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Land snail fauna and Holocene environmental changes in Mediterranean France: A digest from three representative sedimentary sequences

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ABSTRACT

The Holocene terrestrial malacofauna of the northern shore of the Mediterranean remains poorly known. Its importance however is twofold, first to better understand the recolonization of Europe by woodland snails from different kinds of glacial refugia, secondly to bring to light the development of Mediterranean ecosystems. This paper is based on molluscan analyses of three sedimentary sequences from a catchment basin near Aix-en-Provence, all of which being representative of the most common pedo-sedimentary and malacological postglacial successions in southeastern France. A special effort has been made to establish the chronology. The results first show the lasting of temperate steppes, lasting in places all the way into the Boreal period (~9000 cal yr BP). Less open environments appeared soon after with assemblages including thermophilic species. The Boreal period shows unstable conditions in an open and heterogeneous woodland landscape. A malacofauna indicating true woodland developed during the Older Atlantic (~8000 cal yr BP). Dominated by “semi-forest” snails, it still contained some xerophilic ones. These assemblages lost their true woodland character between ~7000 and ~6500 cal yr BP due to anthropogenic influence. An increase in human activity and merchandise flow within a more open landscape caused a progressive but deep turnover of land snail communities since the Early Neolithic. It must be admitted that, during the Holocene as a whole, Mediterranean ecosystems remained heterogeneous and frequently open. The human impact is such that it is difficult to discuss the role of climate since ~7000 cal yr BP.

1. Introduction

The Holocene terrestrial malacofauna of the Mediterranean region seems relatively unknown. This however appears to be a key region for understanding the genesis of European malacofauna.

Firstly, it traditionally is considered to have hosted the main glacial refugia for temperate fauna and flora which would then have extended their distribution in central and northern Europe during the postglacial period (Bennett et al., 1991; Hewitt, 1999; Huntley, 1988; Preece, 1991a; Taberlet et al., 1998). Some of them, however, may have survived the last glacial period in multiple refuge areas

elsewhere in Europe, thus forming a more complex pattern (Ant, 1966; Bilton et al., 1998; Juříčková et al., 2014; Kühne et al., 2017; Pfenninger et al., 2003; Salvi et al., 2013; Stewart and Lister, 2001). Impoverished malacofauna generally indicates a steppe environment during the last glacial stage in Mediterranean France (Magnin, 1989, 2014; Mazonot, 1956). Refugia, probably very localized, are only perceived indirectly (Magnin et al., 2012). Therefore, it is important to reconstruct the phases and modalities of the postglacial recolonization in this area by temperate and forest snails.

Secondly, the Mediterranean region is not only characterized by a contrasting climate whose extreme events can have damaging effects on vegetation cover and soils. Landscapes have also been largely redesigned by human activity, for at least 8000 yrs in the western part of the Mediterranean Basin (Butzer, 2005; Pons, 1984). According to some scholars (Grove and Rackham, 2001) savannah-like landscapes would be fairly characteristic of Mediterranean

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Europe where humans contributed to keeping landscapes diversified since the last glacial period (Blondel, 2006). The standard interpretation of pollen spectra in the south of France did not go in this direction. A recent rereading of the data however seems to consider that, all along the Holocene, the Mediterranean ecosystems were patchy and frequently open (Beaulieu et al., 2005). Other types of proxies, including land snails, can contribute to a better understanding of the role human societies had in the evolution of Mediterranean landscapes (Martin, 2004). Subjected to both the openness of their habitats and, more directly, a redistribution of species by humans, Mediterranean snail communities have themselves been profoundly remodelled (Aubry et al., 2005; Germain, 1930; Magnin and Martin, 2012).

Previous studied Holocene sequences in Provence and Languedoc called attention to unexpected issues, namely a time-lag in the colonization by woodland species from supposedly nearby refuges, and, more generally, the scarcity of Holocene woodland assemblages, in contradiction with pollen records (e.g., Magnin, 1991; Magnin and Martin, 2008; Martin, 2004; Martin et al., 2005). Unfortunately, most of the data are rather to be found in “gray literature”. To fill our knowledge gap and to go into these issues in depth, we first have to study the relationships between malacofauna and changes in the Mediterranean environment at local level before expanding to larger areas. The Mediterranean region is indeed extraordinarily complex and diverse due to a strong tectonic, geomorphological, and biogeographic compartmentalization (Blondel et al., 2010; Woodward, 2009). In the sole Provence, land snail communities present a persistent heterogeneous spatial structure despite recurrent disturbances such as wildfires (Kiss et al., 2004). In addition, there are taphonomic constraints. Mollusc assemblages collected in sediments almost always provide information on the palaeoenvironment at a very local level (Briggs et al., 1990; Davies, 2008; Martin and Magnin, 2010). It is therefore essential to increase the number of observations in a relatively small space to obtain a broader picture of the environment and its evolution. Regarding sedimentation, the Mediterranean Holocene records (excluding lakes) are more or less incomplete, with a large spatial variability in the chronology of geomorphic activity (Dusar et al., 2012).

What we are presenting forward here is a proposed reconstruction of the Holocene palaeoenvironments of the Torse watershed at Aix-en-Provence (western Provence), from snail assemblages of three sections. Their pedo-sedimentary as well as malacological successions are widely representative of the predominantly colluvial sequences observed in the whole region. As underlined, robust chronologies are particularly difficult to obtain for this type of geological formations in the Mediterranean domain (Dusar et al., 2012). The present work relies on numerous radiocarbon dates which allow it to be given a very satisfactory chronological framework.

2. Regional setting

2.1. Study area

The three malacological successions are located less than 3 km from the city of Aix-en-Provence (Bouches-du-Rhône, France), in the Torse watershed (Fig. 1). The Torse River is a tributary on the right bank of the Arc River, 85 km long, that flows into the Berre coastal pond, to the north-west of Marseille. The climate is Mediterranean but rather continental, with higher temperatures and precipitation than at the seaside, and much more severe freezing periods in winter. The Mistral, a dry northerly wind, is one of the prevailing winds. Average temperatures range from 6.2 °C in January to 23.6 °C in July (years 1981–2010, Météo France, 2021).

The average annual precipitation is 586 mm/yr. Precipitations are irregular, with marked summer drought. The Torse and Arc rivers usually have modest flows but experience significant and sometimes devastating floods in heavy rains. The current vegetation consists of open woodlands with *Pinus halepensis*, *Quercus ilex* and *Quercus pubescens*. The soils are most often of the rendzinic or calcareous types (Ladier and Boisseau, 1994). In addition to Quaternary deposits, the watershed is mainly composed of limestone, marl and claystone.

The three sections studied are, from upstream to downstream (Figs. 1 and 2): Platanes (Lat. 43° 33'17"; Long. 5° 27'65"), Lavoir de Grand-Mère (Lat. 43° 31'31"; Long. 5° 28'1") and Marbre Noir (Lat. 43° 31'31"; Long. 5° 28'1"). The Platanes sequence (PL) is in a dry valley that connects further east to the Torse. Lavoir de Grand-Mère (LA) is located on an interfluvium 100 m from the Torse and 7 m above the current bed of the river whose activity was at the origin of part of the sedimentary sequence. Marbre Noir (MN), 240 m from the Torse, on the left bank, and positioned 14 m higher than the current bed of the river, has remained apart from fluvial dynamics. Although they have been excavated during archaeological diagnostics, these trenches, dug at random from urban developments, are outside archaeological sites.

2.2. Archaeological and historical setting

For an overview of long-term population trends and their environmental impact since ca 10 kyr in Mediterranean France, one can refer to the comprehensive study of Berger et al. (2019). More local indications on the archaeological data available in the study area are given below.

The territory of Aix-en-Provence is at the heart of a region that has experienced ancient and considerable human occupation (Février et al., 1989; Nin, 2014a). There are several major Late Palaeolithic and Mesolithic sites within a radius of about 20 km (D'Anna et al., 1987). In the same perimeter, the Mourre de la Barque cave makes it possible to follow the entire evolution of the Early Neolithic (van Willigen, 2004). The recent phases of the Cardial culture are attested in other nearby sites (D'Anna and Sauzade, 2014). Local evidence is more numerous for the Middle Neolithic. Several extensive outdoor sites have been unearthed in recent years around Aix (D'Anna and Sauzade, 2014; Moreau et al., 2017). The Late Neolithic corresponds with a demographic boom that continued and amplified during the final phases of the Neolithic and Protohistory. All types of spaces were occupied (D'Anna and Sauzade, 2014). The Early Bronze Age is represented in the Arc Valley and the south of Aix. Often these are hill sites. As elsewhere in the south of France, the Middle Bronze Age seems marked by land abandonment (Berger et al., 2000). However, there were small settlements near the study area. In the Late Bronze Age we can observe the multiplication of occupations in the plains, the Arc Valley, and Aix itself (Lachenal, 2014). During the Early Iron Age, all known habitats in the region were established on high, often fortified sites (*oppida*). Several of these *oppida* are close to the Torse (Arcelin, 2014). The numerous agrarian traces show the cultivation, at this time, of soils located in varied lands. The city of Aix-en-Provence (*Aquae Sextiae*) was the first Roman foundation in Gaul in 122 BC (Guyon et al., 1998). The landscape, by then definitively structured by human activity, included many *villae*, estates with a dual agricultural and residential purpose (Nin, 2014b). The density of occupation of rural space reached its peak at the end of the 18th century. The agrarian, pastoral, and forestry disuses since the beginning of the 20th century leads to a spectacular increase in woodland and garrigue despite frequent wildfires (Ladier and Boisseau, 1994; Tatoni et al., 1999).

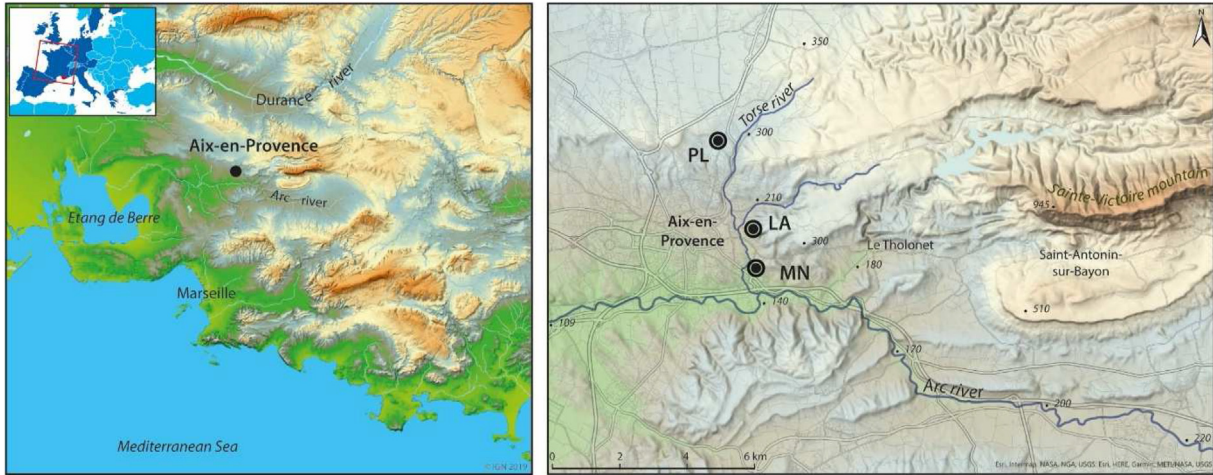


Fig. 1. Location of the Torse watershed and the three sites studied. PL: Platanes; LA: Lavoir de Grand-Mère; MN: Marbre Noir.

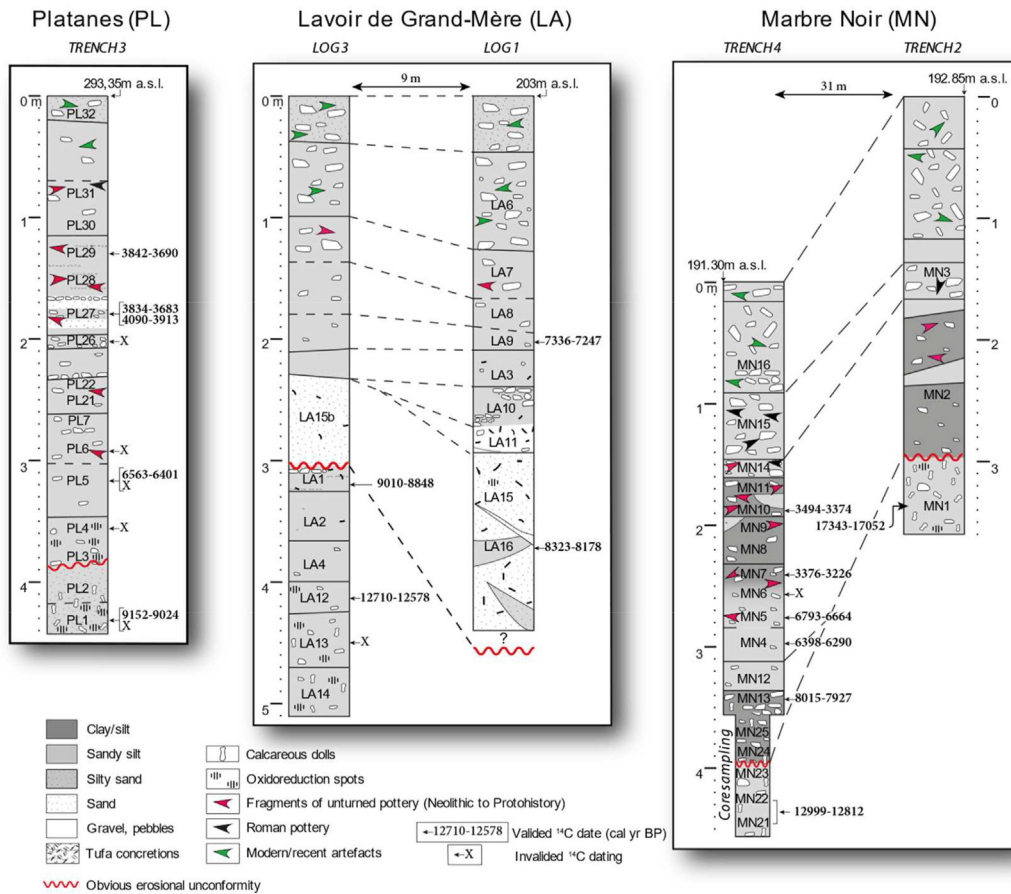


Fig. 2. Stratigraphic profiles of the three sections studied in the Torse watershed showing the positions of malacological samples, artefacts, and radiocarbon-dated levels.

3. Material and methods

3.1. Molluscan analysis

3.1.1. Data collection

Samples of sediment of 10 L each were collected at non equidistant intervals (stratified sampling). Each corresponds to a thickness of about 10 cm. Only the MN 21 to MN 25 samples at

Marbre Noir, taken using a soil auger, had a much smaller volume of about ¼ of a litre. The samples were disaggregated in water and sieved through a 500 µm mesh sieve. For each taxon of each assemblage, a minimum number of individuals (MNI) includes the number of unbroken shells increased by the greatest number of identifiable fragments, either apical or apertural. Identifiable fragments for which a precise number of individuals could not be determined were however still taken into account for those species

which would otherwise not be represented. In the case of *Pisidium*, the number of valves was reduced by half. The taxonomic nomenclature follows that of Welter-Schultes (2012), occasionally revised (supplemental files, Table A).

Sub-fossil *Microxeromagna lowei* and *Xerotricha conspurcata* are very difficult to separate on conchological criteria alone. This has little consequence on palaeoecological interpretation because these two species are often syntopic. A comparison will be necessary between *Vitrea etrusca* from Provence, that of Italy or Corsica, and *Vitrea inae* from Spain (Cadevall et al., 2016; de Winter and Ripken, 1991).

3.1.2. Mollusc diagrams and ecological profiles of the mollusc assemblages

The results are presented in diagrams showing for each assemblage the frequency of each species expressed as a percentage of the total shells. This total excludes *Cecilioides acicula*, a burrowing species (Horsák et al., 2013; Kerney, 1999; Welter-Schultes, 2012), and *Fissuria boui*, a stygobiont linked to underflows (Boeters, 1981). For each of the three sites, a synthetic diagram summarizes the main palaeoecological data: abundance and species richness, composition of assemblages by ecological groups, introduced and/or synanthropic molluscs (species and individuals).

3.1.3. Ecological groups

Although very expressive, the method of “ecological groups” based on the definition of an exclusive or preferred habitat for each species (Juričková et al., 2014; Ložek, 1964; Puisségur, 1976), have the disadvantage of being too rigid and disconnected from an often important regional variability (Cameron, 1978; Cameron and Morgan-Huws, 1975). It does not sufficiently consider the ecological plasticity of species. In addition, the artificialization of landscapes sometimes allows for the presence of certain species outside their original habitats. Despite this, we have opted for ecological groups less general than they are relevant to the region under consideration (Table 1). These groups were defined based on our knowledge of the regional peculiarities of malacological communities and with the help of multivariate analyses (CA). They have the advantage of presenting a reliable picture of the local environment although the assignment of certain species to ecological groups needs to be discussed.

1 Woodland: They are rather shade-loving species with woodland affinities. This woodland attribute should be put into perspective. In the successions of the Torse *Cepaea nemoralis* and *Pomatias elegans* are the only non-rare species of this group (Hill's Index $N2 > 5$). It is generally considered that they exhibit some ecological plasticity and that they can live in semi-open habitats (Ložek, 1964; Puisségur, 1976). In Mediterranean France, the presence of *C. nemoralis* is not only linked to woodland but also to scrubland and ruderal environments (André, 1975). It is sometimes found in damp herbaceous formations (F. Magnin pers. obs.). In the same way, the affinity of *P. elegans* for closed environments must be tempered: it lives in open woodlands and matorrals, hedges and screes (Cadevall et al., 2016; Davies, 2008), seems to be favoured, during the Holocene, in Great Britain, during the opening phases of woodland (Evans, 1972), and can be present in small numbers as soon as a little leaf litter, even herbaceous, is available (Soyer, 1957). *Merdigera obscura* is the only species in the present study recognized most often as a woodland snail strictly speaking (Evans, 1972; Ložek, 1964; Puisségur, 1976) despite nuanced opinions (Boycott, 1936; Cadevall et al., 2016; Davies, 2008; Welter-Schultes, 2012). In Provence, *M. obscura* is frequent in pre-forest environments such as Aleppo pine groves,

or in coppices (Magnin, 1991) and would adapt to a number of agricultural habitats (Bonnet et al. on press). Davies (2008) recalls that *Carychium tridentatum*, long considered in Great Britain to be typical of woodland environments, also lives in tall, dense grassland (Cameron and Morgan-Huws, 1975). It is sometimes simply classified as hygrophilous (Juričková et al., 2014; Ložek, 1964; Puisségur, 1976). In Provence it most often lives in humid wooded environments rich in leaf litter (Magnin, 1991). *Oxychilus clarus*, rather reliant on forest environments, lives under litter, near rivers, but it is also found in herbaceous formations or even in ruderal environments (Combrisson, 2018; Giusti et al., 1985). *Vitrea etrusca* is recorded in coniferous formations of Italy and Corsica (Welter-Schultes, 2012). The remaining species of this group (*Nesovitrea hammonis*, *Punctum pygmaeum* and *Vitrea contracta*) are sometimes considered as mesophiles and having adapted to various habitats (Juričková et al., 2014; Ložek, 1964; Puisségur, 1976), sometimes as living in moist woods, especially deciduous (*N. hammonis*, Cadevall et al., 2016).

- 2 Dry open ground:** Species in this group exhibit less ecological valency regarding habitat structure. They are almost all Mediterranean species of dry grassland or low and open garrigues (Magnin, 1991; Magnin et al., 1995). Some may also be found in more humid or denser herbaceous formations (*Cochlicella* spp., *Ceruella virgata*, *Monacha cartusiana*). In Provence as in Spain (Cadevall et al., 2016) *M. cartusiana* even lives in wet *Phragmites* grasslands. These latter species have been assigned a particular colour on the mollusc diagrams. *Solatopupa similis* is typically saxicolous. In Provence *Xerocrassa geyeri* most often lives in grasslands above 900–1000 m a.s.l., but can exceptionally be found at lower elevation (Magnin, 1989, 1993).
- 3 Mesophilous species/varied habitats:** This group includes species with varying requirements for local moisture or vegetation structure. *Cochlicopa lubrica* and *Oxychilus draparnaudi* retains their status as mesophilous species in Mediterranean France. Some authors classify *Cornu aspersum* among the open ground species (Ložek, 1964; Puisségur, 1976). In Great Britain it is reported in a wide variety of habitats (Davies, 2008). The same is true in Provence if we exclude the most arid environments. *Vallonia costata* is generally accepted as an open environment species comparable to *V. pulchella* (Davies, 2008; Juričková et al., 2014; Ložek, 1964; Puisségur, 1976), or even a xerophilic snail (Boycott, 1936; Davies, 2008). However, it reveals an undeniable ecological valency (Davies, 2008; Puisségur, 1976). In Provence *V. costata* is mainly found in deciduous oak woodlands as well as in highland dry grassland, and sometimes in swamps (Magnin, 1991; Martin, 2004).
- 4 Damp grassland:** These are species living in humid herbaceous formations, even *Phragmites communis* grasslands. *Pupilla muscorum* forma *bigranata*, *Vallonia pulchella* and *Vertigo pygmaea* are most often classified as open habitat species in general (Juričková et al., 2014; Ložek, 1964; Puisségur, 1976). In the Mediterranean region these species live in damp grasslands. They have been associated with *Succinella oblonga* considered by the above authors to be consistently more hygrophilous.
- 5 Marsh and 6 Aquatic:** Concerning these azonal habitats, our classification agrees perfectly with those established for more northern regions. *Galba truncatula*, an amphibious species, indicates intermittent habitats. *Ancylus fluviatilis*, *Radix balthica* rather denote permanent environments of running water and *Gyraulus laevis* standing water.

Finally, we must note the presence of synanthropic species that benefit from the artificialization of the landscape and which, for the most part, have been introduced by humans since the Neolithic,

Table 1

Ecological groups defined for this study. * Indicates synanthropic and/or recently introduced species.

Woodland	<i>Carychium tridentatum</i> (Risso, 1826) <i>Cepaea nemoralis</i> (Linnæus, 1758) <i>Merdigera obscura</i> (Müller, 1774) <i>Nesovitrea hammonis</i> (Strøm, 1765) <i>Oxychilus clarus</i> (Held, 1838) <i>Pomatias elegans</i> (Müller, 1774) <i>Punctum pygmaeum</i> (Draparnaud, 1801) <i>Vitrea contracta</i> (Westerlund, 1871) <i>Vitrea etrusca</i> (Paulucci, 1878)	Mesophilous species, varied habitats	<i>Cochlicopa lubrica</i> (Müller, 1774) <i>Cornu aspersum</i> Müller 1774 * <i>Microxeromagna lowei</i> (Potiez & Michaud, 1835) / <i>Xerotricha conspurcata</i> (Drap. 1801) undiff. * <i>Oxychilus draparnaudi</i> (Beck, 1837) * <i>Rumina decollata</i> (Linnaeus, 1758) * Slug internal plates (small species) <i>Vallonia costata</i> (Müller, 1774)
Dry open ground	<i>Candidula gigaxii</i> (Pfeiffer, 1847) <i>Candidula rugosiuscula</i> (Michaud, 1831) <i>Ceriuella virgata</i> (da Costa, 1778) * <i>Cochlicella barbara</i> (Linnæus, 1758) * <i>Ferussacia folliculum</i> (Schröter, 1784) <i>Granaria variabilis</i> (Draparnaud, 1801) <i>Granopupa granum</i> (Draparnaud, 1801) <i>Jaminia quadridens</i> (Müller, 1774) <i>Massylaea vermiculata</i> (Müller, 1774) * <i>Monacha cartusiana</i> (Müller, 1774) <i>Oxychilus hydatinus</i> (Rossmässler, 1838) * <i>Solatopupa similis</i> (Bruguière, 1792) <i>Testacella haliotidea</i> Draparnaud, 1801 <i>Theba pisana</i> (Müller, 1774) * <i>Trochoidea pyramidata</i> (Drap., 1805) * <i>Trochoidea trochoides</i> (Poiret, 1789) * <i>Truncatellina callicratis</i> (Scacchi, 1833) <i>Vitrea narbonensis</i> (Clessin, 1877) <i>Xerocrassa geyeri</i> (Soós, 1926) <i>Xerosecta cespitum</i> (Draparnaud, 1801)	Damp grassland	<i>Pupilla muscorum</i> (Linnæus, 1758) forma <i>bigranata</i> (Rossmässler, 1839) <i>Succinella oblonga</i> (Draparnaud, 1801) <i>Vallonia pulchella</i> (Müller, 1774) <i>Vertigo pygmaea</i> (Draparnaud, 1801)
		Marsh	<i>Carychium minimum</i> Müller, 1774 <i>Euconulus alderi</i> (Gray, 1840) <i>Oxyloma elegans</i> (Risso, 1826) <i>Vallonia enniensis</i> (Gredler, 1856) <i>Vertigo antivertigo</i> (Draparnaud, 1801) <i>Vertigo moulinsiana</i> (Dupuy, 1849) <i>Zonitoides nitidus</i> (Müller, 1774)
		Aquatic	<i>Ancylus fluviatilis</i> (Müller 1774) <i>Galba truncatula</i> (Müller, 1774) <i>Gyraulus laevis</i> (Alder, 1838) <i>Pisidium</i> sp. <i>Pseudammicola</i> sp. <i>Radix balthica</i> (Linnæus, 1758)

either voluntarily for their consumption, or accidentally (Magnin and Martin, 2012). They are signalled by an asterisk in Table 1.

Informations on ecological groups and synanthropic species are shown on malacological as well as synthetic diagrams.

3.1.4. Local mollusc zones

In order to facilitate the description of the successions, mollusc assemblage zones have been indicated on the two types of diagrams. Their value is entirely local: at this stage it is not a question of establishing a regional “biozonation”, an undertaking which comes up against both the gaps in most of the available sedimentary records and a strong biogeographic compartmentalization (Kiss et al., 2004). The zones boundaries have been positioned by eye. This method somewhat subjective allows to consider meaningful species that occur only at low frequencies (Meyrick and Karrow, 2007). Zones are noted in Roman numerals, e.g., MN IV.

3.1.5. Multivariate analyses

Only the global analysis of the Torse sites is presented. This analysis was performed using C2 software Version 1.7.7 (Juggins, 2014). After several attempts at transformations, the abundances of species were replaced by their proportions in the assemblages. 53 assemblages (observations) and 41 taxa (variables) were taken into account. Only very rare taxa ($N_2 < 2$) were excluded: *Succinella oblonga*, *Trochoidea trochoides* and *Vitrea etrusca*.

3.2. Charcoal analysis

Charcoal fragments were collected in the malacological samples (supplemental files, Table B). Each fragment of charcoal has been observed according to the three anatomical planes of the wood. Most of the identifications were made at magnifications between $\times 100$ and $\times 500$ using the descriptions of species provided

by xylological atlases (Jacquot et al., 1973; Jacquot and Guinier, 1955; Schweingruber, 1990; Vernet et al., 2001). The unit was represented by fragment (Chabal, 1997). Due to the weakness of the data, the interpretation is usually based on presence/absence of taxa along the stratigraphies.

3.3. Radiocarbon dating

Several factors frequently combine to make it difficult to date deposits which essentially are colluvial, with anecic earthworm bioturbations (Carcaillet and Talon, 2007). Initially, duly identified, small charcoal fragments were prioritized for the dating process with the aim to avoid the “old wood” effect. The results were problematic for the Platanes section, possibly due to the conjunction of several factors: i.e., strong fragmentation and diagenetic alteration of the oldest charcoals, helped by significant fluctuations in the water-table; high production of charcoals and charred seeds during Protohistory, with translocation downward of a portion of them; choice of species for analysis that may have led to select intrusive, young elements instead of older ones.

Land snail shells then started being used. As far as possible the selected shells should belong to species (1) characteristic by their abundance of the level where they were found and (2) little subject to the “aging effect”. In order to avoid this “limestone effect” which can result from the incorporation into the shells of carbonates from the soil or from the limestone substrate (see Goodfriend and Stipp, 1983), an effort was made to select as many species as possible which did not ingest soil or scrape limestone rocks, thus providing reliable ^{14}C age calculations. (Brennan and Quade, 1997; Pigati et al., 2004, 2010, 2013, 2015). This was not always possible. Usually recommended species are small wetland snails, but here most species are xerophiles living in habitats in which vegetation and litter irregularly cover the soil. In addition, it should be noted that

local conditions can modify the a priori reliability of a species. This perhaps explains the differences between the results of different authors, regarding *Vallonia* for example (Brennan and Quade, 1997; Pigati et al., 2010), or the occasional successful dating of larger species (Preece, 1991b; Preece and Day, 1994). Among our selected species, *Vitrea narbonensis* and *Oxychilus clarus* do not present any risk of a “limestone effect” because they are likely not to ingest lime. *Granaria* species do not feed on algae or lichens, nor do they usually graze on rocks (Gittenberger, 1973; Gittenberger et al., 2016). Sample PL 27 was twice dated on *Cochlicella barbara* and *Vallonia pulchella* to control possible aging, *Vallonia* theoretically being less subject to the “limestone effect”. The sandy silt at the base of the three sections was dated using its dominant species *Candidula gigaxii*. *Cerneuella virgata* was unsuccessfully used at Marbre Noir, while the same species had given consistent results at another site in Aix-en-Provence (Magnin and Bonnet, 2014). *Cerneuella virgata* is likely to ingest soil at certain periods of its life cycle, and the risk of anomalies in the radiocarbon analyses of this species is known (Romaniello et al., 2008).

Shells and fragments of the selected species were cleaned thoroughly under a dissecting microscope with mounted needles and repeatedly plunged into an ultrasonic bath. Radiocarbon dating was carried out by Beta Analytic laboratory, Miami, USA (Table 2). The dates were calibrated by Beta using the IntCal20 calibration curve (Reimer et al., 2020). Regarding the Lateglacial and Holocene chronozones as well as for the cultural chronology, we adopted those compiled by Cubizolle et al. (2014). An age-depth model would have been inappropriate in this kind of deposits where the heterogeneity of the sedimentation and possible hiatus reflects different processes and variable rhythms.

4. Results and interpretation

4.1. The Platanes section

4.1.1. Stratigraphy and sediment description

The studied trench (Trench 3) was 27 m long and 5 m deep at most (Fig. 2). Noted, from bottom to top:

- 442–388 cm. Massive, brown (10 YR 5/3) silty sand. Calcareous dolls, rhizoconcretions. This deposit remained partly hidden below the level of the water table. [Samples PL 1 and PL 2].
- 388–345 cm. Dark grayish brown (10 YR 4/2) sandy silt, bioturbated, with a well-developed polyhedral structure and pseudomycelia. Many pebbles. Rhizoconcretions. Numerous ferri-manganiferous concretions. [Samples PL 3 and PL 4].
- 345–261 cm. Strong brown (7.5 YR 5/6) sandy silt, bioturbated, with a polyhedral structure. Some pebbles. [Samples PL 5, PL 6, and PL 7].
- 261–208 cm. Two levels of dark grayish brown (10 YR 4/2) sandy silt, bioturbated, with a well-developed polyhedral structure, separated by a stoneline. Rare pebbles. Numerous earthworm granules. [Only the oldest of these levels sampled: PL 21 and PL 22].
- 208–197 cm. Brown (10 YR 5/3) sandy silt and gravel. [Sample PL 26].
- 197–115 cm. Alternating sand and sandy silt layers, dark gray (10 YR 4/1) to yellowish brown (10 YR 5/4). A bed of gravel. [Samples PL 27, PL 28 and PL 29].
- 115–20 cm. Light yellowish brown (10 YR 6/4) to yellowish brown (10 YR 5/4) sandy silt, polyhedral structure. Some pebbles. [Samples PL 30 and PL 31].
- 20–0 cm. Yellowish brown (10 YR 5/4) silty sand, with a polyhedral or crumb structure and strong biological activity. Some pebbles. Topsoil. [Sample PL 32].

The first testimonies of human occupation appear from PL 6 (–290 cm) then are found in variable quantities, but always modest, in all levels up to PL 31: small shards of unturned pottery, but also charred grain seeds, charcoal, burnt bone fragments, sometimes burnt seashells. Sample PL 31 (–80 cm) delivered Roman pottery and PL 32 modern ceramics.

4.1.2. Molluscan succession

Six zones were defined in the malacological succession, designated PL I to PL VI (Figs. 3 and 4).

PL I (Samples PL 1, PL 2, and PL 3). *Candidula gigaxii* is dominant

Table 2

Radiocarbon dates on charcoal fragments and terrestrial shells for Platanes, Lavoir de Grand-Mère and Marbre Noir sections. “X” indicates invalidated dates.

Sample	Laboratory code	Material	Radiocarbon age (BP)	Radiocarbon age (cal. Yr BP 2σ)	Radiocarbon age (cal. AD/BC)
PL 29	Beta - 570255	<i>Pinus, Quercus coccifera/ilex</i>	3490 ± 30	3842–3690	1893–1741 BC
PL 27	Beta - 583079	<i>Cochlicella barbara</i> shells	3680 ± 30	4090–3913	2142–1964 BC
PL 27	Beta - 586739	<i>Vallonia pulchella</i> shells	3470 ± 30	3834–3683	1885–1734 BC
PL 26	Beta - 570253	Monocotyledon, <i>Ulmus</i> sp., <i>Quercus</i> sp.	2640 ± 30	2794–2735	845–786 BC
PL 6	Beta - 570251	Carporest	3670 ± 30	4088–3906	2139–1957 BC
PL 5	Beta - 586740	<i>Vitrea narbonensis</i> shells	5700 ± 30	6563–6401	4614–4452 BC
PL 5	Beta - 570254	Carporest	3210 ± 30	3481–3367	1532–1418 BC
PL 4	Beta - 570250	Indeterminate charcoal	3660 ± 30	4085–3899	2136–1950 BC
PL 1	Beta - 570252	Monocotyledon	3760 ± 30	4236–4073	2287–2124 BC
PL 1	Beta - 570256	<i>Candidula gigaxii</i> shells	8180 ± 30	9152–9024	7203–7075 BC
LA 9	Beta - 507516	<i>Quercus</i> (deciduous)	6360 ± 30	7336–7247	5387–5298 BC
LA 16	Beta - 507515	<i>Quercus</i> (deciduous)/ <i>Quercus coccifera/ilex</i>	7410 ± 30	8323–8178	6374–6229 BC
LA 1	Beta - 570248	<i>Quercus</i> sp.	8020 ± 30	9010–8848	7061–6899 BC
LA 12	Beta - 570249	<i>Candidula gigaxii</i> shells	10680 ± 30	12710–12578	10761–10629 BC
LA 13	Beta - 507514	Indeterminate charcoal	7070 ± 30	7959–7844	6010–5895 BC
MN 10	Beta - 573117	<i>Quercus coccifera/ilex</i>	3220 ± 30	3494–3374	1545–1425 BC
MN 7	Beta - 573116	<i>Quercus</i> f.c.	3090 ± 30	3376–3226	1427–1277 BC
MN 6	Beta - 583078	<i>Cerneuella virgata</i> shells	7520 ± 30	8398–8300	6449–6351 BC
MN 5	Beta - 573115	<i>Quercus</i> (deciduous), <i>Quercus coccifera/ilex</i>	5910 ± 30	6793–6664	4844–4715 BC
MN 4	Beta - 573114	<i>Quercus</i> (deciduous)	5540 ± 30	6398–6290	4449–4341 BC
MN 13	Beta - 583299	<i>Oxychilus clarus</i> shells	7130 ± 30	8015–7927	6066–5978 BC
MN 21–22	Beta - 583077	<i>Candidula gigaxii</i> shells	10980 ± 30	12999–12812	11050–10863 BC
MN 1	Beta - 583300	<i>Granaria variabilis</i> shells	14120 ± 40	17343–17052	15394–15103 BC

(nearly 70% in PL 1), accompanied mainly by *C. rugosiuscula* and *Monacha cartusiana*. The top of this zone (PL 3) is enriched by other taxa with forest affinities and two xero-thermophilic Mediterranean species (*Ferrussacia folliculum* and *Trochoidea pyramidata*). It is a malacofauna that can be found today in dry grasslands, possibly with some woody plants. It indicates a steppe environment and a Mediterranean-type climate with marked aridity.

PL II (Samples PL 4, PL 5, and PL 6). *Pomatias elegans* first significantly increases (20% in PL 4) but rapidly fades (only 5–7% in PL 5 and PL 6). With this “semi-forest” species we find fragments of *Cepaea nemoralis* and rare shells of *Oxychilus clarus*. Adding to the evolution of the fauna of open country, these changes reflect at least a closing of the herbaceous vegetation that could be strewn with trees or shrubs. Introduced, synanthropic species are now added to *Trochoidea pyramidata*: *Cochlicella barbara* and especially *Cernuella virgata*. The anthropogenic impact is already strong, and the landscape is of parkland type.

PL III (Samples PL 7, PL 21, and PL 22). Already small so far, the share of potential woodland molluscs is decreasing. Only remain a few protoconchs and fragments of *Pomatias elegans*. Concerning molluscs from open environments, a decrease in *Candidula rugosiuscula* and *Monacha cartusiana* can be observed. Among synanthropic species, the proportion of *Cernuella virgata* in the assemblages remains stable around 10%, *Cochlicella barbara* is still modestly represented, and *Oxychilus hydatinus* appears for the first time. This zone marks the end of the domination of strictly xerophilic open ground species. It is also the last zone in which species with forest affinities are still diversified, albeit with negligible abundance.

PL IV (Samples PL 26 and PL 27). This zone is marked by the development of wetland molluscs which represent 60% of the PL 27 assemblage. In proportion, however, *Vallonia pulchella*, a hygrophilous species of open environments, quickly becomes predominant (55% in PL 27). At the same time, the sudden expansion of *Cochlicella barbara* can be noted. A single aquatic species is added to this set evoking the existence of a damp grassland: *Galba truncatula*, which can withstand drying up for several months. Zone PL IV corresponds to the development of a non-marshy damp grassland which may be bordered by drier habitats.

PL V (Samples PL 28, PL 29, PL 30, and PL 31). The ecological

spectra are uniform and consist of at least 95% of molluscs from dry open ground. Three species dominate: *Cernuella virgata*, *Cochlicella barbara* and *Candidula gigaxii*. The share of *Candidula gigaxii* remains notable (from 19 to 31%). The importance of *C. virgata* strongly increases in this zone, going from 23% in PL 28–45% in PL 31. The population of this synanthropic snail has practically continued to grow since PL 4, in absolute values. The percentages of *C. barbara* are clearly diminished in PL 31. The discreet manifestation of wetland species reflects slight fluctuations in local humidity. Two other synanthropic species are worth mentioning: *Oxychilus hydatinus* and *Trochoidea pyramidata*. Overall, the context is drier than in zone PL IV. The environment is a grassland with moderate humidity likely to fluctuate.

PL VI (Sample PL 32) The ecological spectrum differs very little from those of zone PL V. Molluscs from dry open ground represent 98% of the assemblage. This group is dominated by the synanthropic species *Cernuella virgata* (42%) accompanied by *Candidula gigaxii* (26%) and *Oxychilus hydatinus* (15%). These three species, which must be associated with at least *Monacha cartusiana* and *Trochoidea pyramidata*, characterize a dry grassland. There are now seven synanthropic and/or recently introduced taxa. They alone represent 64% of the shells collected. The new synanthropic taxa are *Cornu aspersum*, *Theba pisana* and *Massylaea vermiculata*. The environment of zone PL VI is a dry grassland, perhaps in mosaic with ruderal environments.

4.1.3. Charcoal and other fire evidence

Deciduous oak is dominant over the entire succession. The presence of *Fraxinus* sp. and *Ulmus* sp. would indicate the presence of a riparian vegetation. We also find heliophilic and xerophilic taxa such as *Juniperus* sp., *Pinus halepensis/pinea* (especially from PL 28, i.e., –150 cm and above) or *Quercus coccifera/ilex* (from PL 6, i.e., –290 cm and above, with an interruption between –210 cm and –170 cm). More evidence of fire activity is encountered. Burnt shells of terrestrial molluscs are rare (*Pomatias elegans* in PL 5). However, heated gravel or pebbles seem frequent from PL 6 to PL 29. It is difficult to distinguish the results of wildfires from that of agropastoral practices. Several of the burnt elements, however, result from domestic activity: rubefied biocalcarenite in PL 22; bones, teeth, seashells from PL 22 to PL 29; cereal seeds from PL 6 to PL 22.

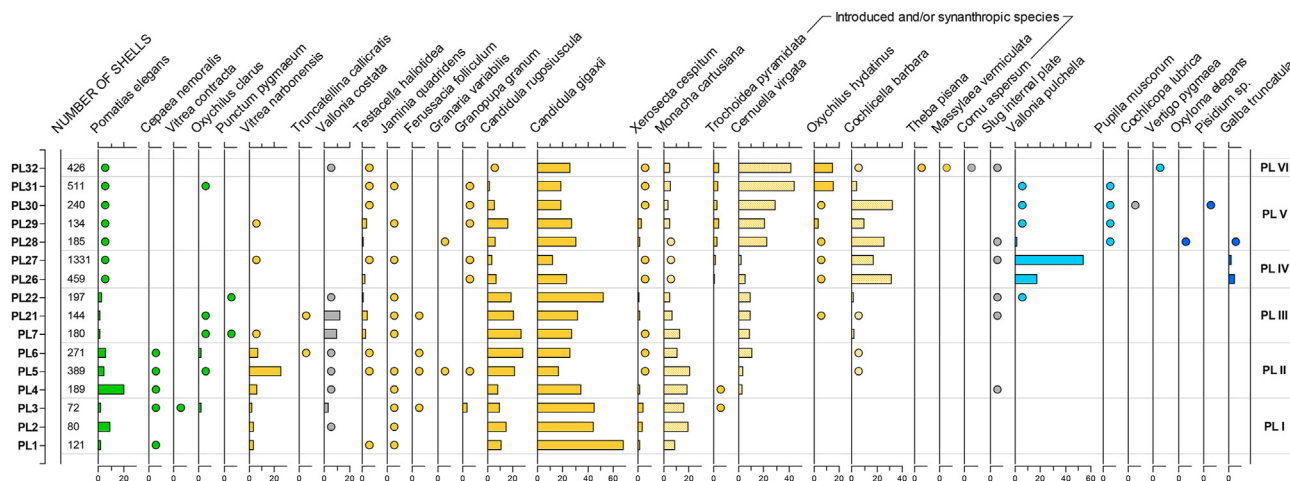


Fig. 3. Platanes, molluscan diagram (percentages). Ecological groups: Green “Woodland”; Orange “Dry open ground”; Orange hatching “More or less dry open ground”; Gray “Mesophilous species/varied habitats”; Light blue “Damp grassland”; Medium blue “Marsh”; Dark blue “Aquatic”. The arrangement of species does not literally follow ecological groups but also consider the pattern of change in the succession. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

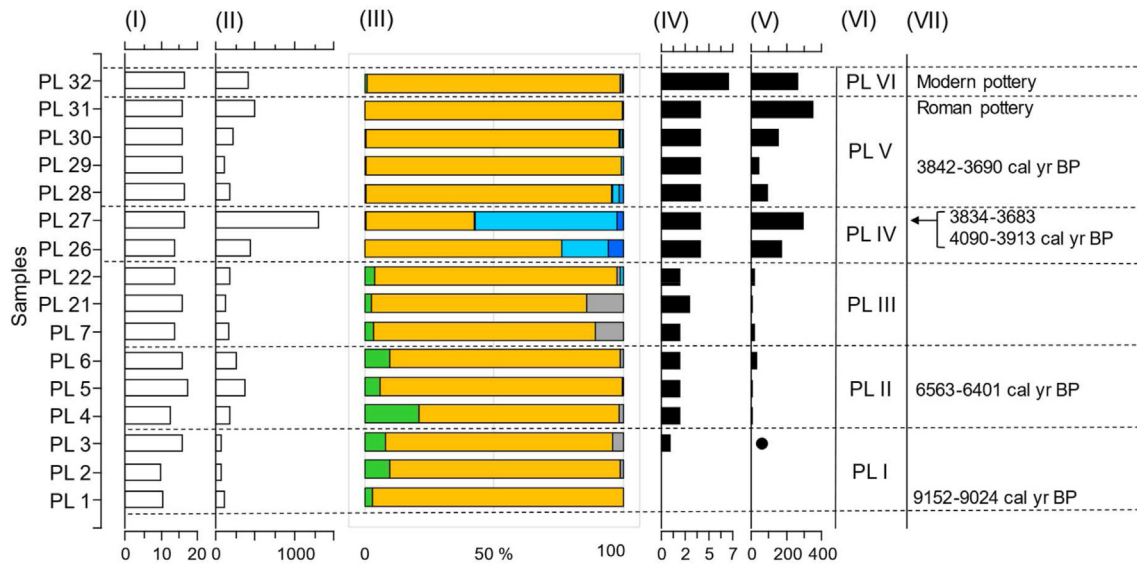


Fig. 4. Platanes, ecological profiles of mollusc assemblages. (I) Species richness; (II) Abundance (without *C. acicula*); (III) Ecological spectra (Groups); (IV) Synanthropic molluscs (Richness); (V) Synanthropic molluscs (Abundance). (VI) Local molluscan zone; (VII) Dates. Ecological groups: Green "Woodland"; Orange "Dry open ground"; Gray "Mesophilous species/varied habitats"; Light blue "Damp grassland"; Medium blue "Marsh"; Dark blue "Aquatic". (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

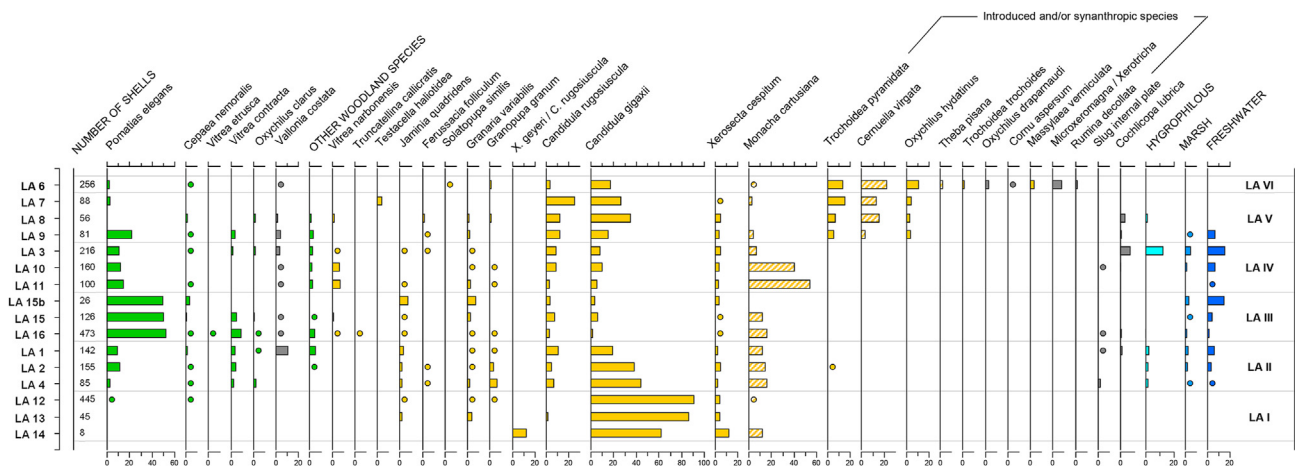


Fig. 5. Lavoir de Grand-Mère, molluscan diagram (percentages). Ecological groups: Green "Woodland"; Orange "Dry open ground"; Orange hatching "More or less dry open ground"; Gray "Mesophilous species/varied habitats"; Light blue "Damp grassland"; Medium blue "Marsh"; Dark blue "Aquatic". The arrangement of species does not literally follow ecological groups but also consider the pattern of change in the succession. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.1.4. Palaeoenvironments at platanes

The Boreal assemblages (9152-9024 cal yr BP) indicate a Mediterranean steppe vegetation (zone PL I). Rare residues of a semi-forest malacofauna could have been reworked or transported. The slight development of shade-loving or semi-forest taxa in the grayish silt with pseudomycelia (zone PL II) does not reflect the emergence of pre-forest formations but perhaps a simple densification of grass that being possibly colonized by some woody plants. Artefacts are present at the top of this zone (PL 6) and several synanthropic molluscs testify to an already strong impact on plant formations. It also is from here that the sclerophyllous oaks are represented almost continuously, with a brief interruption when a damp grassland takes hold (PL 26 and 27). The continuity between zone PL I dated at its base to the Boreal and zone PL II corresponding to the Late Atlantic (early Middle Neolithic, 6563-6401 cal yr BP) is only apparent. There probably is a hidden significant erosion gap.

The anthropogenic impact is accentuated in zone PL III before the development of a damp grassland during the Early Bronze Age (zone PL IV; 4090-3913 cal yr BP) in connection with fluvial inputs and a rise in the water table. This fluvial episode in a damp grassland then gives way to colluvial-fluvial sedimentation within a moderately damp grassland in which synanthropic species continue to gain importance (zone PL V; until Antiquity). The presence of *Pinus halepensis/pinea* in zones PL V and PL VI comes with this artificialization. Synanthropic species are even more numerous at the top of the succession (Modern to contemporary) in an environment that combines grassland and ruderal habitats.

4.2. The Lavoir de Grand-Mère section

4.2.1. Stratigraphy and sediment description

The trench was 16 m long. Its average depth was 2.60 m, but two

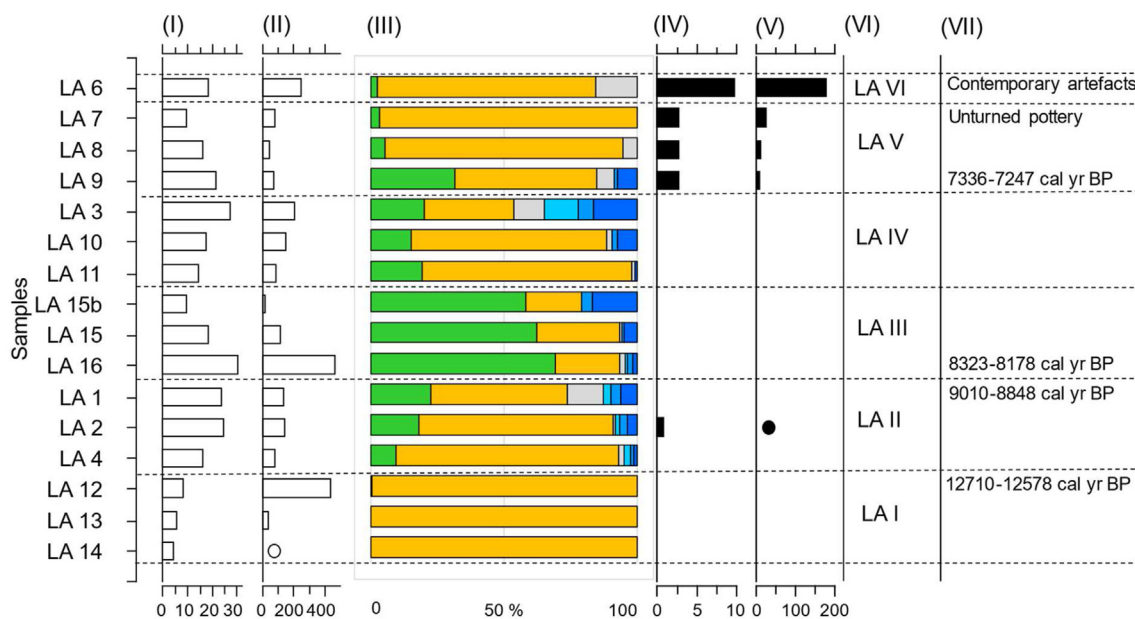


Fig. 6. Lavoir de Grand-Mère, ecological profiles of the mollusc assemblages. (I) Species richness; (II) Abundance (without *C. acicula*); (III) Ecological spectra (Groups); (IV) Synanthropic molluscs (Richness); (V) Synanthropic molluscs (Abundance). (VI) Local molluscan zone; (VII) Dating. Ecological groups: Green “Woodland”; Orange “Dry open ground”; Gray “Mesophilous species/varied habitats”; Light blue “Damp grassland”; Medium blue “Marsh”; Dark blue “Aquatic”. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

deeper holes were drilled at the ends (LOG 3 and LOG 1) allowing the observation of sediments approximately 5 m thick (Fig. 2). Geotechnical studies showed that the Quaternary deposits must be 7–8.5 m thick. They probably lie on the Tortonian bedrock and begin with a silty sequence over 4 m thick, of which only the upper part has been reached by the trench. Noted, from bottom to top: [LOG 3].

- 510–425 cm. Massive yellowish brown (10 YR 5/6) sandy silt, slightly darker at its top (10 YR 4/6), containing rare gravel at its base [Sample LA 14], then loose pebbles [-450 cm; LA 13]. Ferrimanganiferous impregnations.
- 425–399 cm. Dark yellowish brown (10 YR 4/4) sandy silt, strongly bioturbated, with a granular/polyhedral structure. Very abundant rhizoconcretions and numerous earthworm granules. [Sample LA 12].
- 399–325 cm. Dark yellowish brown (10 YR 4/6) sandy silt, still strongly bioturbated, with a polyhedral structure. Abundant rhizoconcretions. Rare tufa concretions and some gravel at the base [Samples LA 4, LA 2].
- 325–302 cm. Dark yellowish brown (10 YR 4/6) sandy silt with beds of coarse sand and pebbles. Some tufa concretions with imprints of Poaceae leaves. [Sample LA 1].

[LOG 1 and LOG 3].

- 440–230 cm. Fluvial channel 4.6 m deep, the base of which was not reached. Decimetre beds of silt, sand, and pebbles up to 20 cm in diameter. The silt levels are bioturbated and have a polyhedral structure. Colour ranging from light yellowish brown (10 YR 6/4) to dark yellowish brown (10 YR 4/6). Many tufa concretions. Imprints of Poaceae, and oogonia of Characeae. Strong erosional base. [Samples LA 16, LA 15, LA 15b].
- 295–270 cm. Chalky-looking sediment, yellowish brown (10 YR 5/4), bioturbated. Pebbles coated with tufa. Tufa concretions, imprints of Poaceae. [Sample LA 11].

- 270–238 cm. Yellowish brown (10 YR 5/4) sandy silt. Granular structure, bioturbations underlined by pseudomycelia. Dull gravel lenticules and small pebbles. Tufa concretions and rhizoconcretions. Erosional base. [Sample LA 10].
- 238–208 cm. Dark yellowish brown (10 YR 4/4) sandy silt, bioturbated, polyhedral structure with small aggregates and very dense pseudomycelia. Rare tufa concretions. Rare gravel. [Sample LA 3].
- 208–99/126 cm. Sandy silt, dark yellowish brown (10 YR 4/6 and 3/6) then dark brown (10 YR 3/3), heterogeneous, bioturbated, discreet pseudomycelia. Tufa concretions less and less abundant. Sand and coarse elements progressively more numerous. Slight erosional base. [Samples LA 9, 8 and 7].
- 99/126–38/45 cm. Dark yellowish brown (10 YR 4/4) silty sand. Many pebbles. Polyhedral structure with medium-sized aggregates, strong bioturbation. [Sample LA 6].
- 38/45–0 cm. Topsoil, darker, granular structure.

Very few artefacts were found: rare shards of unturned pottery in the LA 7 sample and ceramic shards from contemporary times in the upper levels (LA 6 and topsoil).

4.2.2. Molluscan succession

Six zones were distinguished (LA I to LA VI; Figs. 5 and 6).

LA I (Samples LA 14, LA 13 and LA 12). Assemblages in this zone almost exclusively contain dry open habitat species. The oldest assemblage (LA 14), which is not very reliable, is comparable to the following ones because the fragments of *Candidula gigaxii* are largely dominant. Fragments of *Candidula rugosiuscula* and/or *Xerocrassa geyeri* were found, the latter species being a possible relict of colder conditions. The following two assemblages are similar. *Candidula gigaxii* represents around 90% of the shells collected. *Xerosecta cespitum* is not negligible (4%). *Monacha carthusiana*, *Candidula rugosiuscula*, *Granaria variabilis* and *Granopupa granum* can also be found. The whole is typical of a discontinuous dry grassland, with low woody plants and possibly trees. Rare shells of “semi-forest” molluscs (*Pomatias elegans* and *Cepaea nemoralis*)

appear at the top (LA 12). The environment is steppe-like, and the climate is of Mediterranean type.

LA II (Samples LA 4, LA 2 and LA 1). The ecological spectrum is diversifying. The proportion of *Candidula gigaxii*, still dominant, considerably decreases (45% in LA 4, 20% in LA 1). We find two thermophilic species, *Ferussacia folliculum* and *Trochoidea pyramidata*. Taxa with forest affinities are diversifying and their proportion is increasing. *Pomatias elegans* is accompanied by *Cepaea nemoralis*, *Vitrea contracta*, *Oxychilus clarus*, as well as *Carychium tridentatum*, *Merdigera obscura* and *Punctum pygmaeum*. Signs of fluvial activity appear, first with *Galba truncatula* and then with *Pisidium* sp. and especially *Radix balthica* and *Gyraulus laevis*. This last, pioneer species, lives in calm and clear waters (Welter-Schultes, 2012). We probably are in the presence of a grassland in the process of become denser, possibly wooded, progressively more humid, with an increasing fluvial influence.

LA III (Samples LA 16, LA 15 and LA 15b). There is a high proportion of molluscs with forest affinities (around 60%), a low proportion of molluscs from dry open ground (between 20% and 30%) and an increasing fluvial influence. The LA 16 assemblage is the most characterized by a forest affinity. *Pomatias elegans*, very abundant, is accompanied by *Cepaea nemoralis*, *Vitrea contracta*, *Vitrea etrusca*, *Oxychilus clarus*, *Merdigera obscura* and *Punctum pygmaeum*. This forest component then significantly decreases. *Ancylus fluviatilis* is added to the previous aquatic species. It lives in running waters. In mainland France *V. etrusca* is only known from Early Neolithic levels in a Holocene tufa at Manosque, Alpes-de-Haute-Provence (Ollivier et al., 2015). In full, this zone corresponds to an open woodland environment which rapidly is starting to decline.

LA IV (Samples LA 11, LA 10 and LA 3). Molluscs with forest affinities regress quite sharply, while those from dry open ground generally become dominant again. *Pomatias elegans* only represents 11–15%. It is accompanied by rare *Cepaea nemoralis*, *Vitrea contracta*, *Oxychilus clarus*, *Nesovitrea hammonis*, *Punctum pygmaeum*, *Carychium tridentatum* and *Merdigera obscura*, as well as *Vallonia costata*. The composition of the malacofauna of open environments is changing. *Monacha cartusiana* maintains high numbers and accounts for almost half of LA 11 and LA 10 assemblages, probably indicating the existence of denser and more humid grasslands, a pattern confirmed by the development of *Vallonia pulchella* and *Cochlicopa lubrica*. The aquatic influence reaches its maximum in relative values in LA 3. In summary, zone LA IV shows a decline in the tree cover and the development of a mesophilic, ultimately wet grassland.

LA V (Samples LA 9, LA 8, LA 7). The malacofauna of open habitats is considerable. The local environment is drying up and, above all, synanthropic and/or recently introduced snails thrive. It is the appearance of three of these species (*Trochoidea pyramidata*, *Cerņuella virgata* and *Oxychilus hydatinus*) that leads to ascribe the LA 9 assemblage to this zone. In this assemblage, species with forest affinities still represent more than a quarter of the shells. The aquatic influence is still being felt. But the last hygrophilous species disappear from the next assemblage, like almost all of the woodland taxa. The molluscs of dry grasslands are spreading again. Three synanthropic species constitute up to 35% of the assemblages. The environment consists of a dry grassland clearly anthropised.

LA VI (Sample LA 6) This last zone is distinguished by the number of synanthropic and/or recently introduced species (10 taxa) and by their abundance (71% of the shells). Besides *Trochoidea pyramidata*, *Cerņuella virgata* and *Oxychilus hydatinus*, we find *Theba pisana*, *Trochoidea trochoides* and *Massylaea vermiculata* which live in dry open ground, but also the mesophile *Oxychilus draparnaudi*, *Cornu aspersum*, and *Microxeromagna lowei*/*Xero-tricha conspurcata*. The ruderalization of habitats, thus, contributes to the establishment of shade-loving species.

4.2.3. Charcoal and other fire evidence

Dominated by the vine (*Vitis vinifera*) which is associated with Prunoideae, oaks (deciduous *Quercus*, *Quercus coccifera/ilex*) and pines (*Pinus halepensis/pinea*), the most recent charcoal assemblage (LA 6) shows a ruderal environment in keeping with the contemporary rural context. In addition, one can note the frequency of deciduous oak (which can be found in LA 2 and in the whole of LOG 1) and the presence of sclerophyllous oaks in PL 4 and PL 2 (LOG 3) as well as in PL 8 and PL 6 (LOG 1).

In light of the small amount of charcoal, the evidence of fires or wildfires is discreet but reoccurring. In all levels of LOG 3 (except the oldest PL 14 and PL 13) there are remains of burnt shells and sometimes heated gravel or pebbles. Burnt shells are also present in LA 15, PL 11 and PL 3 (LOG 1).

4.2.4. Palaeoenvironments at Lavoir de Grand-Mère

Zone LA I, characterized by the overwhelming predominance of *Candidula gigaxii*, shows the existence of a dry, discontinuous grassland, possibly dotted with woody plants. The climate is temperate but dry. The presence of *Xerocrassa geyeri* in LA 14 makes it possible to consider a transition following a colder climate phase. The discreet pedogenesis described in LA 12, as well as the abundant malacofauna at this level, are signs of a lull in morphogenic processes. AMS dating on *Candidula gigaxii* (12710–12578 cal yr BP) would place this first zone in the Younger Dryas. The conditions are very different in the upper part of the silt sequence (zone LA II): relative closing of the vegetation cover (dense wooded grassland), warmer temperatures and increasing fluvial influence. The presence of strictly Mediterranean thermophilic snails is consistent with that of sclerophyllous oaks. The fluvial influence announces the imminent incision of a major channel followed by its infilling. The top of zone LA II dated on charcoal (9010–8848 cal yr BP) corresponds to the end of the Boreal. The channel infilling is dated to the Older Atlantic (8323–8178 cal yr BP). The incision of this river channel and its infilling could be the consequence of the abrupt climatic event around 8200 cal yr BP, invoked by Berger and Guilaine (2009). In the middle Rhône Valley, the Southern Alps and Provence, this sedimentary crisis is well identified by a brutal erosion and a coarse alluvial sedimentation. During the expanse of zone LA III there is an open forest environment of which the optimum (LA 16) will be short lived. The closing of vegetation cover is accompanied by increased fluvial activity with the formation of tufa. The decline of the tree cover announced at the end of this zone becomes obvious in zone LA IV. A more humid grassland is set up by the time we reach the chalky and terrigenous layer which seals the infilling of the channel. The following gullying and its filling reveal an increase in humidity closely associated with a final fluvial influence. Colluvial inputs, however, become significant from LA 3 on. With zone LA V, we find a dry grassland as the setting for colluvial dynamics and moderate pedogenesis. Even before artefacts can be found, the anthropization process results in the opening of the landscape and the arrival and then expansion of synanthropic species. The base of this zone, and therefore the earliest manifestation of populations of *Cerņuella virgata*, *Oxychilus hydatinus* and *Trochoidea pyramidata*, are dated to the Older Atlantic (7336–7247 cal yr BP) and to the Early Neolithic. A gap of several millennia therefore separates this zone from the next one (LA VI), dated to contemporary times, which shows the full expression of synanthropic species and ruderal environments, as well as the sedimentation of a last colluvial layer.

4.3. The Marbre Noir section

4.3.1. Stratigraphy and sediment description

The substratum was not reached by the trenches of 4.50 m depth

(Fig. 2). Two trenches were used, Trench 2 only providing additional information to Trench 4 (sandy silt at its base). From bottom to top: [Trench 4].

- 455-395 cm. Sandy silt, brown (10 YR 5/3) and yellowish brown (10 YR 5/4) to light brownish gray (10 YR 6/4), rich in rhizoconcretions. The upper part contains limestone gravel. Bioturbated, this heterogeneous deposit contains a few calcareous dolls and presents a polyhedral structure underlined by a dense pseudomycelia. [Samples MN 21, MN 22, and MN 23].
- 395-335 cm. Clayey silt strongly enriched with sand in its upper part. Yellowish brown (10 YR 5/4) to dark brown (10 YR 3/3) towards the top. Much gravel at the base, then lenses of gravel and pebbles. Significant bioturbation and polyhedral structure. Marked secondary carbonatation. Very abundant rhizoconcretions. Strong erosional base. [Samples MN 24, 25, 13].
- 335-145 cm. Sandy silt to silty sequence, dark yellowish brown (10 YR 3/4) at first, then dark brown (7.5 YR 3/2) and finally brown (7.5 YR 4/3) at the top. Polyhedral structure and variable bioturbation. Pseudomycelia. Abundant rhizoconcretions in the lower third (up to MN 6). Coarse elements increase in size and quantity from the base to the top where they can form lenses. Lichen perforations are sometimes numerous (MN 8 and MN 10). Erosional base. [Samples MN 12, 4, 5, 6, 7, 8, 9, 10, 11 and 14].
- 145-90 cm. Dark yellowish brown (10 YR 4/4) sandy silt. Rather abundant pebbles and gravel. Bioturbations and fine polyhedral structure. [Sample MN 15].
- 90-10 cm. Brown (10 YR 4/3) sandy silt, poorly sorted. Abundant pebbles which can form pockets. Probable mixing by ancient ploughing. [Sample MN 16].
- 10-0 cm. Topsoil.

[Trench 2].

- 359-295 cm. Yellowish brown sandy silt. Rhizoconcretions, calcareous dolls. Some gravel bearing traces of oxidation-reduction. [Sample MN 1].
- 295-165 cm. Sequence like that observed between -310 and -145 cm depth in Trench 4. Strong erosional base. [Sample MN 2].
- 165-135 cm. Sequence like that observed between -145 and -90 cm depth in Trench 4. [Sample MN 3].
- 135-40 cm. Sequence like that observed between -90 and -10 cm depth in Trench 4. [Not sampled].
- 40-0 cm. Topsoil.

There are fragments of unturned pottery from the MN 5 and MN 6 samples (around -275 cm). MN 7 delivered a flint shard and fragments of baked clay, possibly cob, in addition to pottery fragments. Unturned pottery is becoming quite abundant in MN 11. The MN 14 sample contains both unturned pottery and fragments of Roman pottery likely from the upper levels. The number of Roman artefacts then increases in MN 15. It is at this level that planting pits (*scrobes*) were dug for vine cultivation. These agrarian traces contain pottery dated between the 1st century BC and the 3rd century AD. The last deposit in the sequence contains Modern or contemporary artefacts (MN 16).

4.3.2. Molluscan succession

Six zones have been defined, denoted MN I to MN VI (Figs. 7 and 8).

MN I (Sample MN 1). The assemblage consists exclusively of species from dry open ground, except for rare fragments of *Pomatias elegans*. Two species constitute 73% of the assemblage: *Xerocrassa geyeri* and *Granaria variabilis*. Together with *Jaminia*

quadridens, these species are common in the loess-like Pleistocene assemblages of the region, and they are currently found in the dry orophilic grasslands of southeastern France (Magnin, 1989, 1993), e.g., Ste-Victoire Mountain (see Fig. 1). The presence of more thermophilic species probably is linked to pollution. The environment is a steppe, arid and cold.

MN IIa (Samples MN 21 and MN 22). The dominant species is *Candidula gigaxii* while fragments of *Xerocrassa geyeri* are rare. Other open ground species are *Granaria variabilis*, *Granopupa granum*, *Candidula rugosiuscula*, *Monacha cartusiana* and *Urticicola* sp. *Pomatias elegans* occurs in very low numbers as well as *Cepaea nemoralis*. The environment is still a dry grassland possibly strewn with a few woody plants. The importance of *C. gigaxii* indicates a climate improvement.

MN IIb (Sample MN 23). The assemblage is shared out between species of open environments, still in the majority, and semi-forest species. *Pomatias elegans* is now dominant without significant changes in the rest of the assemblage. *Granopupa granum* is more abundant. This zone is characterized by a brief progression of woody plants.

MN IIc (Samples MN 24 and MN 25). The malacofauna is again less abundant and has fewer *Pomatias elegans* than in MN IIb. Cover by woody plants probably has decreased.

MN III (Samples MN 13, MN 12, and MN 4). Molluscs with forest affinities and mesophilous species are dominant. There are some hygrophilous and paludal snails. The woodland malacofauna mainly comprises *Pomatias elegans* (from 27% to 44%), *Carychium tridentatum* (from 10% to 19%) and *Oxychilus clarus* (from 6% to 14%), species accompanied in smaller numbers by *Cepaea nemoralis*, *Vitrea contracta*, *Nesovitrea hammonis* and *Punctum pygmaeum*. Relatively abundant (up to 20%), *Vallonia costata* can be assimilated here with woodland species. Dry open ground snails are diverse but not abundant. They include thermophilic species such as *Ferussacia folliculum*, *Trochoidea pyramidata* and *Cerņuella virgata*. The presence of *C. virgata*, a clear synanthropic species, gives evidence for a noticeable anthropization.

MN IV (Samples MN 5, MN 6, MN 7, MN 8, MN 9, and MN 10). Molluscs from dry open ground overwhelmingly dominate. Concerning species with forest affinities, the share of *Pomatias elegans* still decreases from MN 5 (24% of the assemblage) to MN 9 (3%) before a slight increase in MN 10 (9%). The poor conservation of the shells of this species is significant. Many may have been transported or reworked. The other forest or semi-forest species are gradually disappearing. Among the many species of dry open ground, some reach important percentages here, particularly *Candidula gigaxii*, *C. rugosiuscula* and *Monacha cartusiana*. Another notable change is the number of synanthropic or recently introduced taxa. *Trochoidea pyramidata* and *Cerņuella virgata* are well represented. *Oxychilus hydatinus*, *Cochlicella barbara*, *C. acuta*, *Theba pisana* and *Oxychilus draparnaudi* successively appear. A few rare hygrophilous and paludal gastropods are sporadically present.

Assemblage MN 2 of Trench 2 would belong to zone MN III or the base of MN IV in Trench 4. Assemblage MN 3 of Trench 2 is related to MN 9 of Trench 4. It probably corresponds to the top of zone MN IV.

MN V (Samples MN 11 and MN 14). Molluscs from dry open ground represent more than 95%. There are only rare protoconchs and other fragments of the semi-forest *Pomatias elegans*. Dominated by *Candidula rugosiuscula*, *C. gigaxii*, *Trochoidea pyramidata* and *Cerņuella virgata*, this assemblage indicates a dry grassland.

MN VI (Samples MN 15 and MN 16). MN 15 almost exclusively includes taxa from dry open ground, but woodland and mesophilic snails are again more visible in the most recent level of the stratigraphy (MN 16). We note the presence of new synanthropic species, either mesophilic (*Cornu aspersum*, *Microxeromagna lowei*)

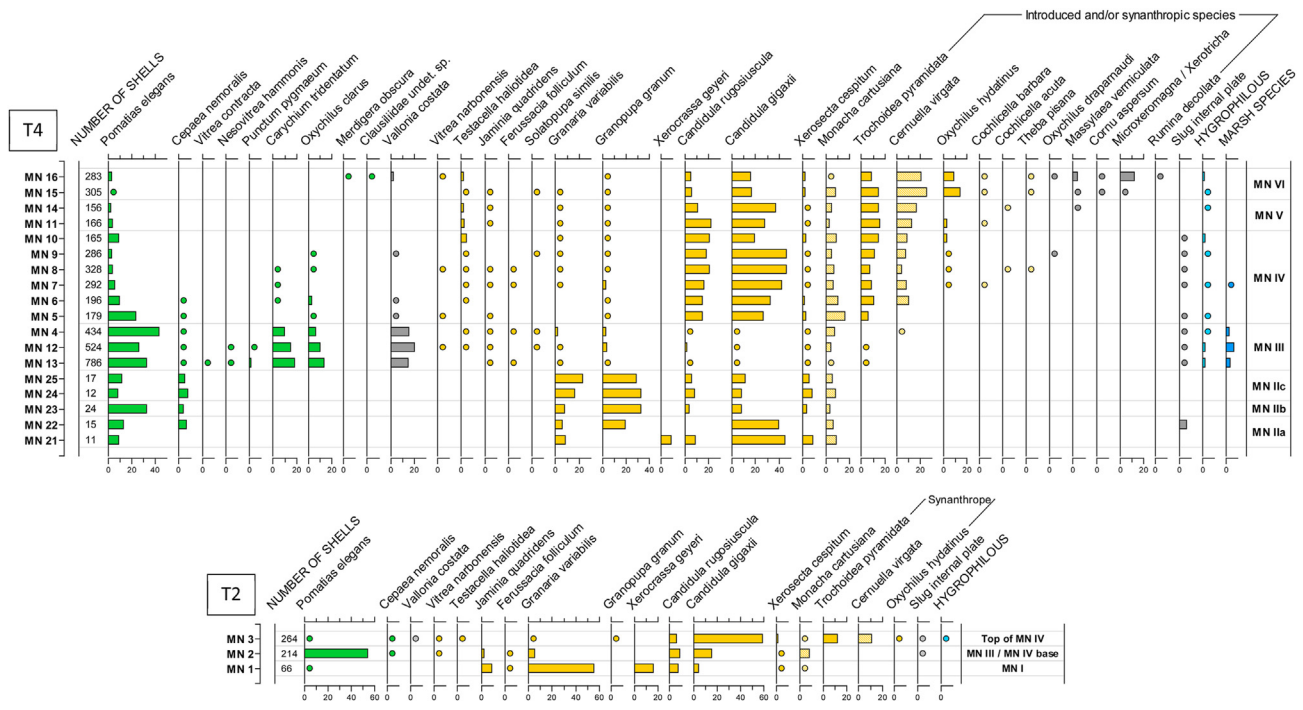


Fig. 7. Marbre Noir, percentage molluscan diagram, Trench 4 (T4) and Trench 2 (T2). Ecological groups: Green “Woodland”; Orange “Dry open ground”; Orange hatching “More or less dry open ground”; Gray “Mesophilous species/varied habitats”; Light blue “Damp grassland”; Medium blue “Marsh”; Dark blue “Aquatic”. The arrangement of species does not literally follow ecological groups but also consider the pattern of change in the succession. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

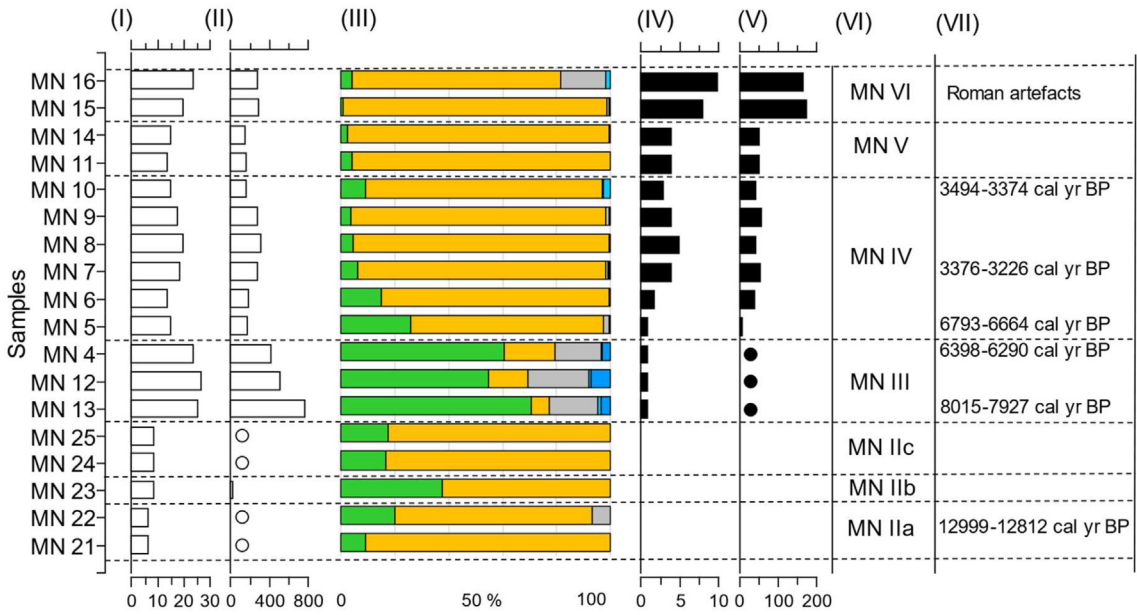


Fig. 8. Marbre Noir, ecological profiles of mollusc assemblages (Trench 4 only). (I) Species richness; (II) Abundance (without *C. acicula*); (III) Ecological spectra (Groups); (IV) Synanthropic molluscs (Richness); (V) Synanthropic molluscs (Abundance). (VI) Local molluscan zone; (VII) Dating. Ecological groups: Green “Woodland”; Orange “Dry open ground”; Light blue “Mesophilous species/varied habitats”; Light blue “Damp grassland”; Medium blue “Marsh”; Dark blue “Aquatic”. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Xerotracha conspurcata) or from open ground (*Massylaea vermiculata*), as well as the return of *Vallonia costata* and woodland taxa such as *Merdigera obscura*. Anthropization helps the maintenance of open environments while creating artificial habitats favourable to certain ruderal, mesophilic and shade-loving species.

4.3.3. Charcoal and other fire evidence

Charcoal fragments are present in Trench 4 from MN 13. They are more numerous in MN 7, in MN 10, then in the Roman and Post-Roman levels (MN 15, MN 16). The data seem to show first a predominance of deciduous oak (present regularly from MN 12 and particularly abundant in MN 7 and MN 8), then a reversal in the

proportions in favour of sclerophyllous oaks (*Quercus coccifera/ilex*) at the level of MN 10, and finally a development of *P. halepensis/pinea* in the Roman or Post-Roman levels where it is accompanied by the olive tree and Prunoideae.

Besides the charcoals, many heated or burnt elements have been observed in almost all the stratigraphy. Remains of burnt shells can be found as of the base of Trench 4 (*P. elegans* in MN 23). Heated gravel and pebbles as well as bone are then observed from MN 5 to MN 8. Heated pebbles are again noted in MN 11 and MN 14.

4.3.4. Palaeoenvironments at Marbre Noir

The predominance of *Xerocrassa geyeri* and *Granaria variabilis* in zone MN I indicates a steppe and cold environment. The assemblage will have subsequently been polluted by thermophilic species. This interpretation is compatible with the dating of *G. variabilis* (17343–17052 cal yr BP) which would place this zone in the Older Dryas. Zone MN II corresponds to more temperate assemblages in which *Candidula gigaxii* plays a major role. The environment is a dry grassland in which woody plants can occasionally reach a certain importance (MN IIb). The dating of *C. gigaxii* (12999–12812 cal yr BP) would place this improvement during Allerød. The MN III zone follows a significant erosion phase revealed by the stratigraphic correlations between the different trenches dug on the site. This major erosional unconformity could correspond to the abrupt climatic event around 8200 cal yr BP, already detected at Lavoisier de Grand-Mère. The date of MN III (8015–7927 cal yr BP), a little more recent than that of LA III, and the absence of alluvial coarse sediment, are probably due to the position of the former sequence, higher and farther from the valley floor. Zone MN III is characterized by the importance of woodland assemblages in a more humid environment. *Oxychilus clarus* plays a remarkable role. The date obtained on shells of this species places the base of this zone and therefore the woodland optimum of the succession within the Older Atlantic. However, the amount of open ground molluscs increases towards the top of the zone where rare shells of the synanthropic snail *Ceruella virgata* are present. This evolution towards more open and somewhat drier environments is dated to the Younger Atlantic (6398–6290 cal yr BP) and can probably be linked to an increasing human activity on the site during the Middle Neolithic. In the next zone MN IV, the species with forest affinities decrease sharply, leaving room almost entirely for species from dry open ground. Artefacts (especially fragments of unturned pottery) are present throughout this phase which is therefore associated with human activity on the site itself. They will then be found all over in the upper part of the stratigraphy. Apart from a slight development of synanthropic taxa, the specific composition of malacological assemblages hardly changes in this zone which corresponds to most of the colluvium in Trench 4, between –275 and –190 cm. The first part of this zone is still dated to the Younger Atlantic (6793–6664 cal yr BP). The slight date inversion is related to a sudden acceleration of anthropogenic impact in the Middle Neolithic. The environment then remains relatively unchanged until the Subboreal (Middle Bronze to Late Bronze Age, 3394–3374 cal yr BP, 3376–3226 cal yr BP). This colluvium is the result of an erosive activity, which is reinforced during the Bronze Age when sclerophyllous oaks prevail over deciduous oaks (MN 10). Zone MN V confirms an opening of the vegetation and xeric conditions, while the fragments of unturned pottery become more numerous. During Roman times (MN VI), the landscape was finally split into dry open environments, associated with a cover of Aleppo pines, and ruderal habitats, while the cultivation of vines and olive trees can be attested. Human activity, as evidenced by agrarian traces and numerous artefacts, lead to an artificialization of habitats favourable both to shade-loving and synanthropic species which have become an essential component of the assemblages.

5. Comparison between successions

A Correspondence Analysis (CA) was applied to the assemblages of the three sites of the Torse watershed (Fig. 9). The factorial plane 1–3 can be split into two. The right half ($F1 > 0$) is characterized by the presence of species belonging to mainly natural or weakly anthropized environments, both open and closed. The left half ($F1 < 0$) predominantly hosts synanthropic and/or recently introduced species which are typical of strongly anthropized landscapes, revealing the turnover which profoundly modified land snail communities during the second half of the Holocene. Four stages are clearly evident in this analysis as in the zonation of the malacological diagrams: Lateglacial/Early Holocene and its cold or more temperate steppe environments; Atlantic, somewhat humid, which is split between open woodland environments and parkland-type grasslands; the end of the Subboreal with open environments, either dry or wet; and finally the Subatlantic, during which dry open and ruderal environments coexist, and where synanthropic and introduced taxa reveal a high degree of artificialization.

The validated ^{14}C dates do not conform to a uniform chronological distribution. They probably underline the discontinuity of sedimentation and geomorphic activity (Fig. 10). Most dates are situated between the very end of the Boreal and the first third of the Younger Atlantic. Some concern the Lateglacial (from the Older Dryas to the Younger Dryas). Finally, others are placed either in the Bronze Age or during the second half of the Subboreal. Roman and contemporary records dated by the artefacts must also be considered.

6. Discussion

6.1. From cool to lasting temperate steppes

The three successions analysed in the Torse watershed begin with light-coloured sandy silt formations, rich in secondary carbonates. The spatial distribution of these formations in the region seems to be modelled on that of the Upper Pleistocene sandy loess (Bosq et al., 2018) which they reworked and from which they can be difficult to distinguish at first sight (Bonifay, 1962; Mazenot, 1956).

The mollusc assemblages of these sediments are of two types. The oldest one is an assemblage with *Xerocrassa geyeri*, *Granaria variabilis* and *Jamnia quadridens* (Marbre Noir, Zone MN I, Sample MN 1). It would seem to date from the Older Dryas (17343–17052 cal yr BP) and to point to a rather cold steppe environment although *X. geyeri*, yet typical of the periglacial environments in southeastern France, is not strictly indicative of cold climate (Magnin, 1993).

The second type of assemblage is characterized by the abundance of *Candidula gigaxii* which can represent 70%–90% of the malacofauna. Present in the south of France since the Lateglacial, populations of *C. gigaxii* will experience a strong growth around 9000 BP (Magnin, 1997 and unpublished data). In zone MN II at Marbre Noir, whose base dates to Allerød (MN IIa, 12999–12812 cal yr BP), we also found *Granaria variabilis*, *Granopupa granum*, *Candidula rugosiuscula* and *Monacha cartusiana*, as well as, secondarily, *Pomatias elegans*, *Cepaea nemoralis* and *Xerosecta cespitum*. The climate is temperate, Mediterranean type. Overall, the environment is a dry grassland dotted with woody plants. The tree cover intermittently gains a certain importance. Zone MN II can be correlated with zone LA I at Lavoisier de Grand-Mère, the top of which is dated to the very beginning of the Younger Dryas (LA 12, 12710–12578 cal yr BP) but the base of which seems to correspond to the base of MN II dated to Allerød (presence of *Xerocrassa geyeri*).

Candidula gigaxii assemblages show little change except for the importance of *Xerosecta cespitum* in the Younger Dryas in LA 12. It

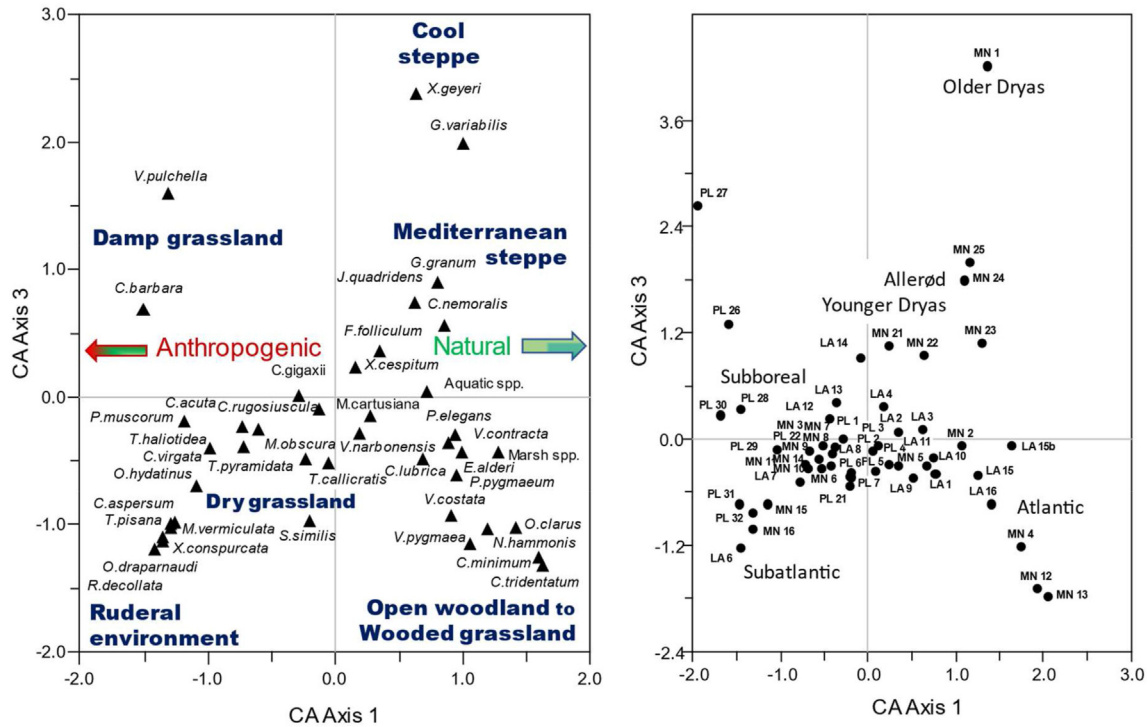


Fig. 9. Correspondence Analysis (CA) applied to the mollusc assemblages of the three sites of the Torse watershed. Projection of taxa on the interpreted factorial plane 1–3 (left) and projection of the assemblages (or samples) on the same plane (right).

should be noted that *X. cespitum* and *C. nemoralis* are, because of their size and their availability, the two species generally consumed in western Provence during the Epipaleolithic and Mesolithic (Boone, 1976; Granier, 1976; Rillardon and Brugal, 2014).

At Platanes, the more recent *C. gigaxii* assemblages from zone PL I are dated to the end of the Boreal (9152–9024 cal yr BP). Their characteristics differ slightly from previous assemblages. They hold a higher specific richness and a more equitable structure, leaving ample space for *Candidula rugosiuscula* and *Monacha cartusiana*. *Vitrea narbonensis*, a species typical of Mediterranean open scrubland, can be found there. Other thermophilic Mediterranean elements appear at the top of this zone (*Ferussacia folliculum*, *Trochoidea pyramidata*). Apart from a more pronounced bioclimatic Mediterranean trait, this modulation in the *Candidula gigaxii* assemblages could simply be the mark of a densification of the herbaceous layer and the presence of a few trees or shrubs.

The permanence of snail assemblages of steppe environments until the Boreal period seems at first glance contradictory with the regional pollen data which show a first woodland development (essentially pines) during the Lateglacial interstadial and then during the Preboreal, but especially the development of a “powerful deciduous oak woodland” the supremacy of which was established around 8000 BP (Andrieu-Ponel et al., 2000; Triat-Laval, 1979).

The *Candidula gigaxii* assemblages could be consistent with the pine woodlands which break up the monotony of the steppes from the Lateglacial interstadial, if these woodlands have been very open. All species in the assemblages concerned can indeed tolerate a light cover of shrubs or pines, including *C. gigaxii*, *C. rugosiuscula* and *Xerosecta cespitum* (Bonavita, 1965; Labaune and Magnin, 2001, 2002). Nevertheless, the low number of semi-forest snails seems to suggest a very light canopy.

Zone PL I (Boreal), on the other hand, is not a priori in agreement with the presence of a vigorous deciduous oak forest as usually suggested by palynology, even if the malacofauna is diversifying

and finally seems to be richer in both Mediterranean and shade-loving taxa. A more detailed examination of the pollen sequences suggests however a significant spatial heterogeneity of the Boreal woodlands. Around the Étang de Berre (which is the outlet of the Arc River, and therefore of the Torse), steppe vegetation persists concurrently with the expansion of the oak forest (Triat-Laval, 1982). In Tourves, east of Aix-en-Provence, Nicol-Pichard (1987) underlines the maintenance of *Juniperus* which reflects the survival of open and xerophilic vegetation despite the importance of deciduous oak woodland. But above all, in central Provence again, charcoal analysis of Baume de Fontbrégoua does not allow to distinguish the vegetation of the Boreal from that of the Preboreal, both characterizing an open environment with *Juniperus* accompanied by *Pinus sylvestris*, *Quercus cf. pubescens*, and more Mediterranean species (Thiébaud, 1997). Finally, only 8 km east of the Torse, the Saint-Antonin tufa (Fig. 2) shows, for the Preboreal-Boreal period, unstable conditions in an open woodland environment (Beaulieu et al., 2005). Indeed, the development at the beginning of the Boreal (8890 ± 70 BP) of calcareous tufa and deciduous oak woodland suggested by leaf imprints, sometimes gives way to a fine detrital sedimentation resulting from the erosion of Jurassic marls (Ali et al., 2003). These silt layers contain mollusc assemblages indicating rather open environments (Magnin and Thion, 1988).

6.2. Immature woodland assemblages at their optimum

The previous silty deposits with their steppe malacofauna are often followed by darker formations characterized by a moderate pedogenesis and containing a malacofauna with more forest-dwelling snails. This is true for the whole region.

At Lavoir de Grand-Mère, *Pomatias elegans* comes, at the end of the Boreal (LA II, 9010–8848 cal yr BP), as a sign of the installation of assemblages characterizing less open environments. With it, we

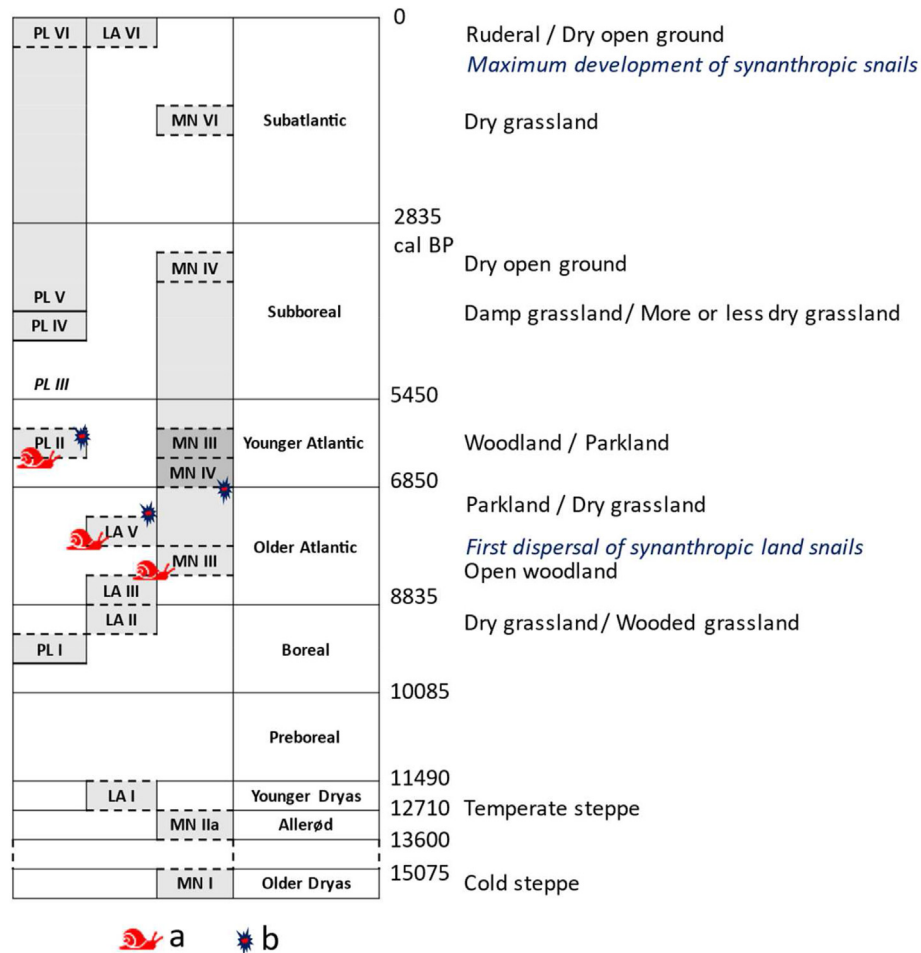


Fig. 10. Correlation between mollusc assemblage zones of local value defined for the three sites of the Torse watershed. Only the parts dated by radiocarbon or archaeology are shown. a: First occurrences of the synanthropic snail *Ceruella virgata*; b: First occurrences of fragments of unturned Neolithic pottery.

also can find mesophilous or forest-related species which afterward will be more abundant. While *Candidula gigaxii* is losing importance, the share of taxa from open environments remains appreciable and outright xero-thermophilic species can be found. The presence of sclerophyllous oaks charcoal fragments and the remains of burnt shells suggest a Mediterranean vegetation crossed by fires. This evolution is compatible with the data of anthracology in central Provence which show, at the end of the Mesolithic and at the beginning of the Neolithic, the development of *Pinus halepensis* which is then better represented than *Quercus cf. pubescens* and whose predominance raises the question of an early human impact (Thiébault, 1997; Vernet, 1980). At Tourves, a sudden development of sclerophyll oaks can be observed, along with a rise in thermophilic taxa. (Nicol-Pichard, 1987).

The first snail assemblages that indicate a true forest environment date from the Older Atlantic: 8323-8178 cal yr BP at Lavoire de Grand-Mère (LA III, Sample LA 16) and 8015-7927 cal yr BP at Marbre Noir (MN III, Sample MN 13). Charcoal fragments of deciduous *Quercus* are most commonly found. Fragments of burnt *P. elegans* are still present, but so are heated bone and rubefied clay aggregates (Marbre Noir), which implies fire activity, possibly of human origin. These woodland assemblages are observed around the 8.2 ka climatic event, and more precisely after the gully phase that, in the middle Rhône Valley, eroded the pedologic covers that had started to develop. Berger and Guilaine (2009) note that the north Mediterranean forest seems less uniform and closed, at

this time, than it has been traditionally described by palaeobotany, and that it is periodically burned by fires, the impact of the first farmers communities of the last Mesolithic being to be clarified. Such observations agree with our data.

What is remarkable is the relative poverty and immaturity of these woodland snail assemblages, even in their most evolved forms. We may be surprised not to find at least certain species relatively common today in Provence, even in rather young coppices and young woodlands (*Acanthinula aculeata*, *Clausilia rugosa*, *Lauria cylindracea* for example, also present in the tufa of St-Antonin (Magnin, 1985), in the absence of those which can be confined in more humid and more mature woodland formations (*Discus rotundatus*, *Helicodonta obvoluta*, *Ciliella ciliata*, *Aegopinella pura*, *Sphyradium doliolum*, Clausiliidae ...). The composition of the "Woodland" ecological group developed for this study from a broad and advantageous definition of forest species is significant (see the definition of ecological groups and Table 1 above). All in all, the two most common "woodland" species in the Torse Holocene deposits, but also quite generally in the French Mediterranean sequences, are *Cepaea nemoralis* and *Pomatias elegans* – i.e. two rather "semi-forest" species with a mesophilic tendency. Here, the frequency of these taxa underlines the amplitude of their ecological valency. *Cepaea nemoralis* is present in 28 of the 53 assemblages studied and *Pomatias elegans* in no less than 50 assemblages. The latter species is present in extremely variable quantities (Min. = 0; Max. = 260; Median = 7). It forms the backbone of "woodland" malacological

assemblages. In the case of the two most forest-like assemblages of the Torse, LA 16 and MN 13, there are 70% of “woodland” snails but *P. elegans* alone represents respectively 52% and 33% of the malacofauna, with still 24% and 7% of molluscs from dry open ground. This predominance of a species that Germain (1931) described as “generally xerophilic” and which manifests on Mont Ventoux a preference for scrubland and open and fairly dry woodland (Magnin, 1991), the indigence of strictly forest-dwelling species, and also the permanence of xerophilic snails from open environments, are all features that one might admit at first as characteristics of Mediterranean woodland assemblages in southern France during the Holocene. This is not completely true. Assemblages rich in species typical of forest habitats exist in Provence. Today they are only found in some places, mainly on the cooler and wetter northern slopes. During the Holocene, in the many studied sites in Provence and Languedoc, such hotspots are rarely uncovered (Martin, 2004), and they are sometimes observed during unexpected time periods such as the Bronze Age (Berger et al., 2000; Bizot and Sauzade, 2015; Martin, 2004; Renault et al., 1996). We must conclude that during the Holocene as a whole, Mediterranean ecosystems remained heterogeneous and frequently open (Beaulieu et al., 2005).

In addition, the French Mediterranean region probably did not play any role in the recolonization of more northern areas of Europe by forest snails in the first half of the postglacial, even as a transit area from the Iberian and Italic peninsulas. The generally available pool of species (Magnin, 1991; Martin, 2004) is indeed very different from the first forest assemblages of central and western Europe (Horsák et al., 2019). Barring some isolated hot spots, the French Mediterranean region holds, during the Holocene, very few assemblages of purely forest snails, those being indicative of forests with dense canopies.

6.3. Early significant woodland clearance

These mollusc assemblages stop indicating a true forest environment around 6500 cal yr BP at Marbre Noir (MN IV) and certainly before 7336–7247 cal BP at Lavoir de Grand-Mère (LA IV). Human activity is likely to have had an impact. At Marbre Noir it is indeed from the beginning of zone MN IV, around 6500 cal yr BP, that we can observe the almost constant presence of unturned pottery fragments, sometimes supplemented by heated bones and pebbles. Concerning charcoal, *Pinus* breaks the hegemony of the deciduous oak. As recorded by the malacofauna in the Torse watershed, the woodland optimum is therefore quite short. West of the studied area (Marais des Baux) the pollen sequences make it last throughout the Atlantic, the deciduous oak woodland remaining dominant at the beginning of the Subboreal, before the first signs of an impact of agro-pastoral activity (Andrieu-Ponel et al., 2000). At the outlet of the Arc River (Étang de Berre), the first decline of the deciduous oak woodland is only expressed by pollen during the Subboreal. It is associated with a rise in sclerophyllous oaks (Laval and Médus, 1989). However, Triat-Laval (1982) underlined in the same area an impoverishment of the biodiversity of the deciduous oak woodland at its maximum extent, during the Atlantic, which she related to a moderate human impact. Further east on the contrary, in central Provence (Nicol-Pichard, 1987), the decline in deciduous oak woodland attributed to human activity would begin before 7040 ± 130 BP, which matches with our data. Closer to the Torse, in the Saint-Antonin-sur-Bayon tufa, the most forest-like snail assemblages are dated to the Older Atlantic (Magnin and Thinin, 1988), whereas the regression of *Quercus pubescens* in favour of *Acer monspessulanum* would already indicate an anthropogenic influence (Ali et al., 2003; Magnin and Thinin, 1988). The heliophilic *Acer* could also be a reflection of

the Mediterranean character of woodland ecosystems during the Holocene optimum. (Beaulieu et al., 2005).

At Platanes, the development of woodland assemblages remains very short-lived and very limited (PL II). These assemblages dated to the Younger Atlantic (6563–6401 cal yr BP) already testify to a strong anthropogenic impact with the probable establishment of an agro-pastoral, parkland-type landscape. Sclerophyllous oaks also develop at the top of this zone, and it is from this point that elements of anthropogenic origin can regularly be found.

Our results well fit with the synthetic regional model of Berger et al. (2019) which shows the first major threshold in the demographic proxy curves around 7500 cal yr BP and simultaneous impacts on the vegetation cover from 7250 cal yr BP.

6.4. Landscape anthropization and the growth of a synanthropic malacofauna

Recent introductions of certain Mediterranean species outside the Mediterranean regions are a remarkable phenomenon. They are deliberate or accidental, and possibly then prolonged by active dispersal (Germain, 1930; Horsák et al., 2019; Locard, 1880; Peltanová et al., 2012). Before becoming a potential source for the colonization of non-Mediterranean regions, southeastern France has first enriched itself, since the Neolithic, with many synanthropic snails (Magnin, 1991, 1992; Magnin and Martin, 2012; Martin, 2004). This enrichment continues today with introductions that may exhibit the characteristics of biological invasions (Aubry et al., 2005, 2006; Brancotte, 2001). All the three successions of the Torse show the growing importance of synanthropic and/or introduced species since the Early Neolithic. Hence, they contribute to a better understanding of the first stages of this phenomenon that is at the origin of a profound renewal of land snail communities in Mediterranean France. We can distinguish three sets of species participating in this turnover:

Introduced Mediterranean xerophilic species. These are xerothermophilic snails which, most often, originally lived in the maritime environments of the coasts of the Maghreb and the Mediterranean. They are rather anthropochorous and sometimes eaten by humans. Today, several of them have a range that extends well beyond the Mediterranean Basin, sometimes with invasive behaviours. They constitute a major contribution to biodiversity and to the “mediterraneanization” of mollusc communities in the open environments of southeastern France. For lack of a sufficient stratigraphic and geographical network, it is sometimes difficult to determine, for some, if this is the result of a real introduction, a reintroduction, or an inland diffusion from possible coastal refugia. They have never been found in Pleistocene deposits in France, except for *Cerneuella virgata* and an archaic form of *Trochoidea trochoides* in the Lower Pleistocene of Marseille (Dubar and Magnin, 1992).

The case of *Trochoidea pyramidata* is unique. It appears twice in the Torse successions. First between 9000 and 8000 cal yr BP with other thermophilic Mediterranean snails, perhaps in connection with the coming of favourable bioclimatic conditions rather than because of an anthropogenic dispersal which would be too precocious. A second wave of dispersal is observed later, continuous and lasting, undoubtedly attributable to human activity. It begins in the Early Neolithic at Lavoir de Grand-Mère, at the beginning of the Middle Neolithic at Marbre Noir, and not before the Bronze Age at Platanes. The growth of *T. pyramidata* populations always remains moderate.

Much more common, *Cerneuella virgata* is now widespread in various European countries and as far as Australia where it is invasive (Baker, 2012; Grossu, 1983; Peltanová et al., 2012; Welter-Schultes, 2012). No glacial refuge has been identified in

southeastern France. However, shells have been dated to LGM in southern Italy (De Santis et al., 2010) and *C. virgata* was one of the species consumed in the Mesolithic in southeastern Spain (Fernández-López de Pablo et al., 2011). The continued presence of *C. virgata* at Lavoir de Grand-Mère begins at the same time as that of *Trochoidea pyramidata*, in the Early Neolithic. Its importance then increases as the assemblages lose their last forest character. At Marbre Noir, it was in the Middle Neolithic, around 6300 cal yr BP that *C. virgata* appeared and then developed together with the regular presence of unturned pottery fragments. It is particularly well represented in the Roman and Post-Roman levels (zone MN VI) whose environments are the most artificial. At Platanes we find *C. virgata* at the beginning of the Middle Neolithic (we are probably missing older Neolithic deposits) and its population considerably increases from the Bronze Age to reach its maximum in the Roman and Post-Roman periods (zone PL VI). These data confirm and clarify the regional evolution already described (Magnin and Martin, 2012; Martin, 2004; Martin et al., 2005; Moreau et al., 2017; Romey et al., 2015). The dynamics of *Oxychilus hydatinus* can be compared to that of *C. virgata* although its arrival can sometimes be delayed. The success of this colonization is surprising, *O. hydatinus* not having the “climbing behaviour” responsible for the long-distance passive dispersal of species such as *Monacha cartusiana*, *C. virgata* and *T. pyramidata* (Aubry et al., 2006; Benke and Renker, 2005; Peltanová et al., 2012).

The case of *Cochlicella barbara* and *Cochlicella acuta* is a little different. Originally closely dependent on maritime influences (Germain, 1930), *C. acuta* and especially *C. barbara* often remain dependent on fairly humid conditions when they are introduced inland (Cadevall et al., 2016; Welter-Schultes, 2012). The *Cochlicella* species are totally absent at Lavoir de Grand-Mère where they probably did not find favourable habitat. At Marbre Noir both species are present sporadically from the Late Bronze Age on (zone MN IV), at the same time as *Oxychilus hydatinus*. At Platanes only *C. barbara* can be found, first in a very discreet way, around 6500 BP (Middle Neolithic), then in the Early Bronze Age when a damp grassland takes place.

To these four species, three later arrivals must be added. It is however difficult to date these arrivals to the Torse because of the weak development of the protohistoric and historical layers. *Theba pisana* is one of the most widely dispersed snails in the world by human activity, whether deliberately or accidentally (Däumer et al., 2012). It is present in Provence, in Martigues, in the 2nd century BC (unpublished result). *Massylaea vermiculata* was introduced in Provence during the Iron Age (5th century BC in Martigues, unpublished result). This species lives in a wide variety of rather dry habitats, in the wake of past or present human occupancy (Cadevall et al., 2016; Grosbois, 2009). Finally, *Trochoidea trochoides* may have been present in the south of France as early as the Middle Neolithic (Martin, 2004).

Introduced Mediterranean mesophilous species. *Cornu aspersum*, widely consumed, native to North Africa (Guiller et al., 2012), is now worldwide dispersed under Mediterranean, temperate, and even subtropical climates (Ansar et al., 2009). It was introduced in the south of France as in England during Roman times (Evans, 1969) the precise chronology of it still needing to be defined. *Xerotracha conspurcata* and *Microxeromagna lowei*, impossible to differentiate here, are often syntopic. According to Welter-Schultes (2012) they probably originated in the western Mediterranean region and were then introduced in the east. In Provence, this introduction can be traced back to Roman times (Magnin, 1990, 1991; Martin, 2004).

Species possibly native, mesophilous or shade-loving, but synanthropic. These are snails whose historical biogeography is still poorly known. *Oxychilus draparnaudi* is nowadays very widely

dispersed throughout the world. The species originates from southwest and western Europe (Welter-Schultes, 2012). It lives in sheltered and humid habitats and in all kinds of anthropized and ruderal environments (Cadevall et al., 2016; Kerney, 1999; Welter-Schultes, 2012). Its populations seem to have developed in Provence from the Late Neolithic (Martin, 2004). In the successions of the Torse, it is mainly represented in the layers of historical age, but it has been found since the Early Neolithic at Lavoir de Grand-Mère. *Merdigera obscura* is a forest species present in the Torse from the end of the Boreal but which reappears later thanks to artificialized habitats, here as in other sequences in the region (Bonnet et al. in press). *Rumina decollata* is frequent in Provence in interglacial deposits (Magnin, 1991; Magnin et al., 1990) and can be found again starting in the Late Neolithic (Martin, 2004). Like other snails already mentioned, this species, initially confined to coastal environments, preferentially colonizes ruderal environments inland.

All in all, the result of this turnover is considerable. In the three successions studied, the synanthropic species, gradually introduced since the Early Neolithic, represent 41–52% of all taxa and 58–71% of individuals in the most recent assemblages (contemporary period). For comparison purposes, in Java, the percentage of individuals of introduced species was proposed as an indicator of disturbance, the abundance of these species decreasing with the closing of the canopy while their number is highest in agroforests (Nurinsiyah et al., 2016).

6.5. Climate change versus human impact

Until the Older Atlantic, the palaeoenvironments of the Torse evolved unambiguously under the sole control of climate: replacement of the last assemblages of “cold” steppe environments with *Xerocrassa geyeri* (MN 1; Dryas Ancien) by steppe assemblages with *Candidula gigaxii* and other Mediterranean species *lato sensu* (MN II, LA I; Allerød/Younger Dryas); development of less open environments during the Boreal with the presence of particularly thermophilic species around 9000 cal yr BP when the average temperature equaled or exceeded present day values (Romey et al., 2015); finally, around 8000 cal yr BP, the growth of an open woodland with Mediterranean traits, which marks the forest optimum in the watershed. Regarding this first half of the Holocene, however, it is difficult to describe the nuances of the climate with precision. It is possible that the assemblages at the top of the PL I and LA II zones, with their xero-thermophilic taxa, bear the mark of the 9.3 ky event which would be characterized, in southeastern France, by an episode of warming and/or dry climate preceding a wetter phase (Audiard et al., 2021). The signal is however very tenuous in a context which was already rather warm and steppe-like. The correlation of zones LA III and MN III (including the hiatus which come first) with the 8.2 ky event could be more convincing. However, rather than the malacofauna on its own, it is all the geomorphological, sedimentological and malacological data that are of significance. For that reason, at Lavoir de Grand-Mère, it is undoubtedly more reasonable to consider the whole river channel infilling (from at least 8200 until a little before 7300 cal yr BP; see Fig. 2) as being able to correspond to the period of enhanced rainfall evidenced, in the western Mediterranean, between ca 8.9 and 7.3 cal yr BP (Zanchetta et al., 2007). During this wet period, the optimum of the woodland malacofauna was however short-lived despite a favourable climate (LA III), the development of assemblages of more open environments (LA IV) suggesting an early anthropogenic impact, while the first clear evidence of anthropization date of ca 7300 cal yr BP (base of LA V).

To find mollusc evidence of climate forcing becomes virtually impossible for the second half of the Holocene. Indeed, the

specific composition of all the assemblages of this period only makes it possible to infer an overall eumediterranean context, impossible to differentiate from current conditions. Only the wet episode dated to 4090–3913 cal BP (PL IV) may be a kind of exception. It may possibly be related to other Old Bronze detrital accumulations described in the region in a context of increased humidity (Bruneton et al., 2002). Despite a proven climatic variability (Mayewski et al., 2004) the Holocene has a relatively stable climate compared to previous glacial/interglacial cycles (Alley et al., 1997), especially since 9000 cal yr BP (Boreal). The absence, in the Holocene assemblages, of snail species clearly indicative of a climate different from our current one, makes any attempt at climate reconstruction based on the ecology of communities difficult (Magnin and Martin, 2008). In addition to this, Holocene palaeoenvironments have also been controlled since the Neolithic by anthropogenic factors (e.g., Beaulieu et al., 2005; Pons and Quézel, 1998; Roberts et al., 2011). Concerning the structure of plant formations and landscape, features to which snails are particularly sensitive (Magnin et al., 1995; Magnin and Taton, 1995), human activity very early on had a greater impact than climate change. From the Early Neolithic, the anthropogenic impact is such that it can completely mask the evidence for climate events. The land snail assemblages of the Torse lost their forest character around 6500 cal yr BP and possibly before 7300 cal yr BC, at the same time as artefacts remains appear regularly in the sequences. On the coastline, malacological analysis had already highlighted non-forest Mediterranean environments since at least 6200 cal yr BP (Romey et al., 2015). The contrast is considerable between these open environments, rich in synanthropic snails, and those of the ephemeral forest optimum during the Older Atlantic. Carroll et al. (2012) showed that it is extremely difficult to reconstruct climate change when the anthropogenic impact is strong, as is the case on the Maltese Islands where cereal agriculture has been maintained since 6800 cal yr BP. The importance of the anthropogenic impact in the Torse watershed is such that the malacofauna alone hardly allows us to discuss the role of climate since the Older Atlantic.

7. Conclusions

Although they probably are incomplete according to the general pattern in this type of geomorphological and sedimentary context, the three malacological successions of the Torse watershed, at Aix-en-Provence, are representative of the evolution observed elsewhere in this key region of the northern shore of the Mediterranean. Using proxies characterized by a low spatial resolution and originating from common sedimentary sequences, predominantly colluvial, this study completes and qualifies palaeoenvironmental reconstructions generally based on proxies with broader spatial resolution from wetland and lacustrine records.

- 1 The data obtained suggest the importance, and in places the longevity, until the end of the Boreal, of a sandy-silty sedimentation with steppe malacofauna.
- 2 The woodland optimum of the Older Atlantic corresponds to assemblages poor in strictly forest-dwelling species. These molluscan assemblages indicate relatively open woodlands with a Mediterranean character.
- 3 The clearing of vegetation and the opening of the landscape by human activity has been noticeable since the Early Neolithic.
- 4 During the Holocene as a whole, the Mediterranean landscapes of southeastern France (Provence and Languedoc) seem to have remained heterogeneous and frequently open, its truly forest-dwelling malacofauna remaining in distinct hot spots.

- 5 Anthropization has not only changed the structure of vegetation and the landscape. The increasing diffusion of many synanthropic species from the Early Neolithic to the present day has also enriched and deeply remodelled the malacological communities of open environments for 7000 yrs in southeastern France.
- 6 The importance of the anthropogenic impact is such that the malacofauna alone hardly allows us to discuss the role of climate since the Older Atlantic.

Author contributions

Stéphane Bonnet coordinated the research project (PCR) on environmental archaeology in the Arc River basin and the Aix-en-Provence area that made this study possible. He organized the field survey, measured and sampled the sections. **Carine Cenzon-Salvayre** contributed with the anthracological data. **Frédéric Magnin** carried out the molluscan analysis. He wrote the manuscript with the contributions of S. Bonnet et C. Cenzon-Salvayre. **Figs. 1 and 2** were drawn by S. Bonnet. **Figs. 3–10** and the tables were prepared by F. Magnin.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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