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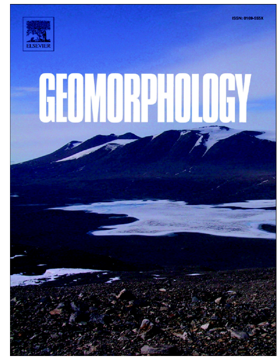

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Origin and Holocene geomorphological evolution of the landslide-dammed basin of la Narse de la Sauvetat (Massif Central, France)

Alfredo MAYORAL[1*], Jean-Luc PEIRY[2], Jean-François BERGER[3], François-Xavier SIMON[4,5], Franck VAUTIER[4] & Yannick MIRAS[1,6]

[1] Université Clermont Auvergne, CNRS, GEOLAB, F-63000 CLERMONT-FERRAND, France.

[2] CNRS UMI3189 ESS, Université Cheik Anta Diop, Faculté de Médecine, BP5005, DAKAR-FANN, Senegal.

[3] CNRS, UMR 5600, EVS-IRG & Université Lyon 2, 5 avenue Pierre Mendès-France, F- 69676 BRON, France

[4] Université Clermont Auvergne, CNRS, Maison des Sciences de l'Homme, F-63000 CLERMONT-FERRAND, France.

[5] Institut National de Recherches Archéologiques Préventives, 9 rue Lavoisier, 25000 Besançon & UMR 6249, Laboratoire Chrono-environnement, 16 route de Gray, 25030 Besançon cedex, France.

[6] UMR 7194 CNRS/MNHN/UPVD Institut de Paléontologie Humaine, 1 rue René Panhard, 75013 Paris. France.

* Corresponding author. E-mail : alfredomayoralpascual@hotmail.com

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ABSTRACT

This work is the first geomorphological analysis of *La Narse de la Sauvetat*, a hydromorphic basin located in the southern *Limagne* plain (French Massif Central) which had never been studied despite its great palaeoenvironmental interest. We explore the potential of its sedimentary archives to provide valuable data on Holocene geomorphic dynamics and their sensitivity to local and regional hydro-climatic changes. In order to characterize the nature and the morphostratigraphic and pedosedimentary evolution of the basin, we used an integrative approach involving geomorphological mapping, hand auger stratigraphic cross-sections, topographic analysis based on LiDAR data and stereophotogrammetric reconstruction, geophysical prospection and radiocarbon dating. Results revealed a palaeotopography fossilized under 6 meters of sedimentary infilling, with a clear shift from fluvial to hydromorphic conditions circa 2800 cal BC, separated by a level with colluvial and lacustrine features. A detailed analysis of the eastern border of the basin also suggests the existence of a former open valley in place of the current closed depression, now locked in by a topographic threshold forming a dam. The sedimentary aggradation of the basin started with an alluvial phase during the Upper Pleistocene and probably continued into the Middle and Late Holocene, consistently with regional alluvial dynamics. In the early Subboreal, a massive landslide occurred on the western slopes of the Puy-de-Corent volcanic plateau, thereby damming the valley and forming a closed depression. This episode coincided with the mid-Holocene climatic shift and an associated phase of slope instability and increased landslides in Western Europe due to changing climatic conditions. This depression evolved into a hydromorphic basin with several high energy hydro-sedimentary episodes after 2800 cal BC; however hydro-sedimentary conditions gradually became more stable towards the Late Holocene. Around 500 cal AD, the drainage deteriorated towards palustrine conditions and caused the formation of a marsh and its consequent evolution into a shallow lake throughout the Middle Ages. This lake was drained in the late XVIIIth Century. The long-term sedimentary record of *La Narse de la Sauvetat*, sensitive to climatic instability periods of the Middle Holocene, makes this landslide-dammed basin a valuable site with an important potential to further development of palaeoenvironmental and geoarchaeological studies.

1. INTRODUCTION

Holocene climatic variability and its interaction with natural systems and human societies have been on the focus of palaeoclimatic and palaeoenvironmental research during at least the last two decades (e.g. Alley et al., 1997; Zolitschka, Behre, & Schneider, 2003; Mayewski et al., 2004; Wanner et al., 2008; Macklin, Jones, & Lewin, 2010). Shifts in long-time climatic tendencies but also rapid climatic changes are of key importance to discuss topics like socio-environmental interactions over the *longue durée*, anthropogenic impacts in earth system, and global change (Crutzen & Stoermer, 2000; Ruddiman, 2003; Kaplan et al., 2011; Wanner et al., 2011; Fletcher & Zielhofer, 2013; Wang et al., 2013). Amongst other periods of climatic variability, Middle and Late Holocene are crucial because of the gradual development of interaction between climate, societies and environment. Analysis of the sensitivity of Middle-Late Holocene geomorphic systems to hydro-climatic changes is one major way to track Holocene climatic variability and socio-environmental interaction (e.g. Van der Leeuw et al., 2005; Cremaschi et al., 2016; Berger et al., 2016). Typical archives to unravel this complex relationships in continental areas are obtained in lacustrine, glacial, caves or major river systems (e.g. Joerin et al., 2008; Notebaert & Verstraeten, 2010; Arnaud et al., 2012). However slope deposits, soils and low-order alluvial systems are less frequently studied but can also be valuable proxies, very sensitive to regional or global hydro-climatic variability (Dotterweich, 2008), and to anthropogenic influence.

In that sense, this study explores the potential of an ancient palustrine area of Limagne plain (central France), in order to obtain Holocene geomorphological and palaeoenvironmental data. The *Limagne* Tertiary and Quaternary geology and geomorphology have been widely studied since the XIXth and early XXth Century (Lecoq, 1867; Giraud, 1902; Glangeaud, 1908; Derruau, 1950; Gachon, 1963). However in the second half of the XXth Century, the main interest shifted to the palaeoenvironmental records of the Upper Pleistocene and the Holocene, whose tephra deposits, dating from the last 90.000 years of local volcanic episodes of the *Chaîne des Puys*, provided a reliable chronological framework (Vernet et al., 1998; Vernet & Raynal, 2000; Nehlig et al., 2003; Boivin et al., 2004; Boivin & Thouret, 2014). As a consequence the relationship between volcanism and human settlements since the Pleistocene has been widely studied (Gachon, 1963; Daugas & Tixier, 1977; Daugas et al., 1978; Raynal, Daugas, & Pelletier, 1979; Daugas & Raynal, 1989).

In recent decades, several geomorphological, geoarchaeological and palaeoenvironmental studies have attempted to reconstruct the Holocene evolution in the *Limagne* plain and its associated socio-environmental interactions (Ballut, 2000, 2001; Vernet & Raynal, 2000; Raynal, Vernet, & Daugas, 2003; Prat, 2006; Macaire et al., 2010; Vernet, 2013). This research is particularly necessary since the *Limagne* record is highly complementary to the well-studied lacustrine and peatlands-based palaeoenvironmental records from the nearby *Plateau des Dômes* (Miras et al., 2004, 2015; Lavrieux et al., 2013). This potential for palaeoenvironmental studies is especially interesting for protohistoric periods, with a dense and well known archaeological record in *Limagne* from the Neolithic to the Roman period (Provost & Mennessier-jouannet, 1994; Vallat, 2002). However, despite these generally favorable conditions, most of the marshy areas provide only partial palaeoenvironmental records, with short and often non-continuous sedimentary sequences and, with some exceptions, a poor preservation of biomarkers (especially pollen) and difficulties for dating (Ballut, 2000).

One important exception, and probably the most studied sedimentary record in *Limagne*, is the palaeolake of Sarliève, situated just at the foot of the *Plateau de Gergovie*. This volcanic plateau has been excavated by archaeologists since the XIXth Century and is internationally-known for having seen active combat during the Gallic Wars (Deberge et al., 2014). Research since the 2000's in the Sarliève basin has included environmental archaeology investigations (Trément et al., 2006; Trément, Argant, et al., 2007; Trément, Mennessier-Jouannet et al., 2007), but also abundant geomorphological and palaeoenvironmental studies. The latter provided remarkable results concerning geometry of the infilling (Hinschberger et al., 2006), local tephro-stratigraphy (Miallier et al., 2004; Fourmont et al., 2006), palaeohydrology (Fourmont, Macaire, & Bréhéret, 2009) and geomorphological and sedimentary evolution during the Lateglacial and the Holocene (Bréhéret et al., 2003; Fourmont, 2006; Macaire et al., 2010). Unfortunately results lack accurate chronological controls for key periods such as the Bronze Age and the Iron Age, often considered as the definitive consolidation of human forcing on natural systems begun during the Neolithic (Ruddiman, 2003; Dotterweich, 2013; Ellis et al., 2013; Notebaert, Berger, & Brochier, 2014). This prevents a precise use of the produced data (e.g. palynological data) and despite taking into account recent refinement of dates (Hatté et al., 2013).

Another remarkable exception is the *Lac-du-Puy de Corent*, an ancient pond situated at the summit of the Puy-de-Corent, within an archaeological site recording 5000 years of human activity (Poux, 2012; Milcent et al., 2014). The *Lac-du-Puy* delivered the first well-dated and consistent palynological record in *Limagne* with remarkable results, such as local landscape evolution and human activities since the late Neolithic, and including impacts related to proto-urban settlement phases (Ledger et al., 2015), as well as original archaeological structures from the first Iron Age (Mayoral et al., 2018). However, the particular topographical, geological, and intra-urban characteristics of this valuable sedimentary record makes it necessary for us to complete the previous findings with additional geomorphological and palaeoenvironmental data taken from the *Limagne* lowlands, in order to understand precisely the socio-environmental dynamics of this key period of the Late Holocene.

Located at the foot of the SW Puy-de-Corent slopes, *La Narse de la Sauvetat* basin is a large hydromorphic depression dug in the calcareous *Limagne* lowlands (Fig.1); it is known to have been a shallow lake in the Middle Ages (X-XIth centuries) and was drained in 1768 (Daugas & Tixier, 1977; Vallat, 2003). It has a similar geomorphological configuration and size to the *Lac de Sarliève* and is surrounded by multiple Roman sites (Vallat, 2002). Despite its great potential interest, the basin has surprisingly been neglected by geomorphologists, palaeoenvironmentalists and archaeologists: only the rescue archaeology report from the construction of a pipeline (Vallat, 2003) provided some basic but incomplete data, confirming that the sedimentary infilling of the basin was at least 1.5 m thick.

Apart from these data, the geomorphology of the basin, its origin, the nature and the stratigraphy of its sedimentary infilling, and therefore its palaeoenvironmental potential remained largely unknown before our study. Thus, this paper has three main objectives: i) to discern the origin, geometry and nature of the basin and of its sedimentary infilling; ii) to outline the main phases of hydro-morpho-sedimentary evolution and to propose their chronological framework; and iii) to assess more effectively the palaeoenvironmental potential of its sedimentary record for future studies. For that we propose to use complementary records obtained from sediments deposited in La Narse de la Sauvetat depression. Our integrative field-based approach combines a large set of methods: a landform analysis based on LiDAR data and photogrammetry modeling, geomorphological mapping, geophysical prospection, the sampling of sediment from hand augering along cross-sections, radiocarbon dating, and an analysis of historical sources.

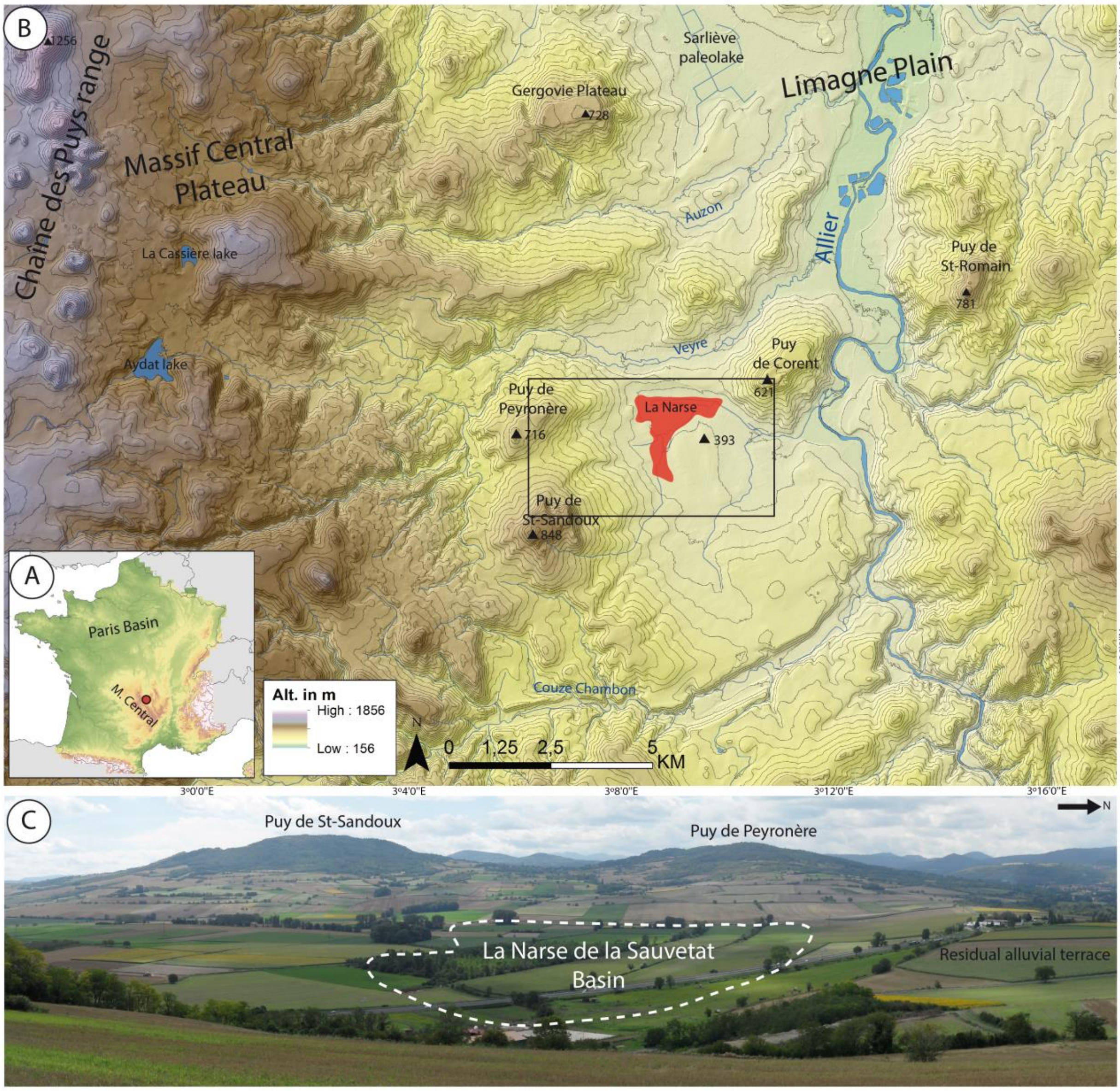

Figure 1. A) Situation of the study area in the French Massif Central. B) Situation of La Narse de la Sauvetat basin between the Puy de Corent and the Puy de Saint Sandoux, in the southern Limagne plain. Black frame represents the study area detailed in Fig. 3. C) General view of La Narse de la Sauvetat basin, currently drained, from the slopes of the Puy de Corent.

2. GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The *Limagne* plain is a Cenozoic sedimentary tectonic depression located in the heart of the French *Massif Central*, resulting from post-orogenical distension processes after the alpine movements (BRGM, 1973; Michon, 2001). It is drained by the Allier River and its main affluent the Dore River.

Despite a long tradition of geological studies in *Limagne* and a relatively abundant literature, the 1:50.000 geological map is not yet available in the area, even though the first geological surveys from the BRGM with this objective started in the 1970's. This lack of information has been mainly compensated by data available in the literature (Bouiller, 1979), with LiDAR data from AYPONA, a palaeoenvironmental multidisciplinary research program around the archaeological site of Corent (Mayoral et al., 2014; Simon et al., 2015; Mayoral, 2018), and with fieldwork carried out for the purposes of the current study.

The Limagne elongated depression has a N-S major axis (90 km) and is 15 to 40 km wide. It is open on its northern border but confined in the east by the *Monts du Livradois-Forez* and in the west by the *Limagne* normal fault and the Paleozoic basement of the Massif Central plateau. This area, locally called *Plateau des Dômes* (800 masl), includes the internationally-known tectono-volcanic complex *Chaîne des Puys-Limagne Fault* (Boivin et al., 2004). The Cenozoic *Limagne* plain is largely dominated by flat or tabular topographies between 300 and 400 masl, developed on sedimentary rocks (mainly marls with thin layers of limestones interbedded). The southern *Limagne*, so called the *Limagne des Buttes*, narrows gradually to the south and includes several volcanic plateaus (500 to 800 masl, see Fig. 2A) formed by relief inversion of Miocene and Pliocene lava flows and domes (Nehlig et al., 2003).

The most recent volcanic activity (Upper Pleistocene to Early Holocene) was produced by cones and lava flows from the *Chaîne des Puys*, forming a N-S alignment of cones parallel to the *Limagne* Fault and culminating at the Puy de Dôme (1465 masl) (Boivin et al., 2004; Boivin & Thouret, 2014). Thus, since the Upper Pleistocene and Holocene, the main morphostructural ensembles of the landscape are inverted reliefs (volcanic plateaus), calcareous lowlands, Allier river valley and Paleozoic basement areas (Fig. 2A).

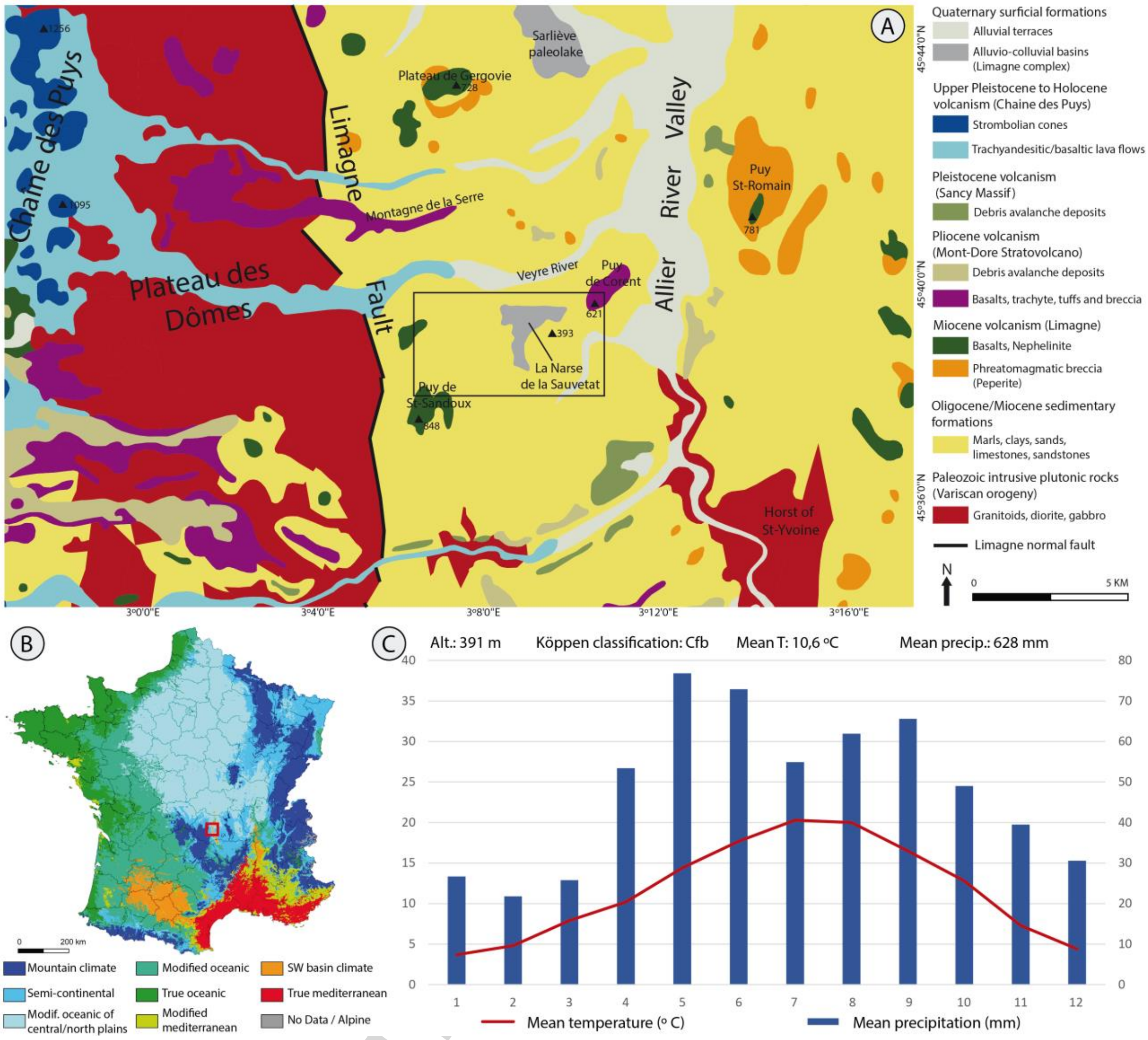

Figure 2. A) Simplified geological map of the study area, modified from BRGM geological map nº717 (Veyre-Monton, in progress). The black frame represents the study area, detailed in Fig.3. B) Location of the study area (red square) in a France "climate type" map (Joly et al., 2010). *C) Precipitation and temperature data of the study area (data Météo-France).*

In southern *Limagne*, the main quaternary deposits are alluvial terraces with estimated ages from 1 MA to Early Holocene (Raynal, 1984; Ballut, 2000; Pastre, 2005). Vast low-topography areas of the impermeable marly tertiary bedrock are poorly drained, causing the recurrent formation of hydromorphic or marshy areas during different phases of the Holocene (Gachon, 1963; Bornand et al., 1968; BRGM, 1973; Ballut, 2000). These lowlands are infilled by alluvio-colluvial deposits derived from marls, so-called *Limagne complex*. Although this complex is better developed in Holocene marshes of the *Limagne des marais* (east and north of Clermont-Ferrand), it can be also seen in southern *Limagne,* chiefly in the *Sarliève* palaeolake (Fig. 2A). Other locally important superficial formations are regolith in the Palezoic basement (*Plateau des Dômes, Horst de Saint-Yvoine*) or volcano-sedimentary colluvium in the slopes of the volcanic plateaus. These colluvial formations can locally have decametric thicknesses, especially on the northern slopes of the volcanic plateaus (Greffier, Restituito, & Héraud, 1980).

La Narse de la Sauvetat catchment is located between the slopes of the volcanic plateau of Corent and the domes of *Peyronère* and *Saint-Sandoux* (Fig. 1 and 2A). It is a closed basin excavated from Miocene marly lowlands of *Limagne* and hitherto interpreted as an alluvio-colluvial infill, similar to the *Limagne complex* (Bornand et al., 1968; BRGM, 1973). The basin has a W-E elongated shape (2 km x 800 m) and covers *circa* 1.2 km^2. A topographic threshold situated in its eastern extremity without any outlet prevents its natural drainage towards the Allier drainage network (see Fig. 1).

Therefore the bottom of the basin concentrates water and sediment flows from several small flat valleys coming mainly from the slopes of the *Puy de Saint Sandoux* and *Peyronère* in the West, and the *Puy de Corent* towards the East. The whole basin has an extremely flat topography with its lowest point at 368 masl. Soils are hydromorphic dark soils with isohumic/vertic characteristics (Bornand et al., 1968). They were drained several times from 1768 to the current day (Vallat, 2003) and are now covered by crops.

The climate is oceanic to semi-continental (Köppen Cfb) with cold and relatively dry winters and hot and stormy summers (Joly et al., 2010; Fig. 2B and C). As the area is mainly influenced by Westerlies, mediterranean influence is very limited or inexistent; however precipitation is drastically reduced (628 mm) by the barrier effect of the Massif Central to the western atmospheric circulation and the foehn effects (Gachon, 1963; Ballut, 2000).

3. MATERIALS AND METHODS

3.1 LiDAR survey, geomorphological mapping, photogrammetric analysis

We used a high resolution LiDAR survey performed by an airborne laser scanner in March 2014 and covering a 22 km^2 area around the Puy de Corent. It partially covers the *Narse de la Sauvetat* basin and is especially relevant in the area closest to the slopes of the Puy de Corent and the threshold closing the basin. The points cloud was classified with an MCC-LiDAR algorithm (Evans & Hudak, 2007), thus improving the filtering results obtained by the data provider (Simon et al., 2015). Classified bare earth points were then interpolated using the natural neighbor method and converted into a raster DTM with a resolution of 0.5 m, considered optimal for geomorphological analysis (Lin et al., 2013; Mcneary, 2014; Tarolli, 2014). The slope raster and the Local Relief Model (Hesse, 2010) were calculated in a selected area of the resulting DTM (topographic threshold, see Fig. 4) using an open source toolbox (Novák, 2014). Both models have proven to be amongst the most efficient techniques to detect microtopographical features (Bennett et al., 2012; Stular et al., 2012; Mayoral et al., 2017). The kernel size used was 25 m, considered optimal to detect metric scale features (Hesse, 2010; Bennett et al., 2012). As the high resolution LiDAR data only covered a small part of the study area, we combined it with data from the open access 10m resolution DTM produced by the *Centre Régional Auvergnat d'Information Géographique* (CRAIG). Color-cast elevation models, hillshade models and slope models were computed at the scale of the whole study area.

The geomorphological mapping of the study area was performed using a classical approach, based on extensive fieldwork combined with an aerial imagery analysis (Otto & Smith, 2013). It allowed us to produce quickly a geomorphological sketch useful for the general analysis of the catchment and to select the most appropriate stations for a hand augering campaign. In order to optimize the fieldwork, all available cartographic data were first analyzed: DTMs, topographic maps (1:25.000), former geological and geomorphological data (Bouiller, 1979; Greffier, Restituito, & Héraud, 1980), and aerial imagery. Secondly, we focused our fieldwork on confirming and detailing the geomorphological interpretation of landforms detected by imagery analysis, and on the pedo-sedimentary characterization of surficial formations in the whole area where outcrops were visible. Thirdly, we combined data from imagery and data collected in the field on ArcGIS 10 in order to digitize the map of the final geomorphological interpretation (Fig. 3). Additionally, historical maps available on this area were studied to complete geomorphological or palaeoenvironmental data concerning the last few centuries: amongst them, only the *Atlas de Trudaine* (1745-1780) had a real geomorphological interest and is therefore presented in this paper.

A crucial point of interest for the geomorphological reconstruction was the topographic threshold area. This was highly disturbed in 1978 by the construction of the A75 highway. In order to understand better how it closed the *Narse de la Sauvetat* basin before the highway construction, a 3D stereo-photogrammetric modeling was performed to reconstruct the former topography : a set of 1962 aerial images and LPS 2012 software (ERDAS Imagine) were used to create a DTM, which was manually corrected by stereoscopic viewing using Terrain Editor module (Vautier et al., 2016). The resulting topographic points cloud was interpolated on ArcGIS to produce a 0.4m resolution DTM.

3.2 Field survey: hand auger logs and geophysical prospection

Firstly, based on the geomorphological mapping, two transects of hand auger logs were implanted (C1 to C22, see Figs. 6 and 7) along two cross-sections perpendicular to the main basin drainage axis. Spaced at 30m intervals, logs were geolocated in XYZ with a Trimble GEO7X DGPS of centimetric accuracy. Drillings of 6 cm diameter were performed as deep as possible down to bedrock or a layer too hard to be drilled. Litho-stratigraphic logs were built based on pedo-sedimentary description and characterization of material. Depths of stratigraphic changes were noted as precisely as possible in order to reconstruct stratigraphy at the scale of cross-sections and sedimentary basin. Field descriptions were sometimes enriched with the observation of the sediment coarse fraction on sieved samples (see 3.3). Systematic sampling was avoided considering that sediment obtained from the hand auger is potentially reworked or contaminated during drilling process. A stratigraphic column was built as a synthesis of sedimentological, pedological and stratigraphic data of the two cross-sections (Fig. 8). Sedimentary environment interpretation was achieved on the basis of classical sedimentary facies interpretation (Miall, 1996; Brown, 1997; Arche, 2010), using key features like grain-size, sorting, geometry of deposits, etc. Secondly, once the structure of the sedimentary infilling was known, three sedimentary mechanical cores were taken in different parts of the basin in order to acquire sedimentary archives suitable for future palaeoenvironmental multi-proxy analysis. The cores, named NAR2, NAR3 and NAR4 (respective lengths: 230, 227 and 284 cm) were obtained with a GeoTool GTR 790 corer (diameter of 7 cm). Considering that these analyses are still being undertaken and are beyond the scope of this work, the current paper only presents the first radiocarbon results for the main core (NAR2, same position as auger C6), in order to provide a first chronostratigraphical framework. Pedostratigraphic references from other well-known sites in the *Limagne* area such as an historical Dark Layer (Ballut, 2000; Bréhéret et al., 2003; Fourmont, 2006; Trément, Argant, et al., 2007; Trément, Mennessier-Jouannet, et al., 2007; Fourmont, Macaire, & Bréhéret, 2009) suggested that Late Holocene sedimentation was probably concentrated in the upper part of the sequence. Additionally, the generally poor pollen preservation in *Limagne* (Ballut, 2000) suggested that only hydromorphic and palustrine/lacustrine facies of the upper part of the sequence would be valuable recorders for biomarkers. Considering that this work focuses on the basin formation and its evolution during the Late Holocene period, the drilling depth of all the cores was intentionally limited to the upper 2.50 m of the sequence, where the hydromorphic and palustrine/lacustrine facies lie (see Fig. 8).

Thirdly, in areas where Roman archaeological remains are known (Fig. 3), geophysical surveys were carried out. Results concern mainly archaeology, and only electromagnetic surveys had a true geomorphological interest and are therefore presented. They provided valuable data on the bedrock depth and the thickness of clayey infilling. Data were collected using an EM31 Geonics ground conductivity meter associated with a GPS positioning. Measurements were collected along profiles separated by 5 to 10 meters with an acquisition frequency of 1 Hz.

3.3 Radiocarbon dating

The main core (NAR2, 230 cm long) was cut into 2cm-thick samples, which were deflocculated in a solution of sodium hexametaphosphate, then sieved at 500µm and 100µm. When present in significant amounts, macro or micro-charcoals were then concentrated using binocular microscope, and dated by AMS ^{14}C (Poznan Radiocarbon laboratory, see Table 1). Charred materials were preferred to bulk sediment or mollusk shells to avoid reservoir effects. An additional radiocarbon dating was performed on a sample from the C6 hand auger drilling, in order to date the first phases of the basin infilling process. The resulting six ^{14}C dates were calibrated using CALIB V7.04 (Stuiver & Reimer, 1993) and IntCal13 calibration curve(Reimer et al., 2013).

4. RESULTS

4.1 Geomorphological settings, Geomatics & Historical Data

The geomorphological map shows main features of the study area (Fig. 3): volcanic plateaus formed by the relief inversion and calcareous lowlands partially infilled by alluvio-colluvial hydromorphic deposits. The area is surrounded by the *Puy de Peyronère*, *Puy de Saint Sandoux* and *Puy de Corent*. The first two are basaltic domes, and the latter is a scoria cone, with remains of a phreato-magmatic breccia ring. The slopes of the three plateaus are simplified in this geomorphological sketch, but most of them are in fact complex and highly variable stacking of volcano-sedimentary colluvium. Only few thalwegs are apparent as the water circulation occurs through or under the thick colluvium. On the other side, some slopes are eroded and subject to an active gullying in thin carbonated surficial formations (e.g. the southern slope of the Puy de Corent).

In the center of the study area, calcareous lowlands consist of an undulated structural relief in marls and limestones (*Le Lieu Dieu* and east to *La Sauvetat* area - see Fig. 3). These little decametric mounds (20-30m of elevation) are nevertheless strong enough to constrain local drainage, which is organized to the east by the Charlet River*,* a small tributary of the Allier River. The western and central parts of the basin are drained by a network of small streams coming from the slopes of the *Puys de Peyronère* and *Saint Sandoux* and gradually converging to the west into the main valley occupied by *La Narse* depression*.* This large and flat basin is enclosed between the slopes of the *Puys (W and E)*, the structural calcareous mounds (S) and a Middle Pleistocene terrace of the paleo-Allier (N). Its eastern outlet is blocked by a higher area situated just under the highway interchange, acting as a massive threshold preventing the drainage towards the *Charlet* River*.* However, *La Narse* is now drained through multiple drains, converging in a single and partly underground drain designed by man to cross this threshold. Downstream from the threshold, the Puy de Corent foot is covered by volcano-sedimentary colluvium and small alluvial fans supplied by thalwegs gullying the Puy de Corent slopes. In 1978, the natural topography was dramatically reworked by the A75 highway construction and the associated earthworks make discernment of the original landforms extremely difficult.

Results of electrical conductivity surveys provided basic information concerning the thickness of clay infilling the basin and the substratum palaeotopography in both areas surveyed : i) upstream from the basin (Fig. 3a) a high electrical conductivity range revealed a clear distinction between bedrock and what is probably a buried thalweg, demonstrating that the former topography must have been much more marked that the current quasi flat topography; ii) in the centre of the basin (Fig. 3b), conductivity variations are smoothed by the stronger thickness of clay, the conductivity range however suggesting variations of bedrock altitude and the presence of a palaeochannel.

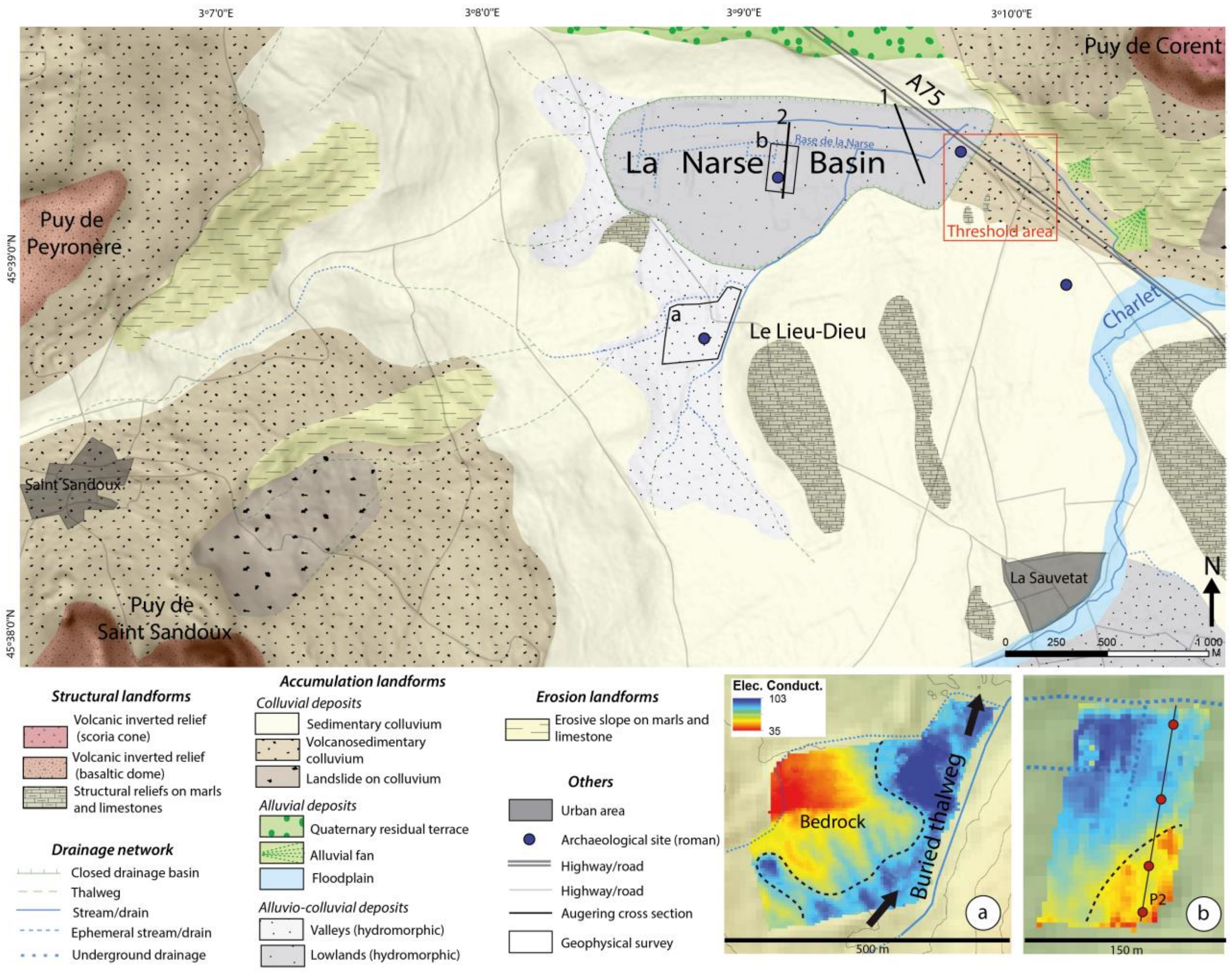

Figure 3. Simplified geomorphological map of the study area. Frames a) and b) correspond to geophysical surveys (electrical conductivity) located on the main map. The red frame represents the geomorphic threshold area.

Considering its particular role in explaining the formation and functioning of *La Narse* basin, the topographic threshold has been studied with a special care. Stereo-photogrammetry from aerial imagery prior to heavy civil engineering works and recent accurate LiDAR data were used together to produce high-resolution topographic models, and so complete the geomorphological mapping and aerial imagery interpretation. Results show a former massive natural deposit of approximately 200x200m culminating at 371-372 masl, 2 to 3m above the current bottom of the depression (Fig. 4A). The topography seems to have been largely modified and raised at least 2m due to the highway interchange (Fig. 4B). This mass is flanked by two lowest corridors: the first one at the north crossed by the current underground drain, the second one at the southwest weakly visible in the topography, which could be the remains of an ancient outlet (situated c. 373m). The LRM (Fig.4C) also highlights the same negative topographic anomaly (blue).

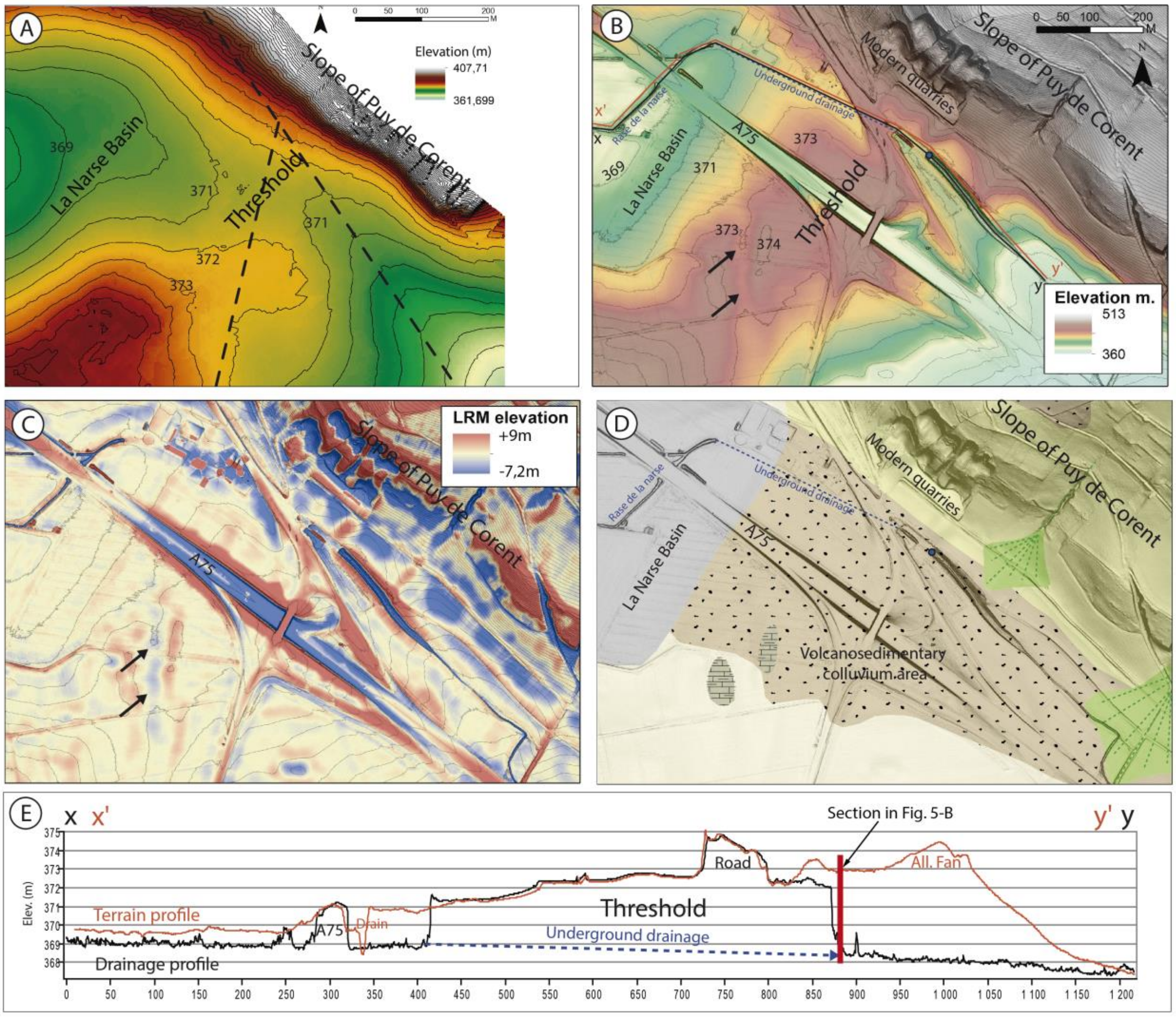

Figure 4. A) DTM of the threshold area obtained from stereo-photogrammetric processing on 1962 aerial imagery. It shows what the topography was before the highway construction. Black dash lines represent the existing roads in 1962. B) High resolution LiDAR topographic map, with location of the 4.E profile. Arrows point to an elongated negative topographic anomaly. C) Local Relief Model (LRM). Positive anomalies appear in red and negative anomalies in blue. Arrows point to the same anomaly as in B. D) Geomorphological map; the legend is the same as that in Fig.3. E) Topographic profiles following the drain (black) and following the topography of the threshold (red). The red bar represents the bridge section in Fig. 5-B.

The geomorphological features of the area (Fig.4D) show that all the threshold area is covered by volcano-sedimentary colluvium, but also the area downstream from the drain at the foot of the Puy de Corent. Above the threshold, on the Puy de Corent flank, the slope itself is covered by a relatively thin sedimentary colluvium, suggesting a purge of the slope's sediments during a polyphased functioning. Topographic long profiles (Fig. 4E), one following the drain (black) and the other following the natural topography of the terrain parallel to the drain (red), clearly show that the slope rises gradually from the eastern limit of the depression, reaching an altitude 4-5 m above the height of the drain.

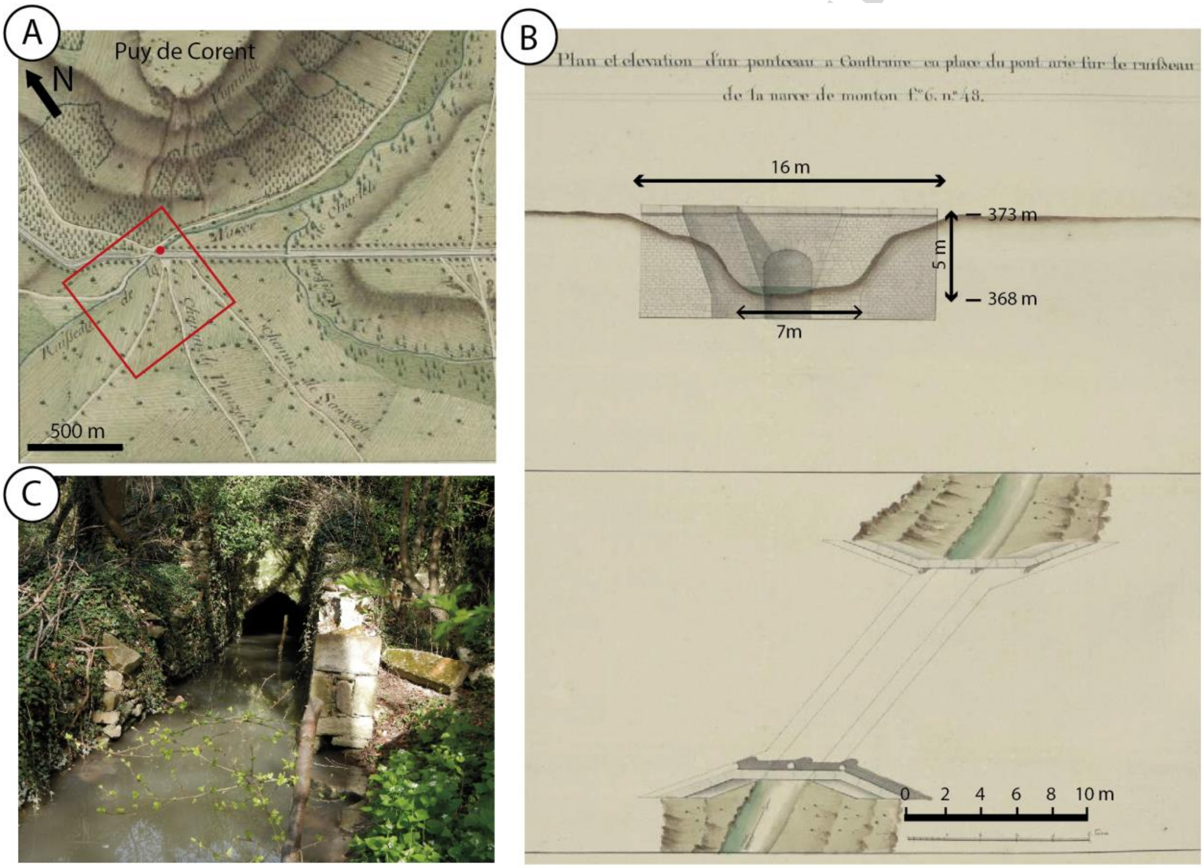

Figure 5. (A and B) Extracts from the XVIIIth Century road Atlas de Trudaine, depicting the threshold area (red frame in A), and showing the cross sectional morphology of the still uncovered outlet before the construction of a bridge (B). Altitudes were extracted from current topography, see Fig. 4-E. (C) Current situation of the gallery outlet (red point in A).

Figure 5 shows data extracted from the historical road map called *Atlas de Trudaine* (1745-1780). As most of the topographic survey was finished before 1755 (Blond, 2007), it is widely believed that this atlas shows landscape state from the second third of the XVIIIth Century. Gullies on *Puy de Corent* slopes (Fig. 5A) seem similar to gullies and alluvio-colluvial cones detected on Fig. 4C&D. The picture of a projected bridge (Fig. 5B) also provides interesting data concerning the morphometry of the outlet across the threshold: it was 16m wide at the top, 7m wide at its base and 5m deep. The stream size and shape suggest natural incision processes of the threshold rather than a drainage trench (Fig. 5-A and B). Hence this Atlas probably depicts a natural state of the basin outlet few decades before drainage works which started after 1768 (Daugas & Tixier, 1977). Mentioned as stream in historical map notes, the outlet had not been buried in the masonried gallery as it is the case today (Fig. 5C), the gallery having probably been built as a part of major road improvement works in the late XVIIIth Century (Blond, 2007).

4.2 Stratigraphy and cross-sections

Cross-sections based on hand auger logs are perpendicular to the main axis of the depression (see location on Fig. 3): section 1 is more complete than section 2 where the basin is much larger. Both of them cover approximately the same length and the same depth (5-6m), until bedrock or a too hard layer (see unit VI, Fig. 6-7-8). Both were drawn from a similar number of auger logs approximately equidistant by 30 m, and show roughly equivalent stratigraphic phases. The stratigraphic column (Fig. 8) is a synthesis of the stratigraphic and pedosedimentary observations in cross-sections 1 and 2. The column includes 7 major sedimentary units numbered I to VII, subdivided in to sub-units. Pedogenic features are present in units I (actual soil), III, V and VI (palaeosoils). A first chronological framework of the middle-upper part of the sequence (Units IV to II) based on six radiocarbon dates from microcharcoals sampled in NAR2/C6 samples (Table 1) dates the stratigraphic sequence from the Upper Pleistocene to the Late Holocene.

Bedrock was reached on several logs, mainly along the downstream cross-section (section 1, Fig.6). In this area, palaeotopography shows a 3m deep relatively flat basin on the south. Close to its northern border, it is deeply incised by a marked thalweg excavated in the bedrock and fulfilled with sediments. This palaeotopography indicates that hydro-sedimentary fluxes were concentrated in the first phases of the basin development, suggesting that entrenchment downstream was controlled by the palaeo-Allier River. In the middle part of the basin (section 2, Fig. 7), the bedrock palaeotopography is not known because it is deeper and was not frequently found in hand augers logs. Nevertheless, the reconstruction of the sedimentary infilling shows that the channel position has laterally changed through time and occupied the basin width as whole (Fig. 7).

Unit VII was notably found in the southern part of cross-sections (See Figs. 6 and 7) with a reduced thickness (10 to 30 cm). It directly overcomes the calcareous bedrock and is rich in rock fragments. Therefore it could be interpreted as sedimentary colluvium derived from carbonated bedrock, analogous to modern surficial formations in surrounding areas, and perhaps slightly pedogeneized as suggested by oxidation mottles. The contact between Units VII and VI is unfortunately to poorly known to be clear.

Unit VI was met in the centre of the deeper thalweg (section 1), but also in a thin layer in the southern part of this same cross-section. It suggests that this unit was strongly eroded after its deposition (Fig. 6). In cross-section 2, unit VI shows a complex stratigraphic configuration of several subunits (VI.1, 2, 3 and 4), suggesting diversified sedimentary environments: high energy deposits probably in channels, river bars and bank deposits, and low energy deposits like floodplain sediments. Although the whole unit shows pedogenic traits (oxidation mottles, bioturbation), these are particularly marked at the top of the unit (See Fig. 8). Thus, unit VI can be interpreted as a polyphased alluvial plain with phases of aggradation, incision or erosion and a lateral migration of channels (Fig. 7).

Table 1. Radiocarbon dates from NAR2/C6 cores

№	Core	Depth (cm)	Lab. code	Material	14C yr. BP	Cal BC/AD (median, 2σ)
1	NAR2	38-40	Poz-86197	Microcharcoal	485 ± 30 BP	1428 cal AD +- 21
2	NAR2	76-78	Poz-86198	Microcharcoal	1540 ± 40 BP	511 cal AD +-89
3	NAR2	106-108	Poz-71624	Microcharcoal	2035 ± 35 BP	56 cal BC +-106
4	NAR2	142-144	Poz-71625	Microcharcoal	2410 ± 40 BP	574 cal BC +- 176
5	NAR2	196-200	Poz-86201	Microcharcoal	4280 ± 60 BP	2881 cal BC +- 206
6	C6	480-483	Beta-475531	Microcharcoal + plant material	27980 ± 280 BP	29992 cal BC +-704

Unit V/VI is a particularly thick and coarse fluvial layer indicating an intense alluvial event (see Figs. 6 to 8). This layer is interstratified between units VI and V and reveals the position of high energy palaeochannels. A radiocarbon date from microcharcoals and plant remains sampled in this unit indicates a Upper Pleistocene age of c. 32.000 yr. cal BP (29992 cal BC) for this event (Table 1).

Unit V is a massive layer which has covered the whole basin with a relatively constant thickness (2-2.5 m) of sediments. The unit is mainly made of greenish silty clay gleyic soils, with abundant interstratified basaltic/carbonated sandy to gravelly lenses. It presents pedogenic features (oxidation mottles, bioturbation, organic nodules) which increase to the top of the sequence. The nature of its contact with unit VI show that an important erosion phase preceded the deposition phase. Deposits from cross-section 2 indicate that a thalweg occupied the southern part of the basin and had accumulated the hydro-sedimentary flows at least in the first sedimentation phases, before that flows had extended and accumulated over the entire floodplain width (Fig. 7). The thin but extended layers of well sorted sands and gravels combined with small channels infillings (Fig. 7 and 8, units V.4 and V.6) suggest an aggradational environment with small, ephemeral and high-energy migrating channels, maybe braided, or perhaps ephemeral sheet flood events. In cross-section 1, sandy-gravelly layers from Unit V are mainly located in the thalweg, completely infilling it (Fig. 6), probably because of the incised preexistent palaeotopography to the east.

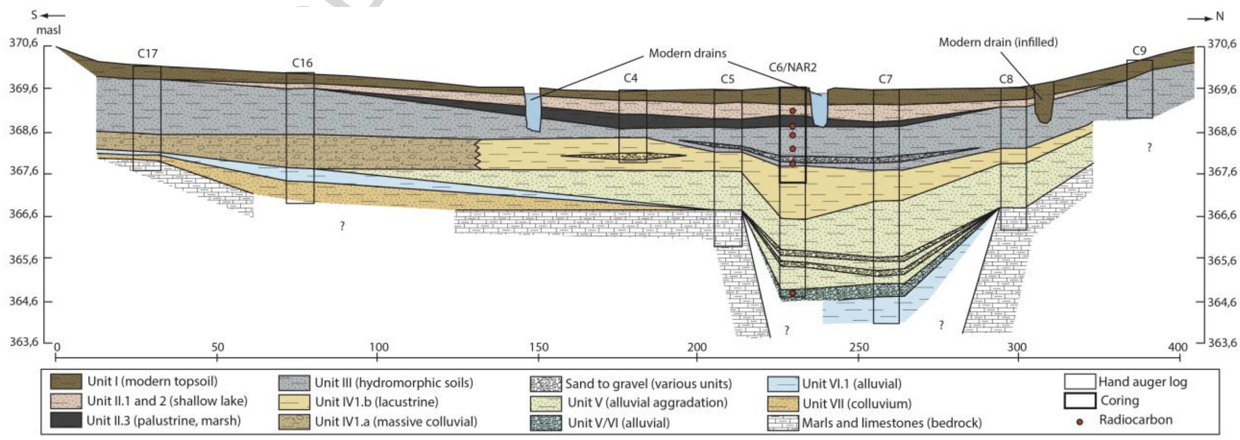

Figure 6. Cross-section 1 (for location, see Fig. 3).

Unit IV includes two stratigraphically correlated subunits but whose characteristics differ. It covers the entire basin thickness with deposits varying from 10 to 100 cm approximately. Subunit IV1a is mainly located in the southern part of the cross-section 1 (Fig. 6). It has a mixed or disturbed facies with limestone and volcanic clasts, including a few small scoria and *peperite* granules (phreato-magmatic breccia), in a clayey matrix rich in organic matter, nodules and marl fragments. This unit has been interpreted as the product of massive colluvial processes probably coming from the *Puy de Corent* as indicated by the presence of *peperite* and scoria (see Fig. 3 and 8).

Deposits from unit IV1b lie in the lower central parts of cross-section 1 and change laterally to IV1a towards the south (Fig. 7); and in the whole cross-section 2 as a thinner but homogenous layer (Fig. 7). Unfortunately the lateral contact between IV1a and IV1b is not precisely known due to the distance between augering points, but the stratigraphic position of both subunits supports the interpretation of a lateral transition. IV1b has a very abundant, homogeneous and compact light yellowish clayey matrix, including rare sandy-gravelly lenses, and sparse small granules of basalt, scoria and limestone suggesting that the sediment origin was the *Puy de Corent* (Figs. 3 and 6). In cross-section 2, IV1b's matrix is finer with less granules of limestone or basalt, probably due to its greater distance from the *Puy de Corent* slopes. Unit IV1b's contact with the underlying unit V is relatively sharp, suggesting that hydro-sedimentary conditions have abruptly changed between both units. This subunit was interpreted as a rapid sedimentary input and deposition in a very low-energy environment, probably lacustrine, submitted to occasional detrital inputs.

Unit III is a very homogeneous layer of dark grey silty clays that are well distributed all across the basin. Its thickness is on average 120 cm and the entire deposit has redox mottles, bioturbation features (rootlets) and abundant malacological remains as well as sparse limestone and basalt granules. This unit is generally interpreted as a pedogenic deposit under hydromorphic conditions. Contact with unit IV is gradual, small layers of both units being intercalated: deposit features suggest that the low-energy aquatic sedimentary conditions of the previous phase alternated with short pedogenesis phases under hydromorphic conditions, before the final installation of the latter. Slight coarsening of the deposits compared to underlying unit is probably due to changes in sedimentary environment (lacustrine to terrestrial-hydromorphic) and/or increased runoff. Several studies have demonstrated that silt increases in Mediterranean soils can be related to Saharan dust atmospheric inputs (Stuut, Smalley, & O'Hara-Dhand, 2009; Longman et al., 2017; Zielhofer, von Suchodoletz, et al., 2017). However, considering the latitude and the position of the study area in inner France surrounded by Massif Central ranges, significant inputs of long distance aeolian dust seem unlikely in *Limagne* (Guerzoni, Molinaroli, & Chester, 1997; Goudie & Middleton, 2001; Israelevich et al., 2012). Nevertheless silt inputs linked to local aeolian erosion are possible, since they have been reported in Limagne during the XXth century, caused by foehn effect on ploughed fields during dry and cold winters (Barathon & Valleix, 1993).

Chronology of the Unit III deposition is well known from four microcharcoal 14C dates (see Table 1 and Fig. 8) between 200 cm (2881 cal BC) and 76 cm depth (511 cal AD). Two subunits have been identified in its upper-central part. From bottom to top: i) III1b is a darker horizon, likely corresponding to permanently wet conditions. It has been dated c. 574 cal BC (Poz-71625, Table 1); ii) III1a contains a higher concentration of orange mottles which indicates oscillating redox conditions. It has been dated c. 56 cal BC (Poz-71624, Table 1).

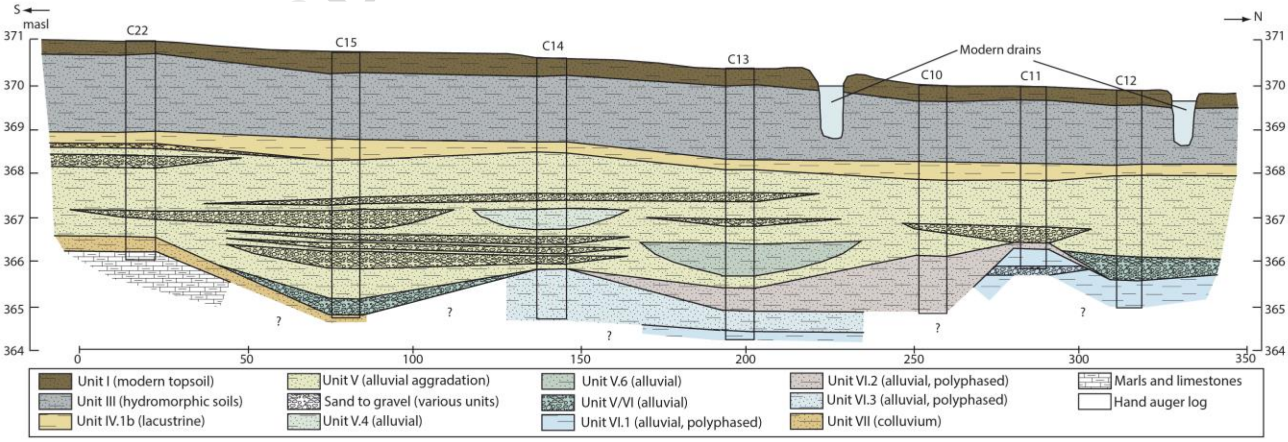

Figure 7. Cross-section 2. For location, see Fig. 3.

Unit II is only present in the central part of the basin (cross-section 1), taking the form of 3 clearly distinct 30-40 cm total thick subunits. It quickly becomes thinner towards the peripheral area (Fig. 6). The entire unit has delivered abundant malacological remains and some bioturbation features, whereas redox mottles have disappeared (Fig. 8). Subunit II.3 is a 10 cm layer of black, highly organic silty clays with abundant vegetal and malacological remains. II.2 is a layer of light grayish brown silty clay with abundant shells and some bioturbation features coming from upper levels. II.1 is beige silty clay containing very abundant inclusions of diatomite, highly disturbed and de-structured by modern deep ploughing. These 3 subunits were interpreted as a rising watertable sequence starting with the setting of palustrine conditions and marsh formation in the central and lower parts of the basin (II.3).

Contact between units II and III is sharp, suggesting an abrupt deterioration of drainage conditions at the beginning of the layer II.3 deposition. Then, the progressive rise of the water level culminated in a shallow lake which occupied the central area of the basin (II.2 and II.1). Transgression caused a lateral extent of palustrine conditions, whereas peripheral areas remained merely hydromorphic. The two more recent radiocarbon dates indicate that these palustrine/lacustrine conditions stand from 511 to 1428 cal AD (roughly the entire Middle Ages).

Unit I roughly corresponds to the modern silty clay topsoil. It is well developed in the entire basin and is 30 to 40 cm thick. Two subunits can be distinguished: i) I.2 has some malacological remains and redox mottles (Fig. 6 to 8) and was interpreted as the result of the modern drainage; ii) I.1 represents the recent incorporation of backfill in the central part of the basin by the landowner; it also contains plough traces due to crops installation.

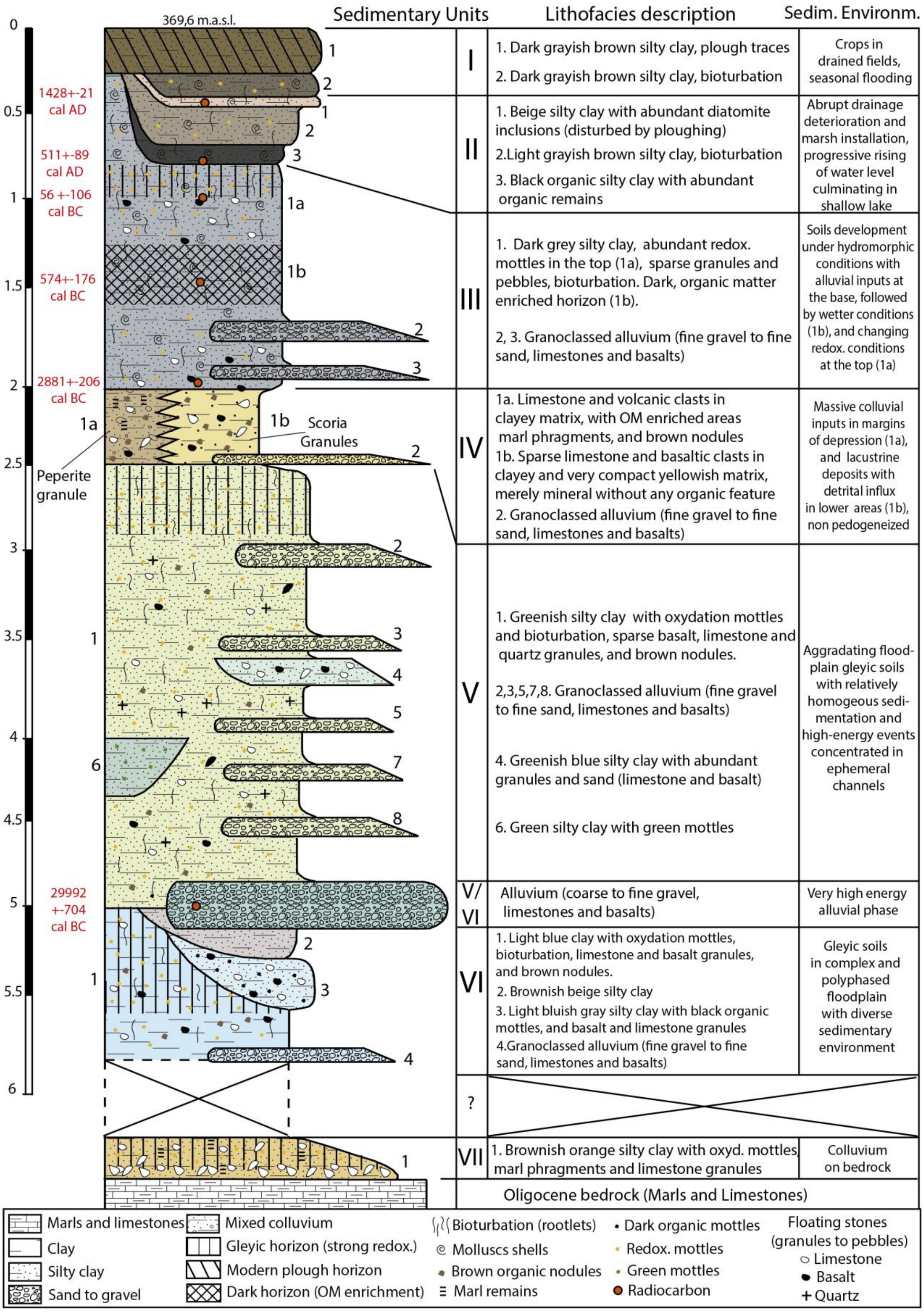

Figure 8. Synthethic stratigraphic column of La Narse de la Sauvetat basin.

5. DISCUSSION

The Limagne poorly drained areas and wetlands have been generally considered to be the result of quaternary fluvial dynamics affecting marly lowlands between the Limagne fault and the course of the river Allier (Derruau, 1950; Gachon, 1963; Lenselink, Kroonenberg, & Loison, 1990; Ballut, 2000, 2001). Their occurrence and arrangement is ultimately controlled by regional structural factors as the N-S Limagne graben. However at la *Narse de la Sauvetat,* alluvial dynamics alone cannot explain the hydromorphic basin formation. In the other hand, karstic phaenomena likely didn't happen in Limagne bedrock where marls and clays are common, whereas limestones are only present as decimetric layers. There is neither clear evidence of neotectonic subsidence movements in the studied area (Ballut, 2000). Therefore interpretations such as consequences of dissolution landforms or subsiding processes have to be discarded to explain the genesis and evolution of la Narse de la Sauvetat depression.

Results of geomorphological, stratigraphic and pedo-sedimentary analysis at *la Narse de la Sauvetat* basin, completed by a high resolution topography reconstruction and a historical data analysis, provided several clues concerning its origin and formation. These data lead us to outline the four stages of the basin formation (Fig. 10) and its main phases of hydro-sedimentary evolution (Fig. 11). Unfortunately the lack of chronological controls in the oldest phases of infilling prevents a precise chronological interpretation of sedimentary processes from the Upper Pleistocene to the Early Holocene.

The reconstruction of cross-section 1 (Fig. 6) and geophysical surveys (Fig. 3) have shown that the pre-sedimentation topography was a palaeothalweg excavated within the marly bedrock. The main valley excavation was clearly posterior to the Fvd terrace formation (+55 m above the River Allier, 580 kyr. BP) during the Middle Pleistocene (Pastre, 2005); and the valley incision into the bedrock was probably related to the Pleniglacial alluvial dynamics which are generally characterized by strong incision of streams in their beds (Gregory & Benito, 2003; Bell & Walker, 2005). The first phases of the alluvial infilling (unit VI) occurred before 32 kyr cal BP (c. 30 kyr cal BC). A complex and polyphased alluvial activity including aggradation, incision and lateral migration of channels gradually infilled the valley (Fig. 11.1). Outside the valley, colluvial deposits covered the bedrock.

The top of unit VI in cross-sections 1 and 2 indicated that a strong erosion phase impacted deposits from unit VI and finally caused an alluvial event of high intensity responsible for the sedimentation of coarse-to-fine gravels from unit V/VI. Considering the intensity of the alluvial process corresponding to this unit, the dated material within the alluvial sediment (c. 32 kyr. Cal BP) was probably reworked, implying that the date represents more likely the age of the eroded top of unit VI than the age of unit V/VI itself.

Above this Upper Pleistocene aged surface, deposits from Unit V have recorded high energy events causing a strong fluvial aggradation and a floodplain enlargement probably caused by the migration of ephemeral maybe braided streams and sheet-flood like deposits (Fig. 11.2). These alluvial dynamics appear to be far more consistent with Lateglacial and early Holocene fluvial activity than with Last Glacial Maximum dynamics: in southern *Limagne* the Last Glacial Maximum was characterized by a major phase of stream incision starting *circa* 30 kyr. BP, while aggradation and channel infilling was characteristic of the Lateglacial and the Holocene in response to a strong sedimentary activity increase (Derruau, 1950; Gachon, 1963; Ballut, 2000). This interpretation is also supported by studies of alluvial dynamics of Western and Northern Europe during the Early to Middle Holocene, especially in the Atlantic period (Brown, 1997; Gregory & Benito, 2003; Bell & Walker, 2005; Notebaert & Verstraeten, 2010). In France, studies frequently report a general relative stability of floodplains during the Early Holocene (Preboreal and Boreal), whereas the Middle Holocene, and especially the beginning of the Atlantic, is often characterized by stronger sedimentary dynamics and increased detritism (Pastre et al., 2002; Berger, 2006; Lespez et al., 2008; Berger et al., 2016). In the *Limagne* lowlands the general frame of moderated aggrading processes during the first part of the Holocene is locally disturbed by the increased *Chaîne des Puys* volcanic activity from the Alleröd to the Boreal. It caused a decay in the vegetal cover and increased slope erosion and floodplain sedimentation before that vegetation recovered at the end of the Boreal and during the Atlantic period (Ballut, 2000; Vernet & Raynal, 2002; Raynal, Vernet, & Daugas, 2003). This pattern is also consistent with the *Sarliève* palaeolake sedimentation, where rates of deposition are high between the Alleröd and the beginning of the Boreal due to volcanic activity, lower in the Boreal, before a slight increase in the Atlantic (Fourmont, 2006; Macaire et al., 2010). Thus, we suggest that a possible sedimentary *hiatus* does exist between units VI and V from c. 30 kyr. BP to the Lateglacial. Unit V deposition probably started in the Early Holocene with relatively high energy alluvial events and continued during Boreal and Atlantic times gradually lowering its energy.

In the two cross-sections, units VI and V deposit assemblages strongly suggest the development of alluvial dynamics from the Upper Pleistocene to the Early or Middle Holocene rather than hydromorphic or palustrine environments: this alluvial functioning would have required an active outlet east from the basin in the area where the topographic threshold is situated, which we do not find in the current topography. A W-E valley and floodplain certainly developed and aggraded at the foot of the southwestern *Puy de Corent* slopes, with a probable bottleneck caused by the structural mounds of tertiary bedrock (Fig. 10A). Palaeovalley slope was likely downstream controlled by the Allier River which allowed fluvial incision in upstream calcareous lowlands.

After this first phase of fluvial functioning, a major pedo-sedimentary break seals underlying alluvial deposits. It can only be the result of a major geomorphological and hydrological disturbance in the catchment. Stratigraphic configuration and characteristics of unit IV suggest the coexistence of lacustrine and colluvial inputs, with evidences of a colluvial source coming from the *Puy de Corent* slopes. Comparing cross-sections 1 and 2 makes evident an east-west thickness gradient of unit IV1b, but also a similar gradient in the grain-size of basalt and scoria clasts from its clayey matrix. That suggests a massive deposition event close to the eastern part of the basin and sedimentary input. It dramatically fossilized the W-E palaeovalley system, blocking the outlet of the palaeovalley and exerting a downstream control on flow dynamics and sedimentary processes into the basin. The size, the morphology, the position but also the volcano-sedimentary composition of this topographic threshold, as well as the nature and the stratigraphy of unit IV1a suggest its colluvial origin from the *Puy de Corent*. An inspection of southern *Puy de Corent* slopes showed that they are currently only covered by thin layer of sedimentary-derived colluvium, suggesting that a mass movement has implied the collapse of the volcano-sedimentary surficial formation from a large area of the former volcano. Given the massive size of the topographic threshold and its configuration, other possibilities such as alluvio-colluvial fan damming which occurred in the nearby *Sarliève* marsh (Lenselink, Kroonenberg, & Loison, 1990; Fourmont, 2006) are highly unlikely.

Solifluction and massive landslides are very common features in the colluvium-covered slopes of the volcanic plateaus in central and southern *Limagne* (Greffier, Restituito, & Héraud, 1980; Vidal, Hervé, & Camus, 1996; Vidal & De Goër, 1997), but also in other volcanized basins of the French Massif Central like the *Bassin du Velay* (Poiraud, 2012; Poiraud, Miras, & Defive, 2012). Some of these events are relatively recent, clearly detectable in the landscape and were well documented in XIXth Century local historical sources and XXth Century technical reports (CETE, 1974, 1981; Bouiller, 1979; Malatrait, 1993). However clues about ancient and massive landslides have often completely disappeared from slopes of volcanic plateaus, some of them remaining thereby largely unknown, such as the one located at the limit of the Veyre River floodplain which was discovered in 2014 during the construction of a retirement home (Fig. 9 B). The exposed cross-section was 12 m high, but the bedrock was only reached 12 m under the building level, implying a total landslide deposit thickness of *circa* 24 m (Fig. 9 A); unfortunately this landslide remained undated. Comparison between hand samples from palaeosoil levels trapped in this landslide deposit and samples from unit IV1a in cross-section 1 showed a strong similarity (see Fig. 9C and D): both of them are characterized by a disturbed mixture of marl remains with clay, organic levels and clasts, supporting the interpretation that unit IV1a is the deposit from a landslide containing palaeosoil remains in secondary position. The presence of basalt granules, but especially reddish scoria and *peperite* grains, both specific to *Corent* scoria cone and its *peperitic* diatreme (Bouiller, 1979; Greffier, Restituito, & Héraud, 1980; Nehlig et al., 2003), strongly suggest quick and massive transport processes from this volcanic plateau rather than other origins.

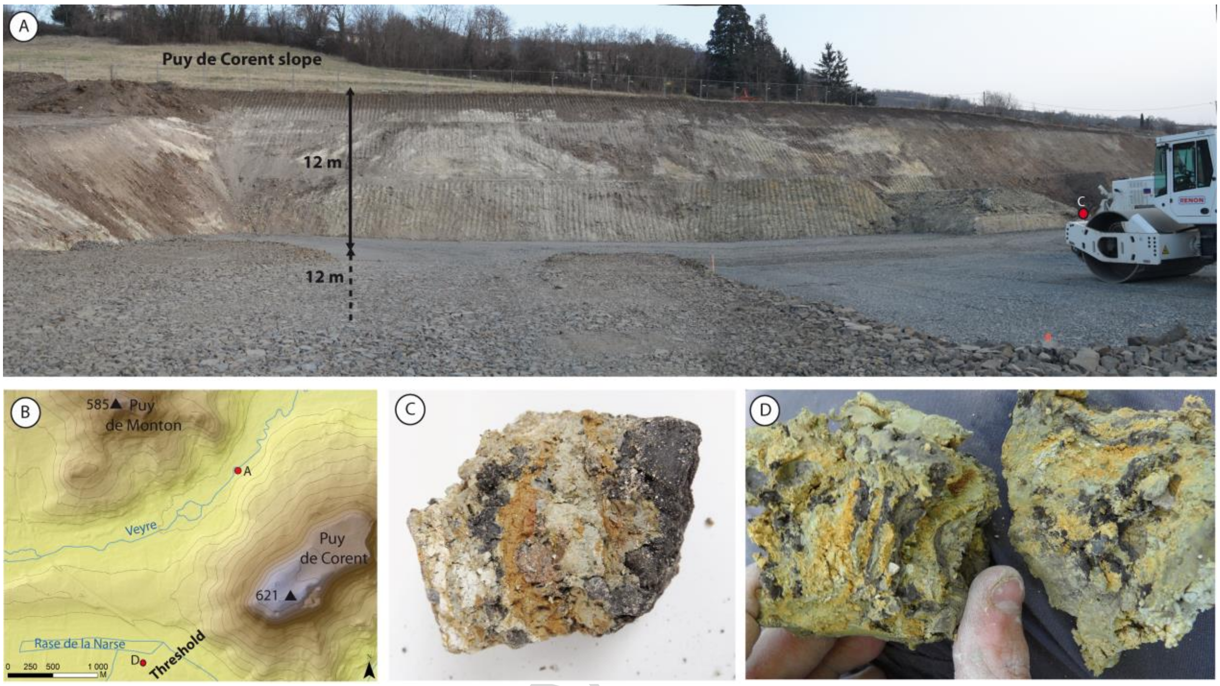

Figure 9. A) Veyre landslide in 2014. Red dot noted "C" indicates location of the hand sample (see below); B) Location of the Veyre Landslide and unit IV1a sample (red dots) ; C) Veyre landslide hand sample; D) Unit IV1a hand sample.

Unfortunately this major geomorphological event, certainly a massive landslide, could not be directly dated due to a lack of organic material available. However the ^{14}C date from the base of Unit III (Table 1 - Poz-86201, Fig. 8) shows that the hydromorphic phase started at c. 2881+-206 cal BC, providing a *terminus ante quem* for the preceding landslide phase (unit IV). The sedimentological characteristics of unit IV1b (see Fig. 8) suggest that it could be the result of an intense alluvio-colluvial reworking of the landslide sediments and of marls erosion from the landslide scar. This reworking was likely followed by fine sediment deposition in a very low energy environment, probably a shallow lake. This interpretation is supported by the merely mineral nature of unit IV1b, massive fine clays without any organic material nor pedogenic features, which suggests a quick transport and deposition of materials from *Corent* slopes, and is consistent with the erosion of marls or marl colluvium after the landslide. Furthermore the first pedogenic features from this alluvio-colluvial sediment are in the hydromorphic soil at bottom of the unit III. All these data suggest that the landslide blocking the palaeovalley could have occurred not much before 2881 cal BC.

Around 5600 cal BP (3650 cal BC), the mid-Holocene climatic shift (Steig, 1999; Wanner et al., 2008; Fletcher, Debret, & Goñi, 2013) implied colder temperatures and increased rainfalls in Europe (Orombelli & Ravazzi, 1996; Magny, 2004; Bell & Walker, 2005; Magny et al., 2006). These mid-Holocene hydroclimatic changes have had a particular incidence in the Mediterranean and in peripheral alpine areas (Roberts et al., 2011; Vanniére et al., 2011; Bosmans et al., 2015; Zielhofer, Fletcher, et al., 2017). In mountain areas, they have been related to increased geomorphic instability (Cremaschi & Nicosia, 2012). For the same period, an increased frequency of landslides has also been noted in the nearby *Bassin du Velay* (Poiraud, Miras, & Defive, 2012) with analogous structural settings (colluvium on volcanic plateaus slopes).

Consequently in the absence of a date at the base of the deposit, we suggest that *the Puy de Corent* landslide could have dammed *La Narse* valley in the early Sub-Boreal, between 3600 and 2800 cal BC (Fig. 10B and 11.3). This proposal is consistent with basin chrono-stratigraphy but also with increased alpine landslides dynamics triggered by mid-Holocene climatic shift (Margielewski, 1997; Borgatti & Soldati, 2002, 2010; Malgot & Baliak, 2002; Dapples et al., 2003; Soldati, Corsini, & Pasuto, 2004; Zerathe et al., 2014). The rainfall increase could have been the main trigger in increasing landslide activity in the slopes of the volcanic plateaus, perhaps aggravated by Neolithic forest clearance episodes (Dreibrodt et al., 2010; Ledger et al., 2015), together with an increased human activity in foothills and hillslopes in lower Auvergne during this period (Daugas & Raynal, 1989; Raynal, Vernet, & Daugas, 2003).

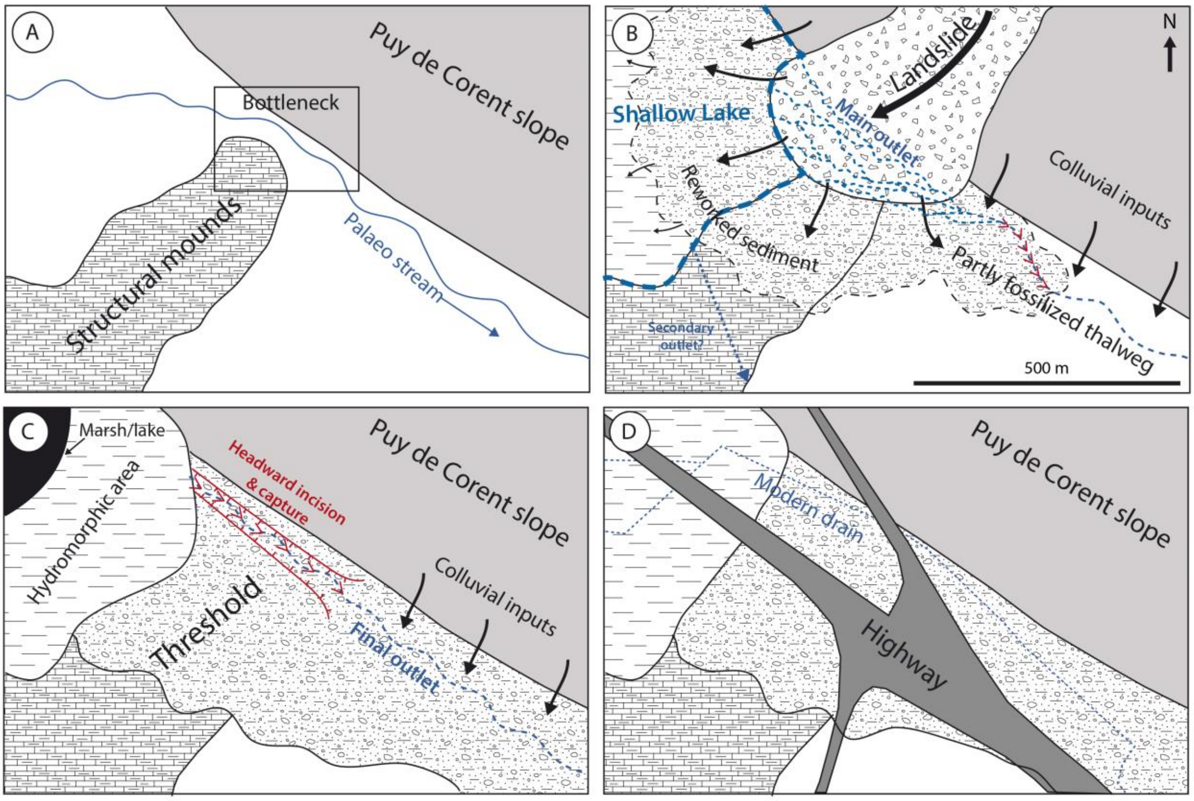

Figure 10. Simplified sequence illustrating the palaeovalley closure and the depression evolution. (A) Palaeovalley during Early and Middle Holocene. (B) Landslide dammed the valley and closed the basin (early Subboreal?). Sediments from the landslide body and scar were reworked and redistributed into the depression occupied by a shallow lake; downstream thalweg was partly fossilized. (C) Regressive erosion controlled by the downstream channel level incised the outlet channel and drained the shallow lake. Hydromorphic to palustrine/lacustrine conditions developed as sedimentary infilling continued (2881 cal BC to late Middle Ages). (D) From Modern to contemporaneous period, the depression was artificially drained (XVIIIth Century) and the outlet buried; a highway was finally constructed in the late XXth Century.

Once the valley was dammed, the body of the landslide acted as a topographic threshold, blocking the valley outlet and causing the quick formation of a shallow water body (Fig. 10B and 11.4). Then, sediment from landslide scar and foothill were reworked by erosion processes and finally deposited in the low energy environment of this shallow lake, the top of the deposits reaching 368.8-369.0 masl approximatively. This scenario explains the lateral transition between Units IV1a and IV1b which pass from a massive colluvial facies to lacustrine facies.

The water level raised to 372-373 masl aprox., and as the bottom of the new closed basin was c. 366.5 masl (top of Unit V, see Fig. 6), the water body reached a maximum depth of c. 5-6m. Then, water flowed from one or two outlet channels that LIDAR imagery and photogrammetry detected (see Fig. 4). In-channel erosion and incision were probably controlled by the downstream stream base level and were certainly facilitated by regressive migration of knickpoints affecting preferentially the non-cohesive landslide sediments (Fig. 10C). At foot of the Puy de Corent, this caused the Northern channel to lower more rapidly than the South-West channel. Incision processes continued until the Northern outlet established around 368 masl, eroding a new channel into lacustrine deposits of the basin (Fig. 6, top of unit IV1.b).

The outlet channel reached a depth of c. 5m (373 to 368 masl) around 2881 cal BC. Then, a new fluvial phase began in a plain now drained downstream by the outlet channel deeply incised into landslide deposits (see unit III, Fig. 6). This interpretation is consistent with altitudes, depth and cross-sectional shape of the outlet thalweg still visible on the XVIIIth century sketch. It also coincides with the current altitudes of the threshold and the drainage gallery (Fig. 4E and 5), even if the thalweg certainly aggraded later. This new phase was characterized by a slow aggradation under hydromorphic conditions: clay sedimentation was occasionally interrupted by more energetic alluvial phases maybe linked to hydro-climatic instability at the end of the Middle Holocene, which are well documented at regional and global scales (Joerin, Stocker, & Schlüchter, 2006; Magny et al., 2009; Brisset et al., 2013; Wang et al., 2013). However low-energy hydromorphic conditions became finally permanent until the late Antiquity (Fig. 11.5). Therefore, at least since 2881 cal BC, hydrological changes (redox conditions, water-table oscillations, downstream channel aggradation or incision, etc.) and alluvial aggradation in *La Narse* basin are mainly controlled by climatic oscillations and/or anthropic activity (e.g. drainage works) rather than by structural factors; they are outside the scope of this work and will be the object of detailed forthcoming research.

In the early Middle Ages (c. 500 cal AD) the water table abruptly rose and/or drainage conditions deteriorated, and a marsh developed in the lower part of the basin (Fig. 11.6). This drainage deterioration is consistent with similar events seen in the *Limagne* plain and the *Sarliève* palaeolake, where it is explained by a combination of climatic and historical factors (Ballut, 2001; Fourmont, 2006; Vernet, 2013). Marsh evolved to a shallow lake where diatomite deposited during the central and late Middle Ages (511 cal AD to 1428 cal AD approx., Fig. 11.7). Here radiocarbon chronology becomes consistent with historical sources evoking fisheries and a mill (Daugas & Tixier, 1977; Vallat, 2003). Certainly in the XVIIIth century the lake was drained for cultivation (Daugas & Tixier, 1977), the outlet channel was buried in a masonried gallery (Fig. 5C), and the basin became a drained hydromorphic plain seasonally flooded (Fig. 11.8). In modern times, several roads and finally a highway interchange were built in the topographic threshold area (Fig. 10D)

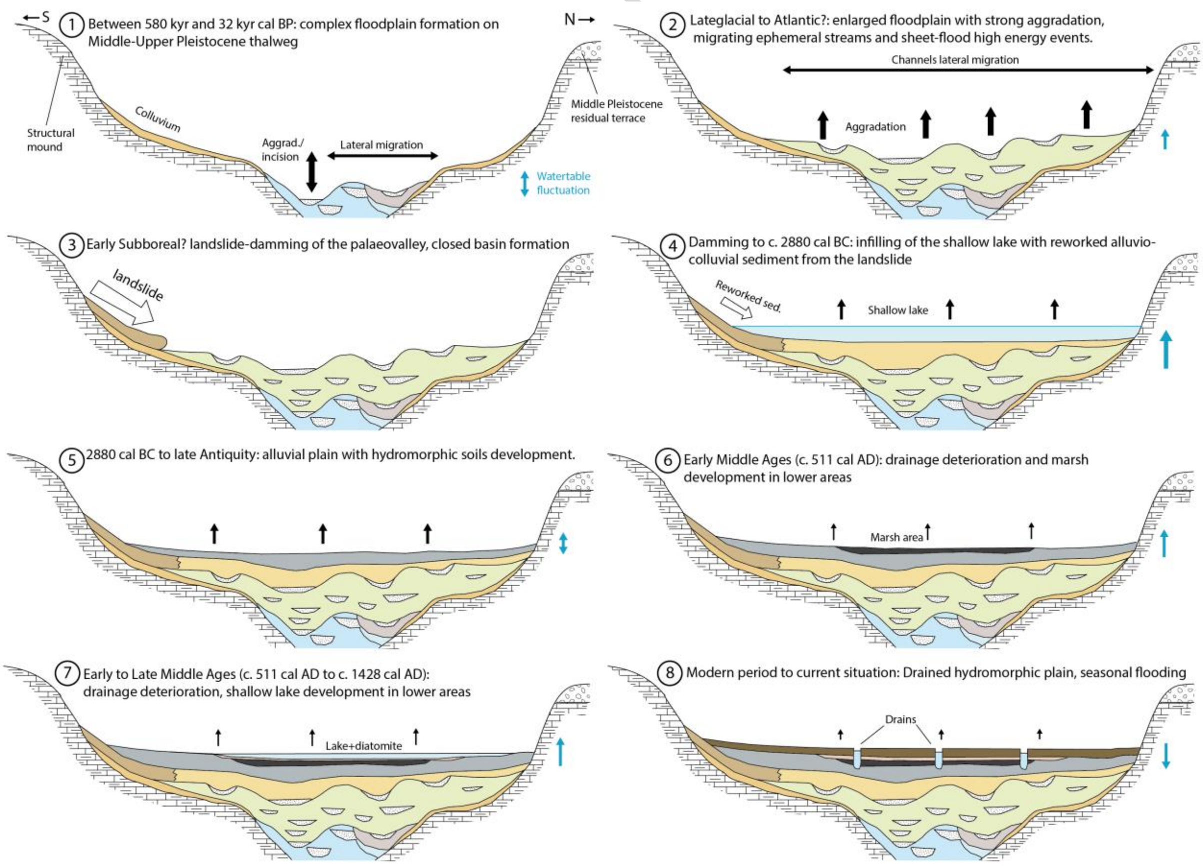

Figure 11. Reconstruction of main hydro-sedimentary phases in the evolution of the basin since the Upper Pleistocene. For sedimentary units colors, see Fig. 6.

6. CONCLUSION

This work is the first geomorphological study of the basin of *La Narse de la Sauvetat*, a hydromorphic depression situated in the southern *Limagne* plain (French Massif Central). An integrated approach based on geomorphological and stratigraphic analysis, pedo-sedimentary characterization, geophysical prospection, geomatics and radiocarbon dating provided valuable information about the basin origin and evolution during Upper Pleistocene and Holocene. At the base of the sedimentary sequence, results demonstrated the existence of a former paleovalley fossilized under about 6m of sedimentary infilling. The geomorphological analysis of the eastern area of the basin, the topographic reconstruction from recent LiDAR survey and former (1962) aerial imagery prior to civil-engineering works made evident the locking in of this former valley by a topographic threshold. Stratigraphic and pedo-sedimentary analysis of the infilling of the depression revealed that alluvial facies fill its deeper part while hydromorphic to palustrine facies fill its upper part. Both of them are separated by a colluvial layer linked to a massive colluvial input from the *Puy de Corent* slopes, and by lacustrine deposits. This event was then interpreted as a massive landslide which completely locked in the palaeovalley forming the threshold and the basin. Using available data we propose that the landslide occurred in the the Early Subboreal and is probably linked to the Mid-Holocene climatic shift, however this hypothesis needs to be confirmed by further research.

This work also allowed us to characterize main phases in the infilling of the depression. We proposed a chronological framework consistent with local and Western Europe Upper Pleistocene and Holocene alluvial dynamics, which will be completed and refined in further studies: infilling of the basin likely began before c. 32 kyr. BP in an alluvial floodplain exposed to aggradation and incision phases constrained to Upper Pleistocene thalwegs excavated in bedrock. A sedimentary hiatus probably existed between c. 32 kyr. BP and the Lateglacial. From the Early Holocene until the Atlantic, the floodplain was likely aggrading which is consistent with local and regional sedimentary yield in the first part of the Holocene. Valley damming, perhaps at the beginning of the Subboreal, was the major event affecting the history of this area, since it blocked the drainage and formed a shallow lake in the closed basin which was quickly captured by the drainage network and became hydromorphic (c. 2881 cal BC) until the late Antiquity (c. 500 cal BC). An abrupt drainage deterioration and/or water table rising occurred at the start of the Middle Ages and caused the formation of a marsh which became a shallow lake standing until the XVIIIth Century, when the basin was definitively drained.

In forthcoming investigations, the sedimentary record from this basin will certainly provide valuable Holocene geomorphological and palaeoenvironmental data: the base of the sedimentary sequence should contribute to the knowledge of regional alluvial dynamics during the Lateglacial and Early Holocene, and also of environmental impacts of local volcanic activity. Younger section of the sedimentary record could provide valuable data concerning Middle-Late Holocene hydro-climatic changes and their geomorphological implications in the area, but also an insight on long term human-environmental interactions from the Neolithic to the Roman period in southern *Limagne*. Hence, this long-time sedimentary record makes *La Narse de la Sauvetat* depression an excellent place for further development of high resolution multi-proxy palaeoenvironmental research.

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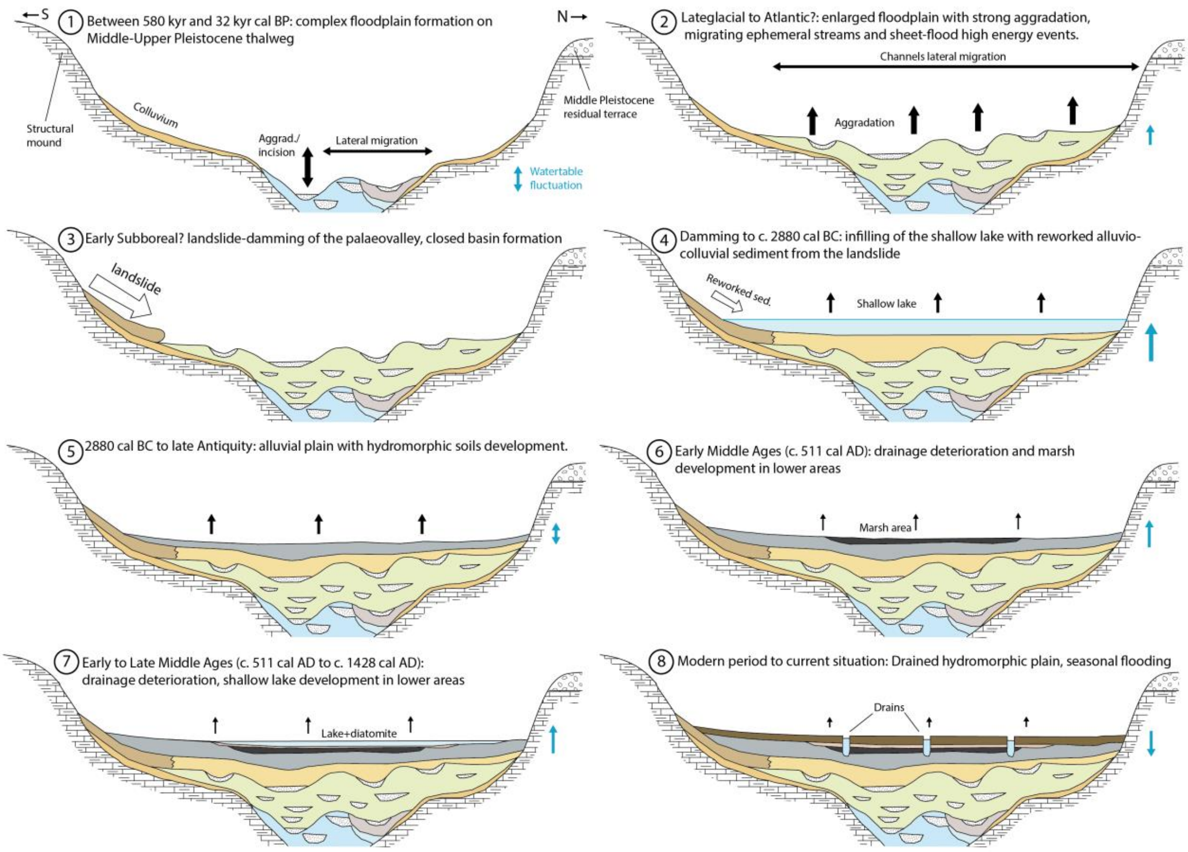
Graphical abstract



HIGHLIGHTS

- A palaeovalley was found under Pleistocene and Holocene alluvio-colluvial sediments
- A landslide dammed the valley in the early Subboreal, forming a short-lived lake
- The depression became hydromorphic between 2800 cal BC and late Antiquity
- The basin was a marsh then a shallow lake during the Middle Ages
- La Narse de la Sauvetat has high potential for further palaeoenvironmental research