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The value of lichenometry and historical archives in assessing the incision of submediterranean rivers from the Little Ice Age in the Ardèche and upper Loire (France)

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Abstract

The geomorphologic impact of the Little Ice Age (LIA) was determined on two French Mediterranean rivers, the upper Ardèche and the upper Loire. In order to evaluate the impact of the LIA on the hydrology of these rivers, two historical flood chronicles were made from historical sources. The LIA can be divided in three phases of high activity (1530–1700; 1750–1810; 1840–1910). A geomorphologic study of the two rivers shows that incision is the principle process at work in the 20th century. In order to date the low terraces and bedforms present in both valleys, lichenometry was used. *Rhizocarpon geographicum* allowed the main features on the bottom of the valley to be dated using two growth curves made for the two studied areas. In the Ardèche, lichenometric dating showed a progressive evacuation of the inherited alluvial stock. The oldest lichens found on the foodplain and the outcrops indicate that incision began between the second half of the 17th century and the end of the 18th century, in the mid Little Ice Age. Incision stopped on the bedrock in the second half of the 19th century. In the Loire, the narrowness of the gorge did not allow sediment to be stored during the first half of the LIA. Very old lichens (>1000 yr of age) are present on the bedrock close to the bed. However at a number of locations, the valley slightly widens, allowing sediment that was transiting through the gorge to be stored. The geomorphologic features that characterise these basins clearly show a hydrosedimentary behaviour different before and after the beginning of the 20th century.

Keywords: Little Ice Age; Lichenometry; Gorge; Incision; Mediterranean rivers

1. Introduction

The Little Ice Age (A.D. 1550–1850) is a climatic period that was characterised by a downstream progression of glaciers worldwide. This period is largely studied in high altitude and latitude regions, but its impact on fluvial systems is poorly known. However, in the French Alps, historical, sedimentological, and geomorphological

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studies show an aggradation of most riverbeds during this period (Bravard, 1989, 2000). Indeed, a large amount of coarse sediments were produced in headwater streams as a result of the temperature decrease and the increased frequency of torrential events. In the upper part of watersheds, rivers widened and metamorphosed from meandering rivers to braided rivers. Having developed in headwater streams, these river mutations progressed downstream toward the piedmont and then the Mediterranean Sea. These riverbed evolutions appeared in the 14th century on the Rhône River at Lyon and reached the river delta in the second half of the 18th century when the torrential crisis was at its peak (Bravard, 2000).

The Little Ice Age (LIA) has been less well-studied in the Mediterranean region, and from the literature it is not possible to highlight trends in the fluvial systems. While in the Northern Alps, riverbed aggradation and mutations leading to braiding are common, in the south of France river responses to the LIA are more contrasted. Some studies have shown a trend of erosion (Dufaure, 1976; Bruneton, 1999; Gob et al., 2003), while some others have demonstrated marked sedimentation (Bravard, 1989; Macklin et al., 1995; Lespez, 1999; Calvet et al., 2002; Devillers and Provansal, 2003; Jorda and Molina, 2004). The scales and geographic contexts of the rivers studied in these papers are heterogeneous and could partly explain this diversity of responses. Nonetheless, all Mediterranean rivers have undergone extensive change during this period. Macklin et al. (1994, 1995) stated that in semiarid Mediterranean mountainous landscapes, as the climate became more humid, vegetation cover increased and as a result hillslope sediment supply decreased.

The methodology used in this paper combines lichenometry, a technique that has not been widely used in fluvial environments, and the analysis of historical archives to demonstrate the geomorphological evolution of several rivers of the Central Massif (southern France) during the last few centuries. Lichenometry is considered an accurate means of dating sediment units from the last 500 yr (i.e. the Little Ice Age) (Innes, 1985; Armstrong, 2004). Meanwhile, analyses of historical documents were very useful in illustrating how the rivers evolved during the very end of this period and throughout the 20th century (Miramont et al., 1998; Gautier et al., 2000; Gurnell et al., 2003; Jacob et al., 2006). By combining the two methods the study seeks to provide an insight into how the valley floor may have changed from the beginning of the LIA to the present. In addition, the information obtained from historical documents shall be compared to the hypothesis made based on lichenometry.

This article also shows how the lichenometric technique has been adapted for river environments. Lichenometry is based on the presence of lichens on river deposits that allows their settlement to be dated. It has been mainly used to study glacier movements in high latitude and altitude regions (Beschel, 1961; Innes, 1985). Lichenometry was elaborated in the 1950s, and since then its methodology has evolved substantially. The first study involving lichenometry in fluvial systems was made by Gregory (1976) who defined and dated flood limits using lichens present on bedrock and river banks. Later, Harvey et al. (1984), Carling (1987), Macklin et al. (1992), Maas et al. (1998, 2001), Jacob et al. (2002, 2006), Gob et al. (2003) and Keesstra et al. (2005) dated sedimentary sequences by measuring lichens on terraces, on alluvial fans, and on bedload material.

2. Study area

The upper Ardèche and the upper Loire drain the southeastern part of the French Central Massif: the former flows southward, toward the Rhone River (Mediterranean Sea), and the latter northward, toward the Loire River (Atlantic Ocean) (Fig. 1). The southern part of the massif is characterised by very steep slopes and deeply incised rivers on the right bank of the Rhone rift. The upper Loire flows in deep and narrow gorges with subvertical versants cutting into the high plateau of the Central Massif. Both of the catchments studied mainly consist of granite, gneiss, and volcanic rock; but their longitudinal and transversal profiles are quite different. The Ardèche has a well-formed concave profile with steep slopes in the headwater streams (1 to 5%). The valley widens after a few tens of kilometres leading to a relatively well-developed floodplain. The river first of all goes through crystalline rocks for about 20 km and then through calcareous rocks in the rest of the basin. The concavity of the upper Loire profile is less pronounced and the slopes are weaker (1 to 2%). The valley is quite narrow for almost its entire length with some small sedimentary basins where the valley widens.

The catchment area studied is 600 km^2 in the upper Ardèche and 880 km^2 in the upper Loire. Both rivers are very powerful as they experience very high flood events created by extremely heavy rainfalls. The maximum specific stream power recorded on the Ardèche during a 1997 event (20 yr of recurrence) is >2000 W/m^2 and over 600 W/m^2 for a frequent flood (Q_2). In the Loire, for the multicentenial 1980 flood, a maximum stream power of 3700 W/m^2 was reached. For a common flood (Q_2), the maximum stream power is about 440 W/m^2.

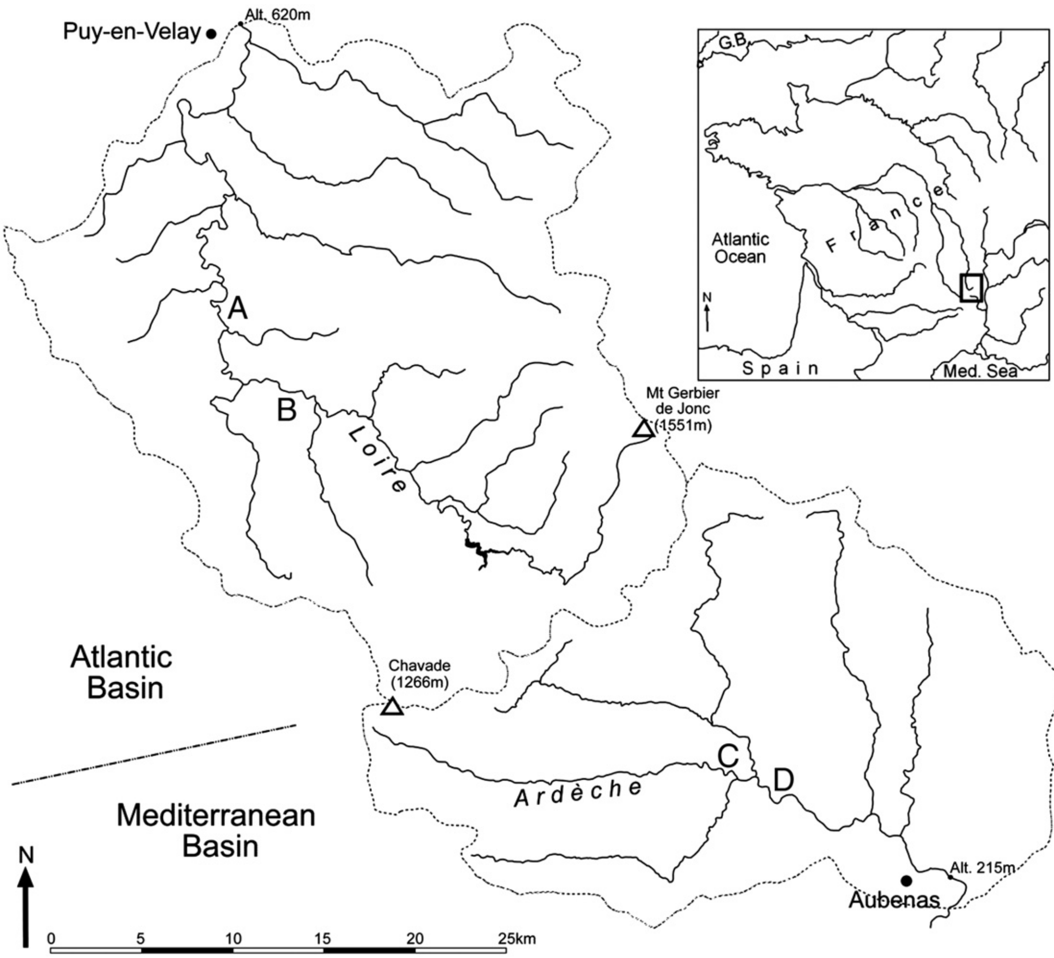

Fig. 1. Location map of the two catchments studied: the upper Ardèche and the upper Loire. The former flows southward toward the Rhone River (Mediterranean Sea), and the latter northward toward the Loire River (Atlantic Ocean). (A), (B), (C), (D): studied sites described in the text.

Even though their bedloads are composed of boulders with an intermediate axis of over 1 m, frequent floods in both rivers are able to move nearly all of the bedload (Gob, 2005).

In order to evaluate the impact of the LIA on the hydrology of the studied rivers, two historical flood chronicles were made for both upper basins. The chronicles were complied from several historical studies from the 19th and the early 20th centuries (de Mardigny, 1860; Champion, 1864; Rouchon, 1907; etc.) based on descriptions from people contemporary with the flood events. These studies were analysed by crossing-checking the information and the historical floods were classified into four qualitative classes based on of their apparent magnitude. In the Loire catchment, ancient events going back as far as the 14th century were identified, and the last four centuries were quite well-documented (Dacharry, 1974; Staron, 1987; Crépet, 1997). In the Ardèche, only a few events have been identified before the 19th century. However, a good historical record exists for the lower basin (Lang et al., 2001; Jacob, 2003; Sheffer et al., 2003). The flood chronicles of the upper Loire and the upper Ardèche correspond quite well with records found in the literature for the Mediterranean region (Gob, 2005). In this region, the LIA is characterised by an increase in flood magnitude and an increase in the number of floods. The LIA seems to be divided into three phases of high activity: one very long phase from about 1530 to 1700 and two shorter phases from 1750 to 1810 and 1840 to 1910. Between these phases, the historical archives reveal that some decades were relatively dry.

3. Methods

One of the main problems in estimating fluvial activity is the age control of erosional phases. These are usually dated by adherence to the ages of previous and subsequent deposits (Vandenberghe, 2003). Lichenometry could provide an answer for recent timescales in high-energetic rivers. Indeed, this technique has been mainly used in glacial studies but has recently shown its potential to date river incision in several catchments (Innes, 1985; Macklin et al., 1992; Gob et al., 2003; Jacob et al., 2006). Grove (1988) defined lichenometry as "a method of dating based on the assumption that the largest lichen growing on a given substrate is the oldest individual and that, if the growth rate for a given species is known, the maximum lichen size will provide a minimum age for the substrate". In fluvial environments, all of the vegetation present on blocks (including lichens) is destroyed due to the shocks generated between particles while blocks are transported by the flood. Once the blocks remain stable, a new generation of lichens may install and grow. Therefore, by simply measuring the diameters of lichens (longest axe) on blocks and using a lichen growth curve, the age of the lichens can be determined and the last time that the blocks were transported can be estimated. In order to reduce the error associated with considering coalescent lichens as a single thallus, the average of the five largest thalli were taken into account (Innes, 1985). However on relatively small surface, such as stream boulder, it is not always possible to find five large lichens. In this case the average was established using the maximum number of large thalli present, considering only the thalli with a near-circular shape.

Lichens can be measured on four types of features close to a river bed (Gob, 2005). (i) The lichens present on blocks in the bed indicate the last flood events responsible for bedform settlement. These measurements may be used to evaluate the competence of the river (Gob et al., 2005). (ii) Lichens may also be found on low terraces. In this case, they indicate the moment at which the river was no longer able to transport the block from the floodplain and thus give an age of the bed incision. Fig. 2 shows a schematic diagram describing the evolution of a river system following climatic or anthropogenic change. On step 1, the river occupies the entire width of the channel and the entire bedload is transported, except on terraces where lichens persist (G1). Step 2 shows that because of

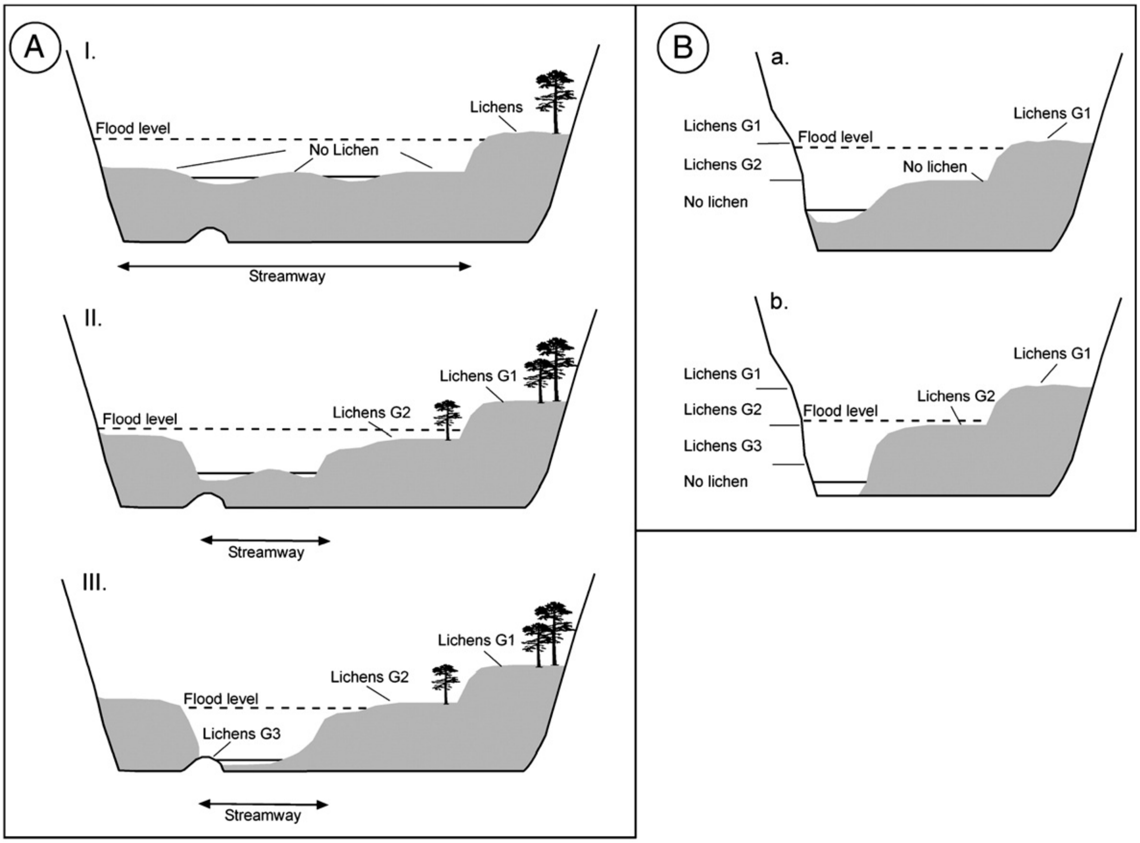

Fig. 2. Schematic diagram describing the evolution of a river system following climatic or anthropogenic change and the colonisation of new valley forms by lichens: (A) in an alluvial channel, and (B) in a bedrock channel.

river incision the floodplain is too high to allow the largest blocks on the river banks to be carried away. Therefore, a new generation of lichens (G2) may colonise the floodplain, and its age indicates when incision began. (iii) If the incision continues until the river bed excavates the bedrock underneath the alluvial sheet, lichens may then settle on the rock (G3). The thallus size gives a date for the bedrock excavation and shows that the rock has not been buried since then, which is important in relation to the hydrogeomorphologic evolution of the river system. (iv) Finally, in incised rivers, lichens can also be measured on valley sides. Often, a gradient of thallus size may be seen, showing an incision into the alluvial sheet, or in some cases paleoflood levels. In this case, the lichens give the maximum level of the suspended load and not the water level because only mechanical erosion, and not immersion, may destroy lichens.

The most frequently used species in lichenometry is *Rhizocarpon geographicum* l.s., which is very easy to recognise because of its yellow colour. This species is ubiquitous, present on every lithology, except calcareous rock, and requires direct sunlight. Its growth is very difficult in shaded conditions. These lichens may live for hundreds of years and, under certain conditions, thousands of years. Several authors have stated, however, that lichenometry is optimal only for the last 500 yr (Innes, 1985; André, 1990; Armstrong, 2004). Regional growth curves have been established for the two studied regions, the Cévennes (Ardèche) and the Haute Loire (upper Loire), mainly by measuring reference points on tombstones and old bridges (Fig. 3). These curves are presented and discussed in Jacob et al. (2002) and Gob et al. (2003, 2005). In both cases, envelop curves were considered in dating the lichens.

The Cévennes curve may be used for the last 150 yr. For older dates, another curve made by the same authors in Corsica may be used. This curve has reference points older than 2000 yr (Gob et al., 2003; Jacob et al., 2002). These authors have shown that these two curves could be used indiscriminately in both regions. The accuracy of the curves cannot be precisely calculated (Jomelli et al. 2007); however, they have been validated for the first 150 yr. Indeed, the lichen populations present within the riverbed have been classified in a size/frequency diagram and compared to the flood chronicles (Gob et al., 2005). A high correlation exists between the largest flood events and the lichen populations, which emphasises the validity of the growth curves. The first 150 yr of the curve is clearly accurate within a range of 5 yr. At 200 yr, the lichens may be dated within a range of accuracy of tens of years. Beyond this, because the small number of reference points, the older the lichens are, the less accurately they may be dated, with the largest lichens providing an approximate idea of their age.

The curve made for the upper Loire has a faster growth rate than the other two curves, mainly because of the higher humidity in the region. The curve's shape is different from the other two and from those found in the

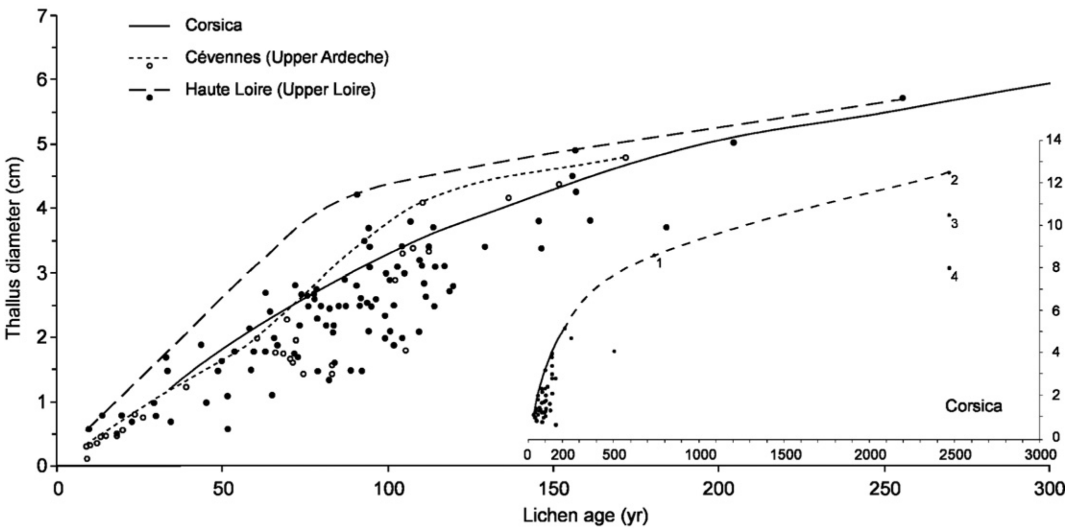

Fig. 3. *Rhizocarpon geographicum* growth curves for Corsica, the Cevennes (upper Ardèche) and the upper Loire. All thalli were measured on crystalline rocks (granite and gneiss). The envelope curves were considered. The ages of the oldest point were determined with the assistance of an historian. Point (1) was found on a block that was cut during the destruction of the dungeon from a castle destroyed in 1259. Points (2), (3) and (4) come from a fortified castle from the ninth century BP, abandoned between 600 and 259 BC. We attributed an age of 2470 yr to these lichens.

literature. Indeed *Rhizocarpon* growth curves generally have the same shape and are parallel (Innes, 1985; Grove, 1988). In this case, the growth in the first 80 yr seems correspond to the climatic conditions of the upper Loire region, but the second half of the curve is rather surprising because the growth rate resembles that of drier regions. The shape of this curve leads us to consider that only the first 80 yr are reliable. Lichen thalli > 4 cm should therefore be considered with caution as their size may only give an approximate idea of their age.

4. Results

In order to determine the rivers' evolution, lichens were measured on the different river features described above. At the same time, the levels of the alluvial sheets (floodplains, low terraces) were noted and schematic cross sections were drawn: 10 of them on the Ardèche and 16 on the upper Loire. Only four cross sections will be presented in this paper as they are the most representative and give a clear idea of the main characteristics of the studied rivers.

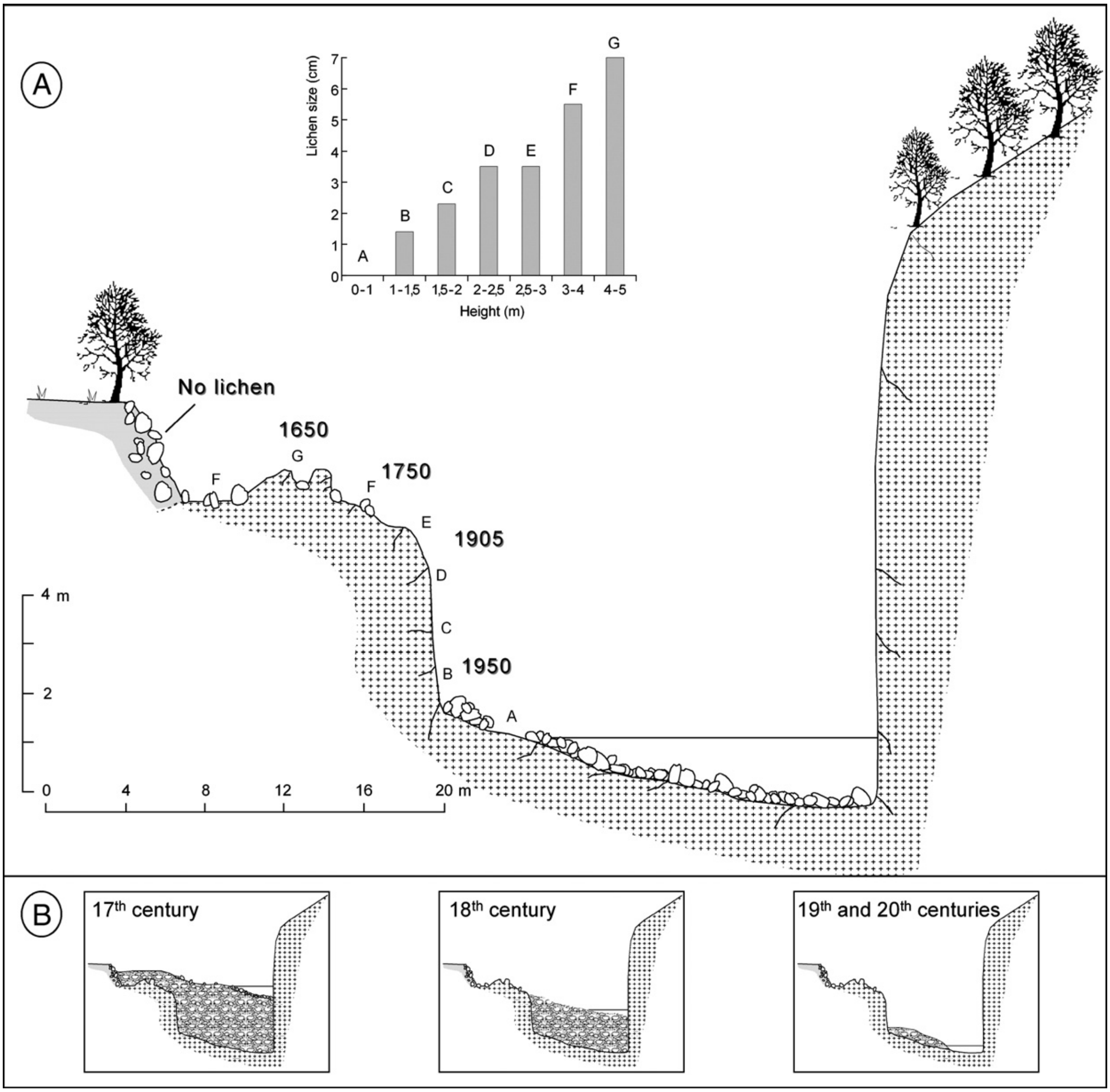

Fig. 4. (A) Sketch of a cross section of the upper Ardèche showing where the lichens were measured and their size, which clearly increases the higher one moves from the bed (from 0 to 7 cm). (B) Schematic evolution reconstructed from the lichens' size.

4.1. The incision of the Ardèche River

4.1.1. Rhizocarpon on the bedrock valley side

Fig. 4A represents the river bed of the Ardèche in the middle valley of the granitic part of the basin (Fig. 1C). At this particular place, the valley forms a bend and the low flow channel is very narrow and incised into an outcrop of bedrock. The rock is present on both sides of the river, but on the right bank (in the concavity) the river is surrounded by a high subvertical bedrock wall. In the convexity, the bedrock is vertical also, but only for about 3.5 m, and then is subhorizontal. After about 10 m, the horizontal part of the outcrop is covered by a 3-m-thick alluvial terrace. Some blocks covered by large *R. geographicum* rest on top of the outcrops at the foot of the terrace.

As the right bank is in the shade for most of the day, lichens are only present on the left bank. They were measured on the bedrock and blocks on top of the outcrops (A to G). Again, the shade created by some trees on the edge of the terrace (H) does not allow lichens to grow there. The size of the thalli measured can be seen in Fig. 4A. This clearly increases the higher one moves up from the bed. Very close to the water level, no lichens are present because frequent floods carry sediment particles large enough to erode the very base of the outcrop. Up to 3 m on the bedrock wall (B to E), thalli diameters reach a maximum of 3.5 cm, corresponding to 95 yr of age. On the shelf (F), they are >5.5 cm (250 yr) and they have colonised both blocks and bedrock. On the top of the outcrops (G), between 4 and 5 m above the bed, the diameters of the lichens are up to 7 cm (>350 yr).

The gradient in the size of the lichens may be explained by two processes: either a decrease in flood magnitude or the removal of an old alluvial sheet that filled the valley floor. In this particular case, the first hypothesis is not realistic because it would mean that during the last 400 yr the floods would have been much stronger than today. But in September 1992, the upper valley of the Ardèche experienced an event close to the 100-year flood showing palaeofloods did not have a much higher magnitude than floods of today (Lang et al., 2001). Though no remains of the alluvial sheet are visible in this particular area, the second hypothesis seems more plausible (Fig. 4B). In the early Little Ice Age, 350 or 400 yr ago, the valley floor would have been infilled by to 2 to 3 m of sediment. The channel aggradation would have allowed the erosion of the terrace on the left bank (H) and therefore excavated the bedrock shelf (F). Then, 250–300 yr ago, the bed would have progressively incised into the alluvial sheet; and the blocks present on the shelf would have been beyond the influence of floods, allowing them to be colonised by *R. geographicum*. The age of the lichens on the left bank bedrock wall indicates that the clearing of the sediment lasted throughout the second half of the Little Ice Age, between 1750 and 1950.

4.1.2. Rhizocarpon on the floodplain

About 5 km downstream a second cross section quite representative of the general morphology of the river was studied in the lower part of the upper basin (Figs. 1D and 5). In this part of the catchment, the valley width reaches up to 250 m, and the low flow channel is about 70 m wide. The floodplain (A) is between 4 and 5 m above the river bed and presents a subhorizontal surface that is alternatively occupied by alluvial forest and grasslands. Where human activity did not remove them, blocks emerge from the sandy surface of the alluvial sheet; lichens were measured on these blocks (Fig. 6A). The surface of these blocks is covered by a rich diversity of lichens and mosses and by some large *R. geographicum*. The percentage of cover and the richness of the biodiversity on the surface clearly show that the

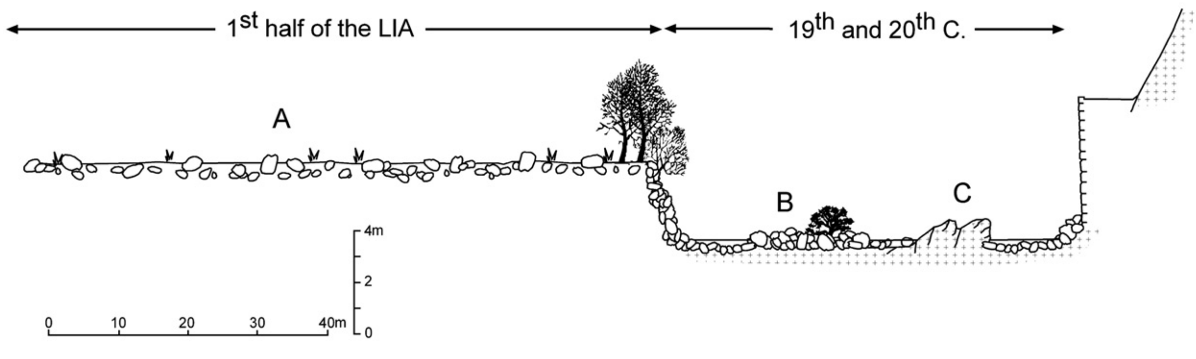

Fig. 5. Sketch of a cross section of the upper Ardèche with (A) the floodplain, (B) the boulders bars, and (C) the bedrock outcrops. This section is representative of the general morphology of the river. Lichens were measured on (A), (B), and (C) showing that the incision of the bed began 200 to 350 yr ago and stopped 160 to 180 yr ago on the bedrock.

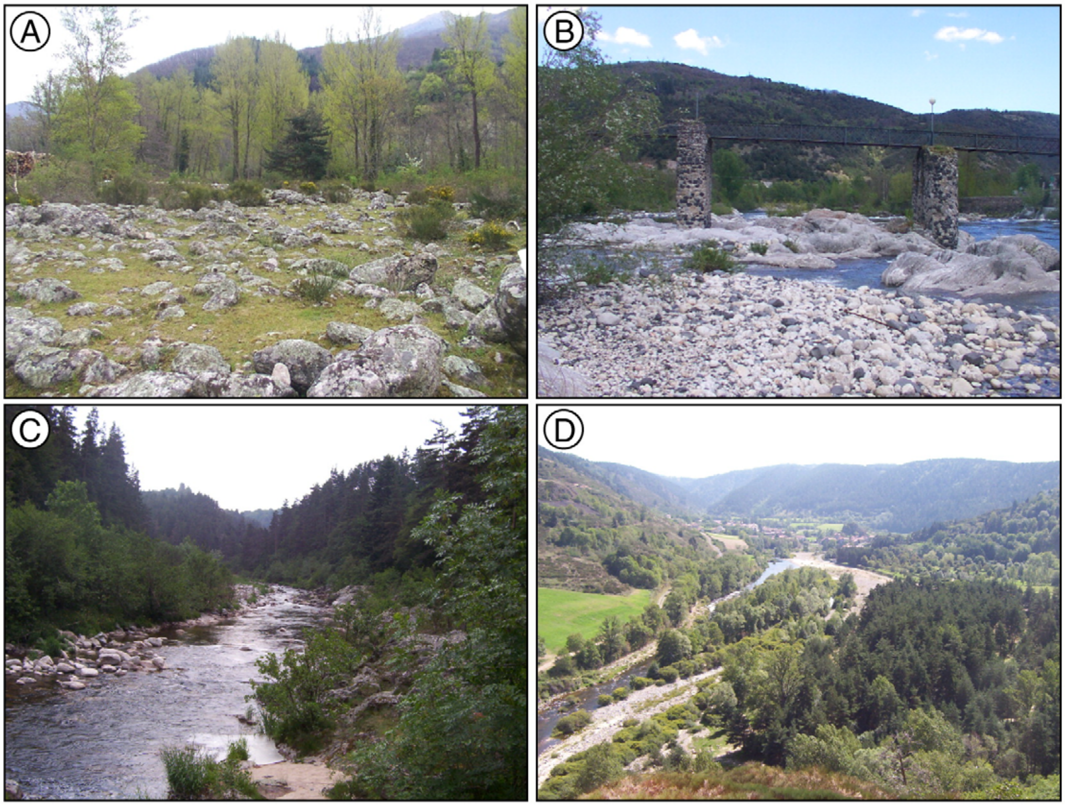

Fig. 6. Photographs of the Ardèche and the upper Loire valleys. (A) Blocks on the floodplain of the Ardèche on which large lichens allow the beginning of the incision to be dated. (B) Bedrock outcrops in the bed of the Ardèche on which 180-yr-old lichens indicate the age of the end of the incision into the alluvial sheet. (C) Narrow and incised valley floor of the Loire. Boulder bars are very small and very large lichens may be found on the bedrock shelf. (D) One of the rare sites were the upper Loire valley widens and where sedimentation could occur. The numerous channels reveal a formerly braided system.

blocks have been stable for a very long time. The largest *Rhizocarpon* have a diameter between 5 and 6.9 cm that indicates an incision of 200 to 350 yr old.

Among the main features of this reach are the large bedrock outcrops that occupy, at some places, almost the entire width of the low flow channel (Figs. 5C and 6B). The top of some of them is relatively close to the water surface (<1 m high); others almost reach the level of the floodplain. All of them are colonised by large lichens which indicates that excavation took place over 100 yr ago. Between 0 and 2 m above the water surface at low flow, the largest lichens are situated in sheltered position and their diameters are 4.7 to 4.9 cm, corresponding to between 160 and 180 yr of age. Not far upstream from the cross section, the outcrops reach 3.5 m high, and their tops are colonised by lichens up to 6.5 cm in diameter (~300 yr). Between these bedrock outcrops, large deposits of boulders (B in Fig. 5) may be found. They are almost completely devoid of vegetation, showing the high mobility of the bedload in the river bed. Only very few blocks are colonised by very small young lichens.

From the analysis of the 10 upper Ardèche cross sections, one may clearly see that river incision is the principle process at work. Lichenometric dating shows a progressive evacuation of the inherited alluvial stock. Indeed, from the source where the bedload has been almost entirely evacuated to the middle valley where the bed is deeply incised in the alluvial sheet, the river bed presents features characteristic of incision. The oldest lichens found on the floodplain and on the outcrops indicate that incision began between the second half of the 17th century and the end of the 18th century.

As the river incised the alluvial sheet, it progressively excavated the bedrock that in some places was covered by only a few centimetres of alluvium (bedrock appeared punctually in the riverbed 300 yr ago). In the first half of the 19th century, numerous outcrops were cleared, and therefore the river incision stopped. Since then, solid discharge has not been as significant as liquid discharge.

Indeed, the lichens present on the outcrops indicate that the bedrock has not been covered since then.

Ancient maps and aerial photographs have been analysed in order to determine the channel dynamics over the past 170 yr. The oldest cartographic document used in this study is the “cadastre”, surveyed between 1835 and 1840. It gives a good idea of the channel layout, shape, and width and has been compared to maps and plans from the second half of the 19th century and the early 20th century. In addition, aerial photographs from the 1950s, the 1970s, and the 1990s have been used to follow recent evolutions. This analysis has shown that the upper Ardèche was not a braided river for the last 170 yr. Despite several channel changes following the largest flood events, the ancient maps show that the channel is relatively stable. During the second half of the Little Ice Age, the Ardèche River was clearly not a braided river and did not use the entire width of the valley. These results are supported by lichenometric observations. Indeed, lichens show that the river has been deeply incised (~4 m) in the alluvial sheet since the first half of the 19th century.

4.2. The upper Loire gorge

The upper Loire is quite different from the upper Ardèche River. The river flows in a very narrow valley for almost its entire course, which leaves little space for sediment deposition. However, the valley widens in several small sedimentary basins of a few hundred meters long. These places have provided very interesting information about the sedimentation record and the evolution of the river system.

4.2.1. Rhizocarpon in the narrow valley

The first cross section described in this paper was surveyed in a narrow part of the valley (Fig. 1B) and represents the main feature found in the upper Loire. The valley width is never wider than 80 m, and in some places the width is <40 m. Ancient deposits are very rare, and the bedrock outcrops generally extend from the valley side to the valley floor. The outcrops contain many well-formed potholes. The only remains of ancient sedimentation are a few convexity deposits, more or less perched above the bed, and very rare small terraces. Vegetation is present on the valley sides almost to the level of the riverbed and very few lichens are present on the rare boulder bars.

Figs. 7 and 6C present the typical form of the valley. The Loire River flows at the bottom of one of the valley sides and is generally separated by a narrow subhorizontal bedrock shelf at a maximum of 2 to 2.5 m above the low flow water surface. In the convexities and in some straight reaches, 2-to-3-m-thick lateral bars occupy almost half of the valley. Almost no vegetation may be found on top of the bars. The largest particles are partly covered by a patina and have a few young lichens whose diameter is always <2 cm, which means that the lichen dates from the last 50 yr. Higher on the bars, more sand, and adult trees do not allow *Rhizocarpon* to grow.

Lichens have been measured on the bedrock shelf close to the channel and on the base of the valley side. The lichens are very large. On the shelf, the largest lichens range from 6.5 to 13 cm; and on the valley side up to 3 to 4 m above the water surface, the lichens reach 16 cm. All of these very large lichens found close to the river bed are very old. Our growth curve made in this region is not reliable for such large diameters, and a precise age cannot be proposed. However, the curve made in Corsica allows us to state that the thalli > 10 cm are more than 1000 yr old and that those of 8 or 9 cm are between 500 and 1000 yr old. Because of the higher growth rate in the Haute Loire, lichens with a diameter of

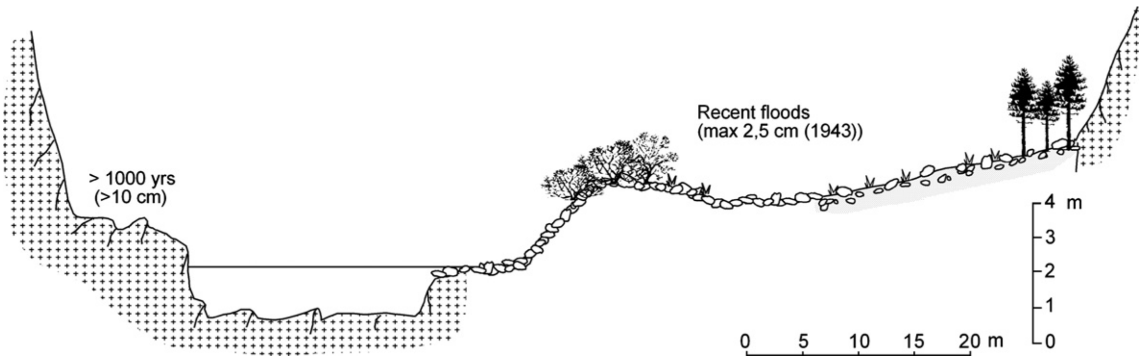

Fig. 7. Sketch of a cross section of the upper Loire. This section is representative of the general morphology of the river. The bedrock shelf at the bottom of the valley side is colonised by very old lichens, while only young lichens were found on the bars.

6 or 7 cm could be contemporary with the Little Ice Age and thus have an age of 250 to 450 yr.

Several cross sections made in the narrow gorge show that the ancient sedimentary stock has been almost entirely removed. Except for several narrow terraces, the only deposits present on the valley floor correspond to bedload transiting in the river bed. Indeed, the absence of lichens older than 80 yr on bars clearly shows that their surface has been very frequently reworked by the recent floods. On the outcrops close to the bed, very old lichens attest to the fact that the bedrock valley floor has been clear of sediment throughout the last centuries and that it has never been totally covered since then. The younger lichens (6–7 cm) and the rare small low terraces located in convexities suggest, however, that there was a more intense sediment transit in the first decades or centuries of the LIA than today. Certain relatively large bars could have been deposited and then reworked and evacuated without erasing the oldest lichens.

4.2.2. Rhizocarpon in the alluvial basins

The second cross section (Figs. 8 and 6D) concerns one of the rare sites where the valley widens up to 250 m (Fig. 1A). On this site, several terraces are clearly visible: the upper terraces probably date from the late Pleistocene and the lower ones are clearly much younger (Defive, 1996). The main unit is 3.5 m above the water surface at low flow. This large deposit is a subhorizontal bar mainly composed of sand with some large blocks. Some very large poplars are remnants of the early stages of colonisation by the vegetation that followed the abandonment of the deposit. Nowadays, this pioneering vegetation has been almost completely replaced by 70-to-80-yr-old pine trees (estimated using dendrochronology). In the upper Loire, the colonisation vegetation of bars follows this sequence: first come willows, then poplars arrive very quickly; this is followed by pine trees, oaks, and eventually beeches. Outside of the river environment, the natural forest of this region consists of beeches with oaks and sometimes *Pinus silvestris* (Valadas, 1984).

Pine trees present on the main level of the floodplain do not allow *Rhizocarpon* to colonise the blocks. This deposit was colonised by the forest because pastoral farming had been abandoned, or more probably because of the decrease of the flood magnitude and frequency in the early 20th century. Indeed, in Fig. 8, multiple channels may be seen. They reveal a formerly braided system and emphasize an excess of sediment load. This period of high hydrosedimentary conditions must have stopped about 100 yr ago considering the age of the pines and the time they need to colonise a deposit (from our observations of the large flood event of 1980, this takes about 20 yr). Before 1900, this site functioned as a sedimentation basin where the transiting load could stop triggering bed aggradation through deposition of sediment.

At this site, old lichens are very rare. Even the largest blocks do not have *Rhizocarpon* larger than 1.5 cm. The site was deeply perturbed by the 1980 flood event (hundreds of years of recurrence). Most of the lichens found in this site were 1 cm in diameter and corresponded to this flood. Two aerial photographs of 1948 and 1987 clearly show that the vegetation had been significantly damaged by the flood. This large flood seems also to have deposited a large volume of sediment in the channel in the centre of the valley, which has been progressively evacuated since then. Indeed, 25-yr-old lichens occupy only the top of several blocks. Their base, which is still completely clear, does not harbour any lichens. This shows that these blocks have been put in place by the 1980 flood but that only the top of them has emerged from the surface of the bar. Since that time, a recent flood (probably 2001) has eroded a part of the deposit without reworking these blocks. This observation shows the very important role played by extreme events in valley sedimentation. The sedimentation process works by fits and starts; with a massive supply during large floods and, between them, progressive erosion made by the more common floods.

In the upper Loire, sedimentation was much more limited in extent during the LIA than in the Ardèche. The gorge narrowness did not allow sediment storage. The

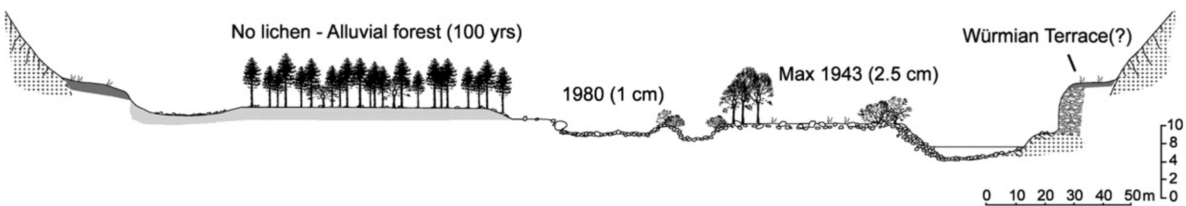

Fig. 8. Sketch of a cross section of the upper Loire. This section is representative of the rare places where the valley widens and where sediment storage is possible. Only young lichens were found on the deposits; but remains of a braided system are still present, showing the high hydrosedimentary activity from the last century.

large lichens present on the outcrops show clearly that an alluvial sheet could not persist in the narrow part of the valley. A few younger lichens indicate that at some places bars have been fixed for several years but that the sheet was never continuous. However, a small number of sedimentation basins in the Loire have allowed part of the sediment that was transiting along the narrow gorge to be stored. The geomorphologic features that characterise these basins clearly show a hydrosedimentary behaviour different before and after the beginning of the 20th century.

5. Discussion

Lichenometry has demonstrated that the Ardèche has experienced significant sedimentation in the first half of the LIA, followed by incision of the river between the second half of the 17th century and the end of the 18th century. This chronology fits rather well with the Mediterranean context. Indeed, the different studies concerning this region indicate that there was significant detritic activity in the first part of the LIA (Arnaud-Fassetta, 2000; Grove, 2001; Calvet et al., 2002; Descroix and Gautier, 2002; Maas and Macklin, 2002; Gob et al. 2003; Jacob, 2003). Fig. 9 represents the periods of strong sedimentation through time in different parts of the Mediterranean region and in different geographic contexts (from the upper part of the basins to the deltas). This figure is based on the literature and shows that the LIA is not homogenous and is characterised by a succession of periods of high activity and periods of calm: one long period (1500–1700) of high activity and two shorter periods of high activity (1770–1815 and 1840–1910). Jacob (2003) has shown three oscillations of the Ardèche alluvial floor from historical archives. He has demonstrated that the river has been characterised by incision after each detritic phase. In his study, he concluded that in the southeastern part of the Central Massif the rivers did not undergo a metamorphosis like those of the Alpine rivers, but rather some phases of short pulsations of the alluvial floor. Note that these periods of strong sediment supply correspond almost exactly to the three torrential phases that affected the Mediterranean region during the LIA (Fig. 9) (these torrential phases have been emphasised from a compilation of 11 papers that give a historical flood series of more than 20 rivers in France, Italy, and Spain).

However, the phases of high activity dated to the 18th and 19th centuries are not evident in every study: indeed, Arnaud-Fassetta (2000), Grove (2001), and Calvet et al. (2002) have shown quite clearly that sedimentation was very strong until the 18th century (17th for Calvet et al.) but much more limited afterwards; Maas et al. (1998) considered that this strong detritic activity finished at the end of the 18th century in Crete; and in this study, the lichenometric dating suggests a decrease of sediment supply during the second half of the LIA. Indeed, *Rhizocarpon* clearly shows that the alluvial floor has been stable since the late 18th century. The two active periods of the 18th and

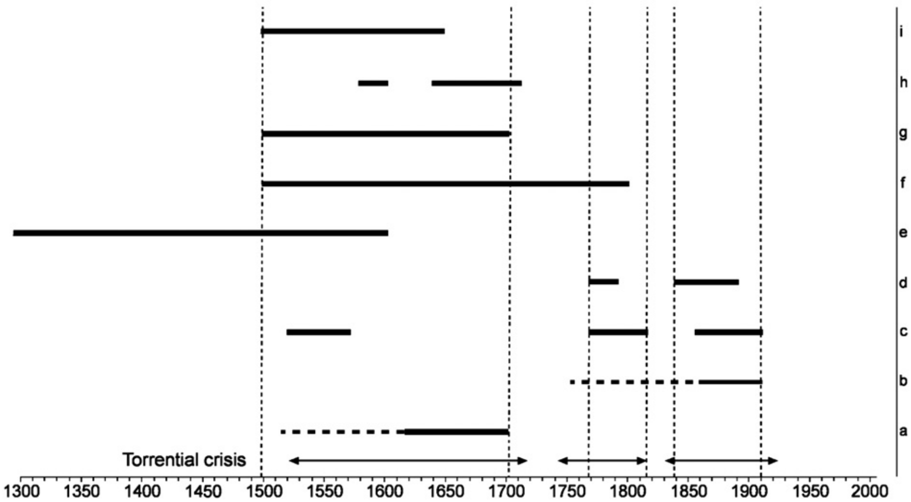

Fig. 9. Evolution through time of the sedimentation of Mediterranean rivers and deltas: (a) upper Ardèche (this study); (b) upper Loire (this study); (c) upper Ardèche (Jacob, 2003); (d) Buëch, southern Alps (Descroix and Gautier, 2002); (e) several rivers in the Western Pyrenees (Calvet et al., 2002); (f) a river in Southwestern Crete (Maas and Macklin, 2002); (g) several deltas in the Mediterranean region (Grove, 2001); (h) the Rhône delta (Arnaud-Fassetta, 2000); (i) Figarella, Corsica (Gob et al., 2003). Black lines show strong sedimentation phases. Double arrows indicate the three hydrological crises.

19th century would have therefore been much less intense than that of the previous 150 yr. Jacobs (2003) highlighted that the 18th and 19th century aggradations of the Ardèche river bed have been relatively limited (to the order of 1 to 2 m). Therefore, though the formation of bars has been well-demonstrated by this author, the lichens present on the bedrock allow us to state that the sedimentation was not spatially continuous since the middle of the 19th century.

The upper Ardèche basin has been influenced by human activity since the early Middle Ages, with a demographic peak in the region at the end of the 18th century and the first half of the 19th century (Bozon, 1974; Jacob, 2003; Gob, 2005). At this time, the slopes would have been at their weakest and the sediment supply at its highest. The last decades of the 18th century are actually characterised by a hydrosedimentary crisis (Fig. 9). Therefore, the overexploitation of the slopes associated with the torrential crisis contributed to the increase in sedimentation. However, sedimentation caused by human activity would have remained relatively limited. On one hand, at the end of the hydroclimatic pressure (around 1810), the river incised even though the demographic pressure was still increasing. On the other hand, in the very last decades of the 19th century, the erosion crisis seems to have been at its maximum precisely when rural depopulation suddenly occurred. Therefore, though the upper Ardèche was extensively exploited by industry and the slopes were strongly denuded by agriculture, the role of the human factors has to be put into perspective. Indeed, the economic and agricultural development of the valley has been accompanied by the construction of terraces and by slope protection techniques (small dam, small valley paving, trees plantation) (Blanc, 2001; Jacob, 2003; Gob, 2005). Our observations lead us to think that despite a high level of industrial, pastoral, and agricultural activity during the second half of the LIA, the slopes were still well-protected.

Our lichenometric observations and Fig. 9 lead us to make a distinction between the first and the second part of the LIA. During the first 150 to 200 yr, the climatic stress was not necessarily stronger but was more continuous. The Ardèche or, more generally, rivers from the north of the Mediterranean region experienced strong sedimentation. In contrast, during the 18th and 19th century, sedimentation was much weaker: firstly, because hillslopes in the Ardèche basin offered a certain amount protection from erosion; but also because the climatic stresses were much shorter. This second reason is probably more important. Indeed, the succession of extreme events during 150 to 200 yr did not allow the basin to adapt and induced a large sedimentologic mutation. The few strong events at the end of the 18th and the 19th century occurred in the space of only several decades. They therefore allowed the river some respite to adjust to the brutal increase of sediment supply.

The LIA sedimentation observed in the Ardèche has also occurred in the upper Loire, but at a much more limited volume and spatial scale. Two elements may explain this phenomenon. First, the inherited alluvial stock is not very abundant in the gorge, thus limiting the supply of bedload, which is then only provided by the relatively small valley sides. Nonetheless, these were exploited for agricultural and pastoral purposes since Medieval times, increasing their erosion and the sediment supply. The second element is the gorge shape. The narrowness of the valley made sediment storage impossible. The dynamic parameters in the gorge are so high that the bedload is very easily transported. Therefore, the LIA succession of extreme events associated with the high energy of the gorge should have allowed the evacuation of the sediment as it was produced.

Even if the sediment volume produced during the LIA was limited, the cross sections studied have shown that sedimentation occurred everywhere possible. In the few places that the valley widens, the river competence drops and sediment storage is therefore possible. In those particular places, the riverbed has aggraded up to 2 to 3 m. This sedimentation sometimes seems to have been facilitated by the formation of large bars that have obstructed the valley.

Though our lichenometric dating emphasises the LIA crisis, defining if the Loire experienced the same hydrosedimentological pulses as the Ardèche was not possible. Nevertheless, the vegetation currently found on the deposits and the alluvial floor morphology clearly shows that the end of the crisis dates from the very end of the 19th century (Fig. 9). Studies concerning the recent evolution of rivers in the upper Loire catchments are rare. However, Burnouf et al. (2001) showed that the main tributary of the upper Loire (the Allier River) changed its course many times since the 13th century. One of its tributaries (the Dore River) experienced a high level of morphodynamic activity between the early 18th century and the first decades of the 20th century (Cubizolle et al., 2001). On the middle Loire, between the end of the 17th century and the early 18th century, a braiding system was probably developed. Crepet (1997), Leteinturier et al. (2000), and Straffin and Blum (2002) have made similar observations downstream of our studied reach. All of these studies demonstrated a high hydrosedimentological activity with a very large amount of sediment (braiding, aggradation). The middle valley seems to have received very large quantities of sand from its tributaries and also from the catchment upstream.

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