beginning of the Holocene, the Verdus had a regular and stable flow, allowing the edification of travertinous facies before ca. 8590–8390 cal. BP. Between ca. 7260–6750 and 5290–4870 cal. BP, the river transported coarse alluvial materials composed of calcareous and dolomitic stones (unit B). This torrential phase, about which we do not know in the present state of results if it was continuous or discontinuous, lasted approximately 2000 years. It seems to reveal an episode of extreme precipitations around Saint-Guilhem-le-Désert.

This hydrological dynamics is different from the Holocene regional hydrological pattern supported by palaeoclimatic reconstructions [28], which point to a significant decrease in river discharge after 7200 cal. BP [15,24,30,45]. According to these studies, high river discharge occurred between 13000 and 7200 cal. BP (*Principal Postglacial Infilling* = PPI). However, we would like to emphasize that PPI sedimentation is mostly observed in alpine zones with a particular precipitation regime, different from that of Mediterranean areas, where abrupt rainfall occurs during the autumn, in particular in the southern Cevennes. These intensive rainfalls result from humid and warm air masses coming from the south and blocked by the relief. Also, it is important to underline the geomorphological particularity of the catchment area (plateau of Lavagnes, 400 m a.s.l.), linked with the Verdus valley through a canyon, and allowing the transport of torrential elements during stormy rainfall on the plateau. Our data underline that local events associated with specific geomorphologic features could induce particular hydrological dynamics different from the regional trend, testifying to a high spatial variability in the Mediterranean hydrological regime [13,24,31]. After these torrential spells, the Verdus flow seems to have resumed a more regular debit up to the Middle Ages (920–770 cal. BP).

The dismantling of the travertine system after the Middle Ages could be related to the local establishment of the Monastery with the exploitation of the travertine system for construction purposes. The geomorphologic dynamics of the Gué des Gours travertine is almost similar to particular dynamics described in the Luberon (Bouches-du-Rhône, southern France) [31].

6.2. Vegetation changes

From the Early Neolithic to the Middle Ages, the vegetation around the travertine system of Saint-Guilhem-le-Désert was dominated by *Pinus sylvestris* type. We suppose that we are dealing here with *Pinus nigra* subsp. *salzmannii* based on the local present-day vegetation, where this species occupies a large area, and because Early Holocene fossil cones of *Pinus nigra* were found within the travertine. *Pinus nigra* subsp. *salzmannii* needs, for its development, draining and flaky soils, as well as relatively high precipitation (1000 to 1500 mm yr⁻¹) [39]. Its presence and development around Saint-Guilhem-le-Désert are related to local favourable environmental conditions (precipitation, colluviums, and alluvial deposits). The history of this pine species in southern France is still poorly documented. Cone imprints belonging to *Pinus nigra* subsp. *salzmannii* were found in Pleistocene travertine deposits located at Castelnau-le-Lez [14], Roquevaire [33], and Meyrargues [44] (Fig. 1), revealing that this species spread over a much larger area than at present.

According to Vernet et al. [55], the present-day fragmentation of *Pinus nigra* subsp. *salzmannii* populations is probably the result of the spatial development of deciduous and evergreen oaks during the Holocene.

Our results show that during the mid Holocene, this pine was dominant at Saint-Guilhem-le-Désert, already associated with deciduous *Quercus* and *Buxus sempervirens* (Fig. 4), corresponding to a formation close to the present-day vegetation, in the highland areas around Saint-Guilhem-le-Désert. After the Bronze Age (3870–3550 cal. BP), *Quercus ilex/coccifera* developed (Fig. 4). This vegetation change corresponds to the establishment of present-day vegetation in the valley. The final settlement of *Quercus ilex/coccifera* may be related to the opening of pine woodlands. It is important to underline that *Pinus nigra* subsp. *salzmannii* is not a competitive pine species because of its low capacity of regeneration after perturbation (fire, cutting...). However, the predominance of a pine forest in this site, since the Early Holocene up to the Present, is an unusual aspect considering other regional sites where the development of oaks corresponds to the decline of pine woodlands at the end of the Mesolithic [10,50,54]. For this reason, the later replacement of *Quercus deciduous* with *Quercus ilex-coccifera* is here probably hidden by the predominance of pine.

At a regional scale, the development of *Quercus ilex/coccifera* is well observed by charcoal analysis of archaeological sites, interpreted as a consequence of the

exploitation of deciduous oak forests by human communities (evergreen oaks are favoured when deciduous oak is cut or/and subject to fire). It is the case at Font-Juvéval, ca. 5300 cal. BP [50], at Lattes Port-Ariane, ca. 3000 cal. BP [9], and at Sallèles d'Aude, ca. 1800 cal. BP [10]. Palynological data record the regional development of *Quercus ilex/coccifera* after ca. 5000 cal. BP [34,38]. Results based on charcoal analyses show that the spread of *Quercus ilex/coccifera* is not a synchronous phenomenon at a regional scale, depending on the development of human settlements and the extent of human activities. Consequently, we suggest that after the Bronze Age, local forcing such as anthropogenic disturbances could have favoured the local development of *Quercus ilex/coccifera* around Saint-Guilhem-le-Désert. Relative frequencies of both pine and deciduous oak decrease. The abundance of charcoal fragments in the travertine systems and natural soils [57] shows that fires, natural and/or anthropogenic, were and still are frequent in the area. Recurrent fire events may be largely responsible for the vegetation changes observed since the Bronze Age in the Verdus valley, resulting in the progressive regression of woodlands dominated by *Pinus nigra* subsp. *salzmannii*.

7. Conclusion

The results obtained in this multidisciplinary study (geobotanical) of the travertine system of Saint-Guilhem-le-Désert (Verdus valley) allow us to identify and understand the possible mechanisms leading to specific Holocene environmental changes in this area. The geomorphological analysis of the travertine system reveals that the Verdus River transported coarse alluvial materials between ca. 7250–6780 and 5290–4870 cal. BP, resulting probably from several local episodes of intense precipitation during this period. Later on, the river had a calm and steady flow, allowing the formation of a lake or marsh within the valley. From the beginning of the Holocene (8590–8390 cal. BP) and up to the Middle Ages (920–770 cal. BP), *Pinus sylvestris* type (most probably *Pinus nigra* subsp. *salzmannii*) was the predominant woody plant. Deciduous *Quercus* growing in the midst of the pine forest was also important up to 3870–3550 cal. BP. After this moment, the development of *Quercus ilex/coccifera* is noticed thanks probably to human activities.

The study of further travertine systems, which may be considered as poorly exploited palaeoecological archives, will allow us to apprehend, at high spatial resolution, environmental changes in the Mediterranean

basin, in response to climatic and/or human disturbances. Several travertine deposits distributed from Spain to the Balkans are still waiting to be studied. They will provide additional information to current palaeoecological reconstructions based on pollen analyses.

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