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Early human impact on soils and hydro-sedimentary systems: Multi-proxy geoarchaeological analyses from La Narse de la Sauvetat (France)

Alfredo Mayoral, Salomé Granai, Anne-Lise Develle, Jean-Luc Peiry, Yannick Miras, Florian Couderc, Gérard Vernet, Jean-François Berger

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Early human impact on soils and hydro-sedimentary systems: multi-proxy ge archaeological analyses from La Narse de la Sauvetat (France)

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| Keywords: | Geoarchaeology, Palaeoenvironment, Socio-environmental interaction, Anthropogenic impact, Holocene, Limagne |
| Abstract: | <p>We analyzed the Late Holocene pedo-sedimentary archives of La Narse de la Sauvetat, a hydromorphic depression in the southern Limagne plain (central France), where chronologically accurate studies are scarce. The multi-proxy geoarchaeological and palaeoenvironmental analysis of two cores from different areas of the basin was carried out through sedimentological, geochemical, micromorphological and malacological investigations. Integration of these datasets supported by a robust radiocarbon-based chronology allowed discussion of socio-environmental interactions and anthropogenic impacts from Late Neolithic to Early Middle Ages. Until the Middle Bronze Age, there was no clear evidence of anthropogenic impact on soils and hydro-sedimentary dynamics of the catchment, but two peaks of high alluvial activity probably related to the 4.2 and 3.5 kyr. BP climate events were first recorded in Limagne. Significant anthropogenic impacts started in the Late Bronze Age with increased erosion of the surrounding volcanic slopes. However, a major threshold was reached c. 2600 cal BP with a sharp increase in the catchment erosion interpreted as resulting from strong anthropogenic environmental changes related to agricultural activities and drainage. This implies an anthropogenic forcing on soils and hydro-sedimentary systems much earlier than was usually considered in Limagne. These impacts then gradually increased during Late Iron Age and Roman periods, but environmental effects were certainly contained by progress in agricultural management. Late Antiquity environmental changes are consistent with regional trend to drainage deterioration in lowlands, but</p> |

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| | marked asynchrony in this landscape change suggests that societal factors implying differential land management were certainly predominant here. |
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6 2 **geoarchaeological analyses from La Narse de la Sauvetat (France)**
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10 3 MAYORAL, Alfredo* (1); GRANAI, Salomé (2); DEVELLE, Anne-Lise (3); PEIRY, Jean-Luc (4); MIRAS,
11
12 4 Yannick (5); COUDERC, Florian (6); VERNET, Gérard (7); BERGER, Jean-François (8)
13

14
15 5 1. Université Clermont Auvergne, CNRS, GEOLAB, F-63000 Clermont-Ferrand, France & Catalan
16

17 6 Institute of Classical Archaeology, Pl. Rovellat s/n, 43003 Tarragona, Spain.
18

19
20 7 2. GéoArchÉon, 30 Rue de la Victoire, 55210 Vigneulles-lès-Hattonchâtel & CNRS, Université Paris 1,
21

22 8 UPEC. UMR8591, Laboratoire de Géographie Physique : Environnements Quaternaires et Actuels, 1
23

24 9 place Aristide Briand, 92195 Meudon, France
25

26
27
28 10 3. UMR 5204 EDYTEM, Université Savoie Mont Blanc, CNRS, 7337 Le Bourget du Lac, France
29

30
31 11 4. Université Clermont Auvergne, F-63000 Clermont-Ferrand & CNRS, EDYTEM, F-73000 Chambéry,
32

33 12 France
34

35
36 13 5. CNRS, UMR7194, Histoire Naturelle de l'Homme Préhistorique, Département de Préhistoire,
37

38 14 Muséum National d'Histoire Naturelle, Institut de Paléontologie Humaine, Paris, France & Université
39

40 15 Clermont Auvergne, CNRS, GEOLAB, F-63000 Clermont-Ferrand, France
41

42
43
44 16 6. UMR 5608 TRACES, Université Toulouse 2 Jean Jaurès, CNRS, Toulouse, France
45

46
47 17 7. Université Clermont Auvergne, CNRS, INRAP, GEOLAB, F-63000 Clermont-Ferrand, France
48

49
50 18 8. CNRS, UMR 5600, EVS-IRG & Université Lyon 2, Lyon, France
51

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53 19 *corresponding author : alfredo.mayoral@uca.fr
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23 two cores from different areas of the basin was carried out through sedimentological, geochemical,
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34 usually considered in Limagne. These impacts then gradually increased during Late Iron Age and
35 Roman periods, but environmental effects were certainly contained by progress in agricultural
36 management. Late Antiquity environmental changes are consistent with regional trend to drainage
37 deterioration in lowlands, but marked asynchrony in this landscape change suggests that societal
38 factors implying differential land management were certainly predominant here.

39 **Keywords:** Geoarchaeology, Palaeoenvironment, Socio-environmental interactions, Anthropogenic
40 impact, Holocene, Limagne

41 **1-Introduction**

42 Middle Holocene is now generally considered as the beginning of anthropogenic impact on natural
43 systems, which becomes gradually stronger and more generalized during the Late Holocene (Crutzen
44 & Stoermer, 2000; Ellis et al., 2017; Nichols & Gogineni, 2018; Ruddiman et al., 2015; Ruddiman,
45 2018). From a geomorphological perspective, the crucial step is the generalized and intensive
46 anthropogenic modification of geomorphic processes, such as soil erosion, hydro-sedimentary

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3 47 system forcing and pronounced development of anthropogenic landforms (Brown et al., 2016;
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5 48 Goudie and Viles, 2016; Walsh et al., 2019).
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8 49 In north-western Europe, this threshold appeared to occur in the third millennium BP (Dotterweich,
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10 50 2013; Ellis et al., 2013; Notebaert, Berger, & Brochier, 2014; Ruddiman, 2003). While the forcing of
11
12 51 geomorphological processes in Roman times or at the end of the Iron Age is now accepted, some
13
14 52 authors argue that it could have occurred centuries earlier (e.g. Dreibrodt et al., 2010; Gebhardt,
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16 53 Occhietti, & Fechner, 2014; Houben et al., 2012; Lang, 2003; Notebaert & Berger, 2014), in
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18 54 connection with the development of a centralization and complexification phenomenon sometimes
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20 55 qualified as “proto-urban” in central-western Europe (Fernández-Götz, 2018).
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25 56 However, there are still some key open questions as the rates and thresholds in the broadly
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27 57 increasing pace of anthropogenic impacts, or the relative contribution and interactions between
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29 58 anthropogenic and climatic drivers. Spatial and temporal variability of anthropogenic impacts and
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31 59 associated geomorphological responses, and a general scarcity of high-resolution, continuous and
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33 60 robust datasets are amongst the main difficulties (Brown et al., 2013; 2016). Indeed, some areas such
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35 61 as the Rhône valley in SE France are extensively studied (e.g. Berger, Shennan, & Woodbridge, 2019),
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37 62 whereas other neighboring areas suffer from a dearth of analysis, poor data resolution or other
38
39 63 issues making a regional synthesis and discussion problematic.
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44 64 Our work aimed to contribute to this scientific challenge providing new data in the Limagne plain
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46 65 (central France) where even recent Holocene palaeoenvironmental and geoarchaeological research
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48 66 often lacked chronological accuracy. This lack of chronological accuracy has hindered proper
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50 67 discussion of socio-environmental interactions during critical protohistoric periods, despite abundant
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52 68 studies conducted since the 2000s (Ballut, 2001; Macaire et al., 2010; Trément, 2007a; Trément,
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54 69 2011; Vernet, 2013). The main objective of this study was therefore to bring out new multi-proxy
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56 70 palaeoenvironmental and geoarchaeological data at high chronological resolution in Limagne, and
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3 71 subsequently use them to discuss interactions of human activities with natural landscapes, especially
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5 72 with soils and hydro-sedimentary system of the catchment, as well as local vegetation and hydrology.
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8 73 We focused on a hydromorphic depression called La Narse de la Sauvetat located in the marly
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10 74 lowlands of the southern Limagne, surprisingly neglected by palaeoenvironmentalists until recently.
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13 75 Since 2014, first preliminary works detected particularly high potential for palaeoenvironmental
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15 76 studies, encouraging further research (Mayoral et al., 2018). The basin is a flat depression with a W-E
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17 77 elongated shape (2km x 800m approx.) and a surface of c. 1,2 km², dug in the Cenozoic calcareous
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19 78 rocks of southern Limagne lowlands (Fig. 1).

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23 79 In this area, the so-called *Limagne des Buttes*, incision of the drainage network after Miocene and
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25 80 Pliocene volcanism (Nehlig et al., 2003) gradually created inverted volcanic reliefs from the basaltic
26
27 81 lava flows and domes (500 to 800 masl.), which now dominate the eroded sedimentary lowlands
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29 82 (300-400 masl.). The slopes of these volcanic reliefs are covered by sedimentary or volcano-
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31 83 sedimentary colluvium, sometimes with decametric thickness, and are affected by mass movements
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34 84 and landslides (Greffier et al., 1980). Lowlands around the basin have a gentle topography, with
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36 85 some structural reliefs in marls and limestones. La Narse de la Sauvetat catchment (c. 16 km²) is
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38 86 therefore limited by volcanic plateaus and domes at the East and West (Puy de Corent, Puy de Saint-
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40 87 Sandoux and Puy de Peyronère), a Pleistocene residual terrace of the Allier river to the North, and
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42 88 small structural mounds to the South (Fig. 1B-C).

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46 89 Water and sediment fluxes come mainly from westward colluvial slopes (Puy de Saint-Sandoux, Puy
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48 90 de Peyronère), concentrated in several small flat valleys and are finally directed to the bottom of the
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50 91 depression to the east (min. 368 masl.). The basin is naturally closed by a topographic threshold in its
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52 92 eastern border and is therefore disconnected from drainage network, causing development of dark
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54 93 hydromorphic soils with isohumic/vertic features which are nowadays artificially drained and
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56 94 cultivated (see Fig. 1). Climate in the area is oceanic to semi-continental with cold and relatively dry
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58 95 winters, and hot and stormy summers (Joly et al., 2010). Soils of the catchment include a variety of
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3 96 brown soils on volcanic and/or calcareous materials, colluvial soils and regosoils on marls, gleyic
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5 97 alluvial soils, and the aforementioned hydromorphic soils in the depressions (Bornand et al., 1968,
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7 98 see Fig. 1D).
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10 99 First research works provided supplementary geomorphological data on the nature of the basin and
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12
13 100 its main phases of morpho-stratigraphic and pedo-sedimentary evolution (Mayoral et al., 2018). A
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15 101 6m-thick alluvio-colluvial sedimentary infilling was investigated through hand auger cross-sections
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17 102 (Fig. 2). Alluvial sedimentary dynamics have shown that La Narse de la Sauvetat was a palaeovalley
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19 103 connected to local drainage from the Upper Pleistocene until the mid-Holocene period, when a
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21
22 104 massive landslide formed the topographic threshold blocking its eastern outlet (see Fig. 1). Sudden
23
24 105 damming of the valley temporarily formed a lake, ultimately recaptured by headward erosion. The
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26 106 drainage network remained nevertheless disturbed and poorly hierarchized and consequently the
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28 107 area became an hydromorphic plain after c. 4850 cal BP, with palustrine and lacustrine phases until
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30 108 its drainage in 1768 AD (Daugas and Tixier, 1977; Mayoral et al., 2018).
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33
34 109 The basin is also situated within the rich protohistoric archaeological context of the Limagne plain,
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36 110 with a particularly dense and well-known record from the Neolithic to the Roman period (Provost
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38 111 and Mennessier-jouannet, 1994; Vallat, 2002). However, at a local scale the neighboring hilltop site
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40 112 of the Puy de Corent, with multi-period occupations (Fig. 1C) crucial for territorial structuring from
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42 113 the Neolithic to the Iron Age, has been the focus of almost all the research and findings. As a
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44 114 consequence of this research bias, archaeological discoveries are rather scarce in the lowlands
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46 115 surrounding La Narse de la Sauvetat basin. In general the Neolithic is poorly known in the lowlands
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48 116 due to the lack of findings, however in the Puy de Corent developed settlements are known
49
50 117 especially in the second part of the Middle Neolithic (Poux et al., 2018). Most phases of the Bronze
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52 118 Age are also poorly documented in the study area, however during the Middle Bronze Age a small
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54 119 occupation is noted (Pranly, Fig. 1C). By contrast, extended settlements develop at Corent during the
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56 120 Middle and the Late Bronze Age, and also during the Early Iron Age (Milcent et al., 2014; Poux et al.,
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3 121 2018). During the latter period, a small site is also known in the lowlands (Les Orneufs, Fig. 1C). The
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5 122 area is especially known for the Late Iron Age (La Tène) extensive *oppidum* of Corent (Poux, 2012;
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7 123 Poux et al., 2018), however lowlands around La Narse de la Sauvetat again lack archaeological
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9 124 remains for this period. The only phase with abundant archaeological remains in la Sauvetat plain is
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11 125 the Roman era, as a secondary agglomeration develops at Corent. Several sites are documented
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13 126 around La Narse basin, including farms, a sanctuary and an extensive *villa*, indicating an intense
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15 127 exploitation of the area (Simon et al., 2017; Vallat, 2002).

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19 128 With a view to fully use the set of palaeoenvironmental records of this sedimentary archive from the
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21 129 second part of the Holocene, we present here a multi-proxy geoarchaeological and
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23 130 palaeoenvironmental analysis of the upper infilling of the basin, broadly covering 3800 yr. between
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25 131 the Late Neolithic and the early Middle Ages (5000 to 1200 cal BP). Sedimentological, geochemical,
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27 132 micromorphological and malacological investigations were performed on two cores and supported
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29 133 by AMS radiocarbon dating. Results were here synthetized and discussed with other regional climate
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31 134 and palaeoenvironmental data for each archaeological period between the Late Neolithic and the
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33 135 early Middle Ages, in order to provide a more comprehensive perspective of socio-environmental
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35 136 interaction and human forcing of natural systems since the Mid-Holocene.

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46 139 Figure 1. A) Location of study area, black line delineates Auvergne region; B) General view of study area from the summit of
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48 140 the Puy de Corent (location: see Fig. 1C, view direction: ESE). La Narse hydromorphic basin and its catchment are indicated
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50 141 with white and red dashed lines respectively. Light blue dashed line indicates hypothetical position of former river course
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52 142 (Pleistocene and Early Holocene), from cross sections and current topography (see Mayoral et al., 2018); C)
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54 143 Geomorphological sketch of la Narse de la Sauvetat catchment (modified from Mayoral et al., 2018) ; D) Main soils of the
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56 144 catchment (red dashed line) following Bornand et al., 1968 : a) lithosols and brown soils on basalts ; b) Calcareous and
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58 145 calcic brown soils on marls and basaltic colluvium ; c) Colluvial soils and regosols on marls and platy limestone ; d)

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3 146 Calcareous brown soils on gentle slopes ; e) Clayey grey soils of marly depressions, hydromorphic and isohumic; f)
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5 147 Calcareous brown soils from thin residual terraces ; g) Gleyic soils from clayey alluvium of streams and marly lowlands.
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11 149 **2-Materials and Methods**

13 150 ***Coring and litho-stratigraphic analysis***

15 151 Three cores were retrieved from the basin in December 2014 using a Geotool GTR 790 corer with a
16 152 diameter of 7 cm. Drilling areas were selected after a preliminary survey consisting of c. 30 hand
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18 153 auger litho-stratigraphic logs distributed along several cross-sections (Mayoral et al., 2018). NAR2
19
20 154 (depth 230 cm) was situated in the lower part of the depression, whereas NAR3 (depth 227 cm) and
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22 155 NAR4 (depth 284 cm) were located in a drier peripheral area (Fig. 1C and 2). NAR4 was not subject to
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24 156 multi-proxy palaeoenvironmental analysis and is therefore not presented in this work. Detailed litho-
25
26 157 stratigraphic and sedimentary description of NAR2 and NAR3 cores was performed (See Table 1 and
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28 158 Fig. 3), in order to refine the description of sedimentary units (SU) from previous work (Mayoral et
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30 159 al., 2018).

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36 160 Figure 2. Selected stratigraphic cross-sections of the basin (P1 and P2, adapted from Mayoral et al., 2018) with location of
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38 161 cores NAR2 and NAR3 (see also Fig. 1C).
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43 163 ***Radiocarbon dating and age-depth modeling***

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45 164 Radiocarbon database from the first study (Mayoral et al., 2018) was completed with 9 AMS
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47 165 radiocarbon dates in cores NAR2 and 3 (see Table 2). Two were performed in selected gastropod
48
49 166 shells (*Vallonia pulchella*) in order to test if terrestrial species could locally provide accurate
50
51 167 radiocarbon ages in the absence of other datable material. Other dates were performed on
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53 168 microcharcoal manually concentrated using a binocular microscope, after deflocculating sediment
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55 169 with sodium hexametaphosphate and sieving at 500 and 100 µm. Raw radiocarbon dates were
56
57 170 calibrated with Calib 7.0 (Stuiver and Reimer, 1993) and IntCal13 calibration curve (Reimer et al.,

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3 171 2013). Age-depth models (ADM) were built using smooth spline method under CLAM (Blaauw, 2010),
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5 172 based on radiocarbon data and unambiguous stratigraphic correlations between cores (Fig. 3).
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7 173 Sediment Accumulation Rate (SAR) was then calculated.
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10 174 ***Micromorphological analysis***

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12 175 A half-section of NAR2 core was cut between 64 and 195 cm in 11 micromorphological blocks (see
13
14 176 Fig. 3). After induration, thin sections were made from these blocks at the OMEAA laboratory of UMR
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16 177 5600 EVS (University Lyon 2) following a common protocol (Guilloré, 1980). Thin section description
17
18 178 was performed using a Leica M80 binocular microscope (x2.5 to x60) and a Leica DMLP polarizing
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20 179 microscope (x16 to x400), under Cross-Polarized Light (XPL) and Plane Polarized Light (PPL), and
21
22 180 according to state-of-the-art references (Delvigne, 1998; Loaiza et al., 2015; MacKenzie et al., 1982;
23
24 181 Scholle and Ulmer-scholle, 2003; Stoops, 2003). A Leica camera was used to take microphotographs
25
26 182 and measurements. Micromorphological features were semi-quantitatively recorded (see Fig. 4 to 6
27
28 183 and Table 3 in Supplementary Information (SI)) and interpreted on the basis of up-to-date reference
29
30 184 works (Macphail and Goldberg, 2018; Nicosia and Stoops, 2017; Stoops et al. 2010b). Micro-charcoal
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32 185 was semi-automatically quantified using image analysis software (Aphelion Dev) and
33
34 186 microphotographs taken each centimeter under Oblique Incident Light (OIL) (Berger et al., 2016).
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36 187 Reddish scoria particles, whose local sources are limited to the Puy de Corent slopes in the eastern
37
38 188 part of La Narse catchment (Bouiller, 1979), were manually counted and their surface measured each
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40 189 centimeter with a binocular microscope in order to be used as a tracer of sedimentary sources.
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47 190 ***X-Ray Fluorescence***

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49 191 X-Ray Fluorescence (XRF) measurements were performed in NAR2 and NAR3 cores using an Avaatech
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51 192 XRF *core-scanner* (EDYTEM, Université Savoie Mont Blanc). Cores were analyzed with 5 mm
52
53 193 resolution under 10 kV (1mA, 10s) and 30 kV (0.75 mA, 30s) beams generated by a Rhodium anode.
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55 194 Results include detection in counts per second (cps) for Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, Rh, Cu, Zn,
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57 195 Ga, Br, Rb, Sr, Y, Zr, Nb, Mo, Pb and Bi. A Principal Component Analysis (PCA) was performed using
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3 196 Xlstat software on selected elements of NAR2 (Fig. 8), in order to assess relationships between
4
5 197 elements and with sedimentary units (Bajard et al., 2016; Birks & Birks, 2006 ; Sabatier et al., 2010).
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7 198 To improve the PCA interpretation and especially to refine the sedimentary source identification, we
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9
10 199 added 20 supplementary individuals (not contributing to the PCA) obtained from XRF analysis of a
11
12 200 core situated in the top of the Puy de Corent (Fig. 1C). These individuals reflect the geochemical
13
14 201 signature of a 100% volcanic soil and sediment (data from Mayoral, 2018). Elementary ratios were
15
16 202 selected as palaeoenvironmental proxies based on PCA analysis, local geology and soils, litho-
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18 203 stratigraphy, micromorphological analysis and sedimentological data, and following up-to-date
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20
21 204 references (e.g. Croudace and Rothwell, 2015).

24 205 ***Sedimentological analysis***

26 206 Grain-size analysis was undertaken on NAR2 core using a Coulter LS230 granulometer. We analyzed
27
28 207 contiguous 2cm-thick sediment slices of NAR2, between 30 and 230 cm (see Fig. 3). Data were then
29
30 208 processed under Gradistat (Blott and Pye, 2001), and resulting statistical parameters (D50 and D99)
31
32 209 were used to build a Passega (or CM) diagram (see Fig. 8) in order to identify hydro-sedimentary
33
34 210 processes (Bravard and Peiry, 1999; Passega, 1977).

38 211 Magnetic susceptibility (MS) of NAR2 and NAR3 was measured using a Bartington MS2E meter. Four
39
40 212 measurements were performed each cm, and the mean value was retained in order to integrate
41
42 213 signal variability (Dearing, 1999). Loss on ignition (LOI) was used to assess contents in organic matter
43
44 214 (OM) and carbonates in both cores. We analyzed contiguous 2cm-thick sediment slices (see Fig. 3) of
45
46 215 NAR2 (30-230 cm) and NAR3 (54-227 cm), following a standard two-step protocol (Heiri et al., 2001).

50 216 ***Malacological analysis***

53 217 Malacological analysis was performed in both cores in order to assess the development of the
54
55 218 structure of the vegetation cover and to reconstruct hydrological dynamics in the depression. We
56
57 219 sampled contiguous 2cm-thick sediment slices (see Fig. 3) in NAR2 (70-202 cm, half-section) and NAR
58
59 220 3 (84-201 cm, full section). Samples were sieved at 500 µm and studied under binocular microscope.

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3 221 When necessary, samples from the same SU were grouped in bigger sets (4 to 14 cm, see Tables 4
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5 222 and 5 in SI) in order to reach a significant number of shells, since at least 150 individuals per sample
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7 223 were required to run a reliable statistical analysis (Evans, 1972). Samples comprising a boundary
8
9 224 between two SU were not analyzed. Determination of species was performed on the basis of
10
11 225 identification guides (Horsák et al., 2013; Kerney & Cameron 2006; Welter-Schultes, 2012). 23
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13 226 terrestrial and 14 freshwater species have been listed (Tables 4 and 5 in SI). On the basis of the
14
15 227 faunal lists, an analysis of the species composition of the malacological assemblage of each sample
16
17 228 was carried out and each species was assigned to an ecological group, which was defined in the light
18
19 229 of the habitats described in the species guides used for determination. Terrestrial species were
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21 230 divided into four ecological groups (shade-demanding species, mesophile species, marshland species
22
23 231 and open-ground species) while freshwater species were combined in a single group (Fig. 9).
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30 232 **3-Results**

31 32 33 233 **3.1 Stratigraphy and age-depth models**

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35 234 Litho-stratigraphy of both cores is broadly similar, with some thickness and grain-size variability due
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37 235 to lateral change of facies and position in the depression (see Figs. 1 to 3). Four Sedimentary Units
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39 236 (SU) are concerned by multi-proxy analysis: SUIII.2-3, SUIII.1b, SUIII.1a and SUII.3. For a complete
40
41 237 description of NAR2 and NAR3 litho-stratigraphy, see Table 1. SU III.2-3 consists of grey silty clays,
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43 238 including (in the core NAR2) two well-sorted and fining-upwards coarse sand levels. SUIII.1.b is
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45 239 composed of more or less dark grey silty clay with traces of pedogenesis: this layer is representative
46
47 240 of the locally extended hydromorphic and isohumic soils, so-called Limagne “dark earths” (Bornand
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49 241 et al., 1968). SUIII.1a is similar to SUIII.1b, but has a more brownish color and includes several
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51 242 oxidation mottles, indicating drier or more fluctuating hydrological conditions. Finally SUII.3 is
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53 243 composed of black and very dark grey silty clays, rich in non-degraded vegetal debris, suggesting
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55 244 deposit under palustrine conditions (Mayoral et al., 2018).
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245 Table 1. Litho-stratigraphic description of cores NAR2 and NAR3, and stratigraphic correlations between them.

| NAR2 | | SU | NAR3 | |
|--|-----------------|---------|---------|---|
| Description (Munsell color, grain size, inclusions, pedofeatures) | Cm. | | Cm. | Description (Munsell color, grain size, inclusions, pedofeatures) |
| 2,5Y4/2 Silty clay with macrocharcoal and OM remains, few fine sands, bioturbation (current topsoil) | 0-12 | I | 0-25 | 2,5Y3,5/2 Silty clays with darker mottles. Some fine to medium sparse sands. Organic remains and malacoremain. Bioturbation (current topsoil) |
| 2,5Y4/2 Silty clay to clayey silt, abundant OM remains, few fine sands, bioturbation (roots) | 12-16 | | | |
| 2,5Y4/2 Silty clay, some fine sands, few small charcoal, rootlets | 16-26 | | | |
| 2,5Y4/2 Clayey silt, pale yellow inclusions (diatomite), small yellowish brown oxidation mottles, small charcoal, some fine to medium sands, rare malacoremain | 26-35 | II.1 | - | - |
| 2,5Y4,5/2 Clayey silt, rare sands, abundant pale yellow inclusions (diatomite), few small yellowish brown oxidation mottles, some malacoremain | 35-44 | | | |
| 2,5Y5/2 Silty clay, darker dots, some malacoremain | 44-59 | II.2 | 25-47 | 2,5Y3,5/2 Silty clays, some sparse medium sands |
| 2,5Y5/2 Silty clay, sparse fine to medium sands, darker inclusions from underlying unit, irregular inferior limit, abundant malacoremain | 59-64 | | | |
| 5Y4/1 Silty clay, sparse fine sands, darker inclusions from underlying unit, incipient subangular to granular aggregation, abundant malacoremain | 64-70 | II.3 | 47-54 | 5Y3/2 Silty clays, darker inclusion from underlying unit, and brown from overlying unit. Rare medium sands, rare malacoremain |
| 2,5Y2/0 Silty clay, brown inclusions from underlying unit, few fine sands, small organic debris and abundant OM, incipient granular to crumbly aggregation, abundant malacoremain. | 70-79 | | 54-61 | 5Y2,5/1 Silty clays, with darker mottles. Abundant malacoremain and sparse fine to medium sands. |
| 5Y4/1 Silty clay, several black inclusions from overlying unit, several small yellowish brown oxidation mottles, few malacoremain. | 79-85 | III.1a | 61-76 | 5Y3,5/2 Silty clays, brown oxidation mottles (top), some darker mottles from overlying unit. Rare fine to medium sands. |
| 5Y4/1 Silty clay, rare black inclusions from overlying units, rare oxidation mottles, rare malacoremain | 85-90 | | | |
| 5Y4/1 Silty clay, rare fine sands, rare malacoremain | 90-100 | III.1b | 76-103 | 5Y4/1,5 Silty clays, small malacoremain |
| 5Y4/1 Silty clay, incipient granular aggregation to the base, few malacoremain | 100-114 | | 103-113 | 5Y3/1 Silty clays, small malacoremain. |
| 5Y3,5/1 Silty clay, incipient crumbly aggregation, several malacoremain, | 114-122 | | 113-128 | 5Y3/2 Silty clays, small malacoremain |
| 5Y3/1 Silty clay, incipient crumbly aggregation, abundant malacoremain | 122-132 | | 128-147 | 5Y3/2 Silty clays, small malacoremain |
| 5Y3/1 Silty clay, incipient crumbly aggregation (top), abundant malacoremain | 132-154 | | 147-158 | 5Y3/2 Silty clays, several malacoremain |
| 5Y4/1 Silty clay, sparse fine sands, abundant darker mottles from overlying unit | 154-158 | | | |
| 5Y4/1 Slightly silty clay, few dark mottles, one dark lamination, some sparse fine sands | 158-163 | | | |
| 5Y4/1,5 Silty clays, several fine to medium sands, several small oxidation mottles, irregular contact with underlying unit. One dark lamination. | 163-168/171 | III.2-3 | 158-172 | 5Y3/1,5 Silty clays, small malacoremain |
| 5Y4/1,5 Fine to coarse sands, poorly rounded grains (limestone, basalt, quartz). Fining upwards sorting. Few silts and clays. Irregular top and base. | 168/171-178/180 | | | |
| 5Y4/1 Silty clays abundant sparse fine to coarse sands (limestone, basalt, quartz), rare malacoremain. | 178/180-185 | | | |
| 5Y4/1,5 Fine to coarse sands (limestone, basalt, quartz), poorly rounded, silts and clays. Fining upwards sorting (poorly marked). One angular basaltic gravel at the base. | 185-194 | | | |
| 5Y4,5/1 Silty clay, some sparse fine sands | 194-196 | | | |
| 5Y4,5/1 Silty clay, with intercalations of 5Y6/2 heavy clay, including oxidation mottles. Sparse fine to coarse sands | 196-202 | IV.1b | 193-203 | 5Y5/1 (top) to 7/2 (base, with several darker intercalations) Heavy clays. |
| 5Y6/2 Heavy clay with oxidation mottles and darker mottles from upper units (bioturbation?). Rare and sparse fine sands | 202-212/214 | | | |
| 5Y6/2 Slightly silty clay with oxidation mottles, some fine to medium sands | 212/214-217 | | | |
| 5Y6/2 Heavy clay with rare oxidation mottles, rare fine to medium sands | 217-222 | | | |
| 5Y6/2 Slightly silty clay, big oxidation mottles, sparse fine to medium sands | 222-228 | | | |
| 5Y6/2 Heavy clay, rare oxidation mottles, sparse fine to medium sands | 228-230 | V | 203-220 | 5Y6/2 Heavy clays. Rare and sparse fine sands. 2 dark laminations. Oxidation mottles. |
| - | - | | 220-225 | 5Y6/2,5 Heavy clays. Rare and sparse fine to coarse sands. Very abundant oxidation mottles. One dark lamination (base). |
| - | - | | 225-227 | 5Y6/2,5 Heavy clays, Rare and sparse fine to coarse sands. Few oxidation mottles. |

246 The radiocarbon database includes 14 dates distributed within the two cores and performed mainly
247 on charcoal (Table 2). The two dates on gastropod shells were rejected because they provided
248 significantly older results than charcoal, clearly inconsistent with the chrono-stratigraphic
249 framework. The Age-Depth Model (ADM) constructed for NAR2 (smooth spline) was extrapolated to
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3 250 230 cm and SAR was calculated, showing a peak c. 2200-2300 cal BP (Fig. 3). Using radiocarbon and
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5 251 stratigraphic correlations with NAR2 (SUIV.1b and SUII.3), a less robust (especially under 150 cm) but
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7 252 nevertheless satisfactory ADM was also constructed for NAR3. SAR in NAR3 shows a disproportionate
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9 253 peak, between two comparable dates (Table 2), suggesting a virtually instantaneous deposit such as
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11 254 flood overbank deposits or anthropogenic backfill linked to nearby Roman archaeological remains
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13 255 (Fig. 1 and 2). The best age-model estimation from both models was used to discuss multi-proxy
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15 256 analysis results.
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19 257 Figure 3. Litho-stratigraphy, stratigraphic correlations, sampling and age-depth model of NAR2 (left) and NAR3 (right) cores.
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280 Table 2. Radiocarbon dates from NAR2 and NAR3 cores. 1,3,4,5 and 9 were published in Mayoral et al. (2018). *Dates in italic were rejected.*

| Nº | Core | Depth (cm) | Lab Code | Material | ¹⁴ C yr. BP | Cal BP (median, 2σ) | Cal BC/AD (median, 2σ) |
|----|-------|------------|-------------|----------------------------------|------------------------|---------------------|------------------------|
| 1 | NAR2 | 38-40 | Poz-86197 | Microcharcoal | 485 ± 30 BP | 522 ± 21 | 1428 ± 21 cal AD |
| 2 | NAR2 | 70-72 | Poz-71623 | Microcharcoal | 1505 ± 30 BP | 1418 ± 100 | 532 ± 100 cal AD |
| 3 | NAR2 | 76-78 | Poz-86198 | Microcharcoal | 1540 ± 40 BP | 1439 ± 89 | 511 ± 89 cal AD |
| 4 | NAR2 | 106-108 | Poz-71624 | Microcharcoal | 2035 ± 35 BP | 2006 ± 106 | 56 ± 106 cal BC |
| 5 | NAR2 | 142-144 | Poz-71625 | Microcharcoal | 2410 ± 40 BP | 2524 ± 176 | 574 ± 176 cal BC |
| 6 | NAR2 | 160-162 | Beta-434189 | Microcharcoal | 2460 ± 30 BP | 2537 ± 171 | 587 ± 171 cal BC |
| 7 | NAR2 | 183-184 | Poz-86199 | Microcharcoal | 3415 ± 30 BP | 3699 ± 120 | 1749 ± 120 cal BC |
| 8 | NAR2 | 190-192 | Poz-86200 | Microcharcoal | 3910 ± 30 BP | 4335 ± 86 | 2385 ± 86 cal BC |
| 9 | NAR2 | 196-200 | Poz-86201 | Microcharcoal | 4280 ± 60 BP | 4831 ± 206 | 2881 ± 206 cal BC |
| 10 | NAR3 | 98-100 | Poz-86203 | Microcharcoal | 1540 ± 50 BP | 1437 ± 102 | 513 ± 102 cal AD |
| 11 | NAR 3 | 114-120 | Poz-103585 | <i>Vallonia pulchella shells</i> | 2425 ± 30 BP | 2526 ± 172 | 576 ± 172 cal BC |
| 12 | NAR3 | 120-122 | Poz-86204 | Microcharcoal | 1930 ± 35 BP | 1901 ± 88 | 49 ± 88 cal AD |
| 13 | NAR3 | 130-132 | Poz-86205 | Microcharcoal | 2010 ± 30 BP | 1963 ± 78 | 13 ± 78 cal BC |
| 14 | NAR 3 | 174-181 | Poz-103586 | <i>Vallonia pulchella shells</i> | 6480 ± 50 BP | 7379 ± 98 | 5429 ± 98 cal BC |

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283 3.2 Micromorphology

284 Detailed micromorphological descriptions can be found in Table 3 in SI. The key features used to
 285 define micromorphological units (named MI to MVII) were semi-quantitatively recorded in Fig. 6.

286 Units MVII and MV (195-188 and 178-166 cm) are formed by roughly sorted coarse to fine alluvial
 287 sand with fining-upwards sorting. Sand is rich in carbonated and volcanic grains (basalt with analcime
 288 crystals and scoria, see Fig. 4), and rounded fragments of tuffaceous/pisolithic coatings and
 289 biospheroids. These fragments together with some organic remains (chiefly vegetal tissues, bone or
 290 charcoal) and inherited pedosedimentary aggregates, indicate a polyphased genesis of these sandy

291 layers. Both are likely the result of an intense hydro-sedimentary event that eroded soils and
 292 riverbed deposits of the catchment, separated by a phase of incipient soil formation (MVI).

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294 Figure 4. Selected micromorphological features of lower NAR2 (Micromorphological Units MVII to MIV, see text and Fig. 6). A) Cluster of
 295 mite droppings, microcharcoal-rich micromass (MIV, N211, PPL-Plane Polarized Light). B) Platy microstructure (MIV, N211, transmitted
 296 light). C) Spore remains (MIV, N211, PPL). D) Rounded pedosedimentary aggregate (reddish matrix), surrounded mainly by carbonated
 297 micritic sands (MV, N212B, XPL-Crossed Polarized Light). E) Bone fragment (MVI, N213, XPL). F) Fragment of micritic to micro-sparitic
 298 carbonated root concretion (MIV, N212A, XPL). G) Contact (arrows) of coarse sands with silty clays. Note the big stromatolitic/tuffaceous
 299 fragment of limestone, with a secondary microlaminated calcite coating (MV, N212B, XPL). H) Fragment of basalt with a coating of
 300 microlaminated calcite (micrite and microsparite) and rounded by transport (MVI, N213, XPL). I) Volcanic reddish scoria fragment, including
 301 translucent plagioclases (MV, N212B, OIL-Oblique Incident Light). J) Cluster of charcoal and in-situ charred remains (MIV, N211, PPL). K)
 302 Portion of dark matrix, with more abundant coarse fraction, more humic and enriched in microcharcoal, probably from a surficial soil
 303 horizon (MIV, base of N211, OIL). L) Clayey aggregates with striated B-Fabric (arrows), likely degraded fragments of slaking crust (MIV,
 304 N212A, XPL).

305 Sediment forming MVI unit (186-178 cm) has finer texture, with abundant clayey matrix.
 306 Pedofeatures suggest some soil development despite a poorly developed microstructure, with few
 307 orthic sparite nodules and organo-manganic aggregates, within abundant floated materials (bone
 308 and charcoal).

309 Unit MIV (172-152 cm) matrix is made of silty clays with few coarse particles, and
 310 micromorphological features (microstructure, pedofeatures) broadly indicate more mature soil
 311 development than in previous phases. Reduced porosity, few biospheroids and presence of calcite
 312 and manganese nodules suggest a massive soil, with fluctuating water table level and short but
 313 repeated water saturations of soil (Courty et al. 1989; Durand et al., 2010; Freytet and Verrecchia,
 314 1998; Lindbo et al. 2010; Zamanian et al., 2016). Abundance of mite droppings (Fig. 4 and 6) instead
 315 of traces of earthworm activity indicate massive soil development under damp conditions, which
 316 would be consistent with the reconstruction of a wet grassland environment (Gerasimova and
 317 Lebedeva-Verba, 2010 ; Jeffery et al., 2010 ; Kooistra and Pulleman, 2010).

318 The top of the unit presents striking micromorphological differences with the underlying units, such
 319 as platy microstructure, increased porosity (vughs, small rootlets channels), calcitic earthworm

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3 320 biospheroids and more abundant organic remains including micro- and macrocharcoal (Fig. 4 and 6).
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5 321 In addition, some small aggregates with striated b-fabric are likely fragments of a slaking crust from
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7 322 superficial soil palaeohorizons (Fig. 4). Taken together, these features clearly indicate a major soil
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9 323 disturbance at the summit of unit MIV that might result from agricultural activities and use of fire to
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11 324 clear the ground (Adderley et al., 2010; Deák et al., 2017a; Jongerius, 1970; Macphail et al., 1990;
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13 325 Pagliai and Stoops, 2010a; Spek et al., 2003).

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17 326 MIII unit (148-100 cm) shows confirmation of the new soil dynamics already outlined at the top of
18
19 327 MIV, namely agricultural activities probably involving use of fire. MIII has a silty clay matrix with rare
20
21 328 coarse grains, and well-developed blocky subangular to granular microstructure (Fig. 6). Intrapedal
22
23 329 porosity is dominated by small grass channels. The lack of intra-aggregate biogenic macro-porosity
24
25 330 despite abundant organic matter (OM) and biospheroids, and lack of true granular or excremental
26
27 331 microstructures, strongly supports human-induced reaggregation by repeated ploughings (Adderley
28
29 332 et al., 2010; Macphail et al., 1990 ; Spek et al., 2003). Absence of coarse textural features such as
30
31 333 silty-clay coatings is not critical here, since they are not a *sine qua non* condition for cultivated
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33 334 horizons (Deák et al., 2017a; Usai, 2001), especially in fine-textured carbonated rocks context: in
34
35 335 these cases, alternative indicators are charcoal increase, loss in gastropod diversity (Macphail and
36
37 336 Goldberg, 2018; Whittle et al., 1993) and/or loss of micro-arthropods population due to soil
38
39 337 disturbance (Jeffery et al., 2010).

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45 338 Vegetal debris, fine organic matter and biospheroids, and especially microcharcoal are clearly more
46
47 339 abundant than observed before and are distributed homogeneously within the unit (Fig. 6). These
48
49 340 features indicate the continuous development of a relatively homogeneous organo-mineral A
50
51 341 horizon (Adderley et al., 2010; Durand et al. 2010; Gerasimova and Lebedeva-Verba, 2010; Stoops et
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53 342 al., 2010a). Resulting soil profile could be described as isohumic with cumulic and slightly
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55 343 hydromorphic processes.

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3 344 Redox pedofeatures of MIII are of limited intensity and vertically heterogeneous, indicating that they
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5 345 corresponded to repeated flooding of the depression with variable frequency and duration (Kovda
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7 346 and Mermut, 2010 ; Lindbo et al., 2010). Together with other pedofeatures (erosion markers,
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9 347 carbonates, microstructure) these redox indicators allowed us to distinguish four alternating sub-
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11 348 phases within MIII (see Fig. 6). Micromorphological indicators (microstructure, calcite and iron
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13 349 nodules, iron hypocoatings, spores, see Fig. 4) suggest that MIII.4 and MIII.2 were affected by more
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15 350 intense watertable fluctuations with repeated and long-term floods, alternating with dry phases
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17 351 (Fedoroff and Courty, 2002; Kovda and Mermut, 2010; Lindbo et al., 2010; Stoops et al., 2010a).
18
19 352 Hydrological conditions were probably drier and more stable for phases MIII.3 and MIII.1, less
20
21 353 affected by seasonal floodings (few calcite and iron nodules). Additionally, micromorphological
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23 354 evidence (macrocharcoal, pedosedimentary aggregates) indicates increased soil erosion and fires
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25 355 during MIII.3 (Adderley et al., 2010 ; Fedoroff et al. 2010).
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30 356 MII unit (100-79 cm) is broadly comparable to MIII. Increasing soil erosion in the catchment is
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32 357 suggested by more abundant volcanic mineral fraction and well-rounded calcite biospheroids. More
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34 358 abundant organic matter features (especially macrocharcoal) and presence of some incipient
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36 359 microlaminated clay coatings (partly oriented, limpid to dusty) in underlying unit (MIII) point to
37
38 360 increasing soil disturbance and illuviation, probably connected to more intensive agricultural activity
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40 361 (Kühn et al., 2010) in a context of general low accretion and soil profile stability. Atypical redox
41
42 362 features distribution (iron hypocoatings at the top, and manganic nodules at the base) together with
43
44 363 other micromorphological features, suggest a broadly drier phase. This was subsequently followed by
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46 364 very wet conditions probably due to floods during MI deposition (see below), similarly to paddy soil
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48 365 redox patterns (Stolt and Lindbo, 2010).
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368 Figure 5. Selected micromorphological features from upper NAR2 (Micromorphological Units MIII to MI, see text and Fig.6). A) Orthic tuffaceous
 369 concretion, from aggregation of smaller micritic elements and pseudomorphs (MI, N204, XPL-Crossed Polarized Light). B) Tuffaceous calcite capping.
 370 Note dark micromass, rich in organic matter (MI, N204, XPL). C) Orthic calcite nodule in a dark crystallitic to isotropic micromass (MI, N204, XPL). D)
 371 Micromass rich in calcitic grains strongly bioturbated and reorganized by biological activity (MI, N204, XPL). E) Complex microstructure, subangular
 372 with granular substructure or crumbly subangular (MI, N204, transmitted light). F) Diatoms embedded in carbonate-rich micromass (MI, N204, PPL-
 373 Plane Polarized Light). G) *Characeae* oogon. Note the two different types of micromass: brown, clayey, rich in organic fragments and microcharcoal
 374 (base) vs. massive micritic-microsparitic micromass (top) (MI, N204, XPL). H) Iron and micritic hypocoatings around a chamber and fissural to
 375 canalicular voids (MIII, N208, XPL). I) Subangular blocky microstructure of an organo-mineral unit (MIII, N207, transmitted light). J) Iron hypocoating
 376 and biospheroid, note silty clay micromass rich in microcharcoal and small organic fragments (MII, N205, PPL). K) Granular microstructure of a
 377 organo-mineral unit, note partial collapse of porosity due to secondary clogging (MIII, N210, transmitted light). L) Silty clay matrix highly
 378 impregnated by oxidized iron, and injection of matrix aggregates (rich in organic matter) from upper layers (MII, N205, XPL). M) Concentration of
 379 micritic to microsparitic calcite in the matrix (and in voids), some evolving to nodules (MIII, N208, XPL). N) Calcite nodule (micritic to microsparitic) in
 380 development by impregnation of the matrix (MIII, N209, XPL). O) Small bone fragment embedded in a silty clay matrix with microcharcoal and
 381 organic microdebris (MII, N205, PPL).

382 MI (79-64 cm) presents micromorphological features radically different from all other units. The
 383 matrix is globally very crystallitic, extremely rich in brown to black organic fragments with frequent
 384 microsparitic to sparitic calcite nodules (orthic), and abundant bio-mineral microfossils (ostracods,
 385 *characeae* pseudomorphs and oogons and tuffaceous concretions, see Fig. 5 and 6) indicating aquatic
 386 conditions (Nicosia and Stoops, 2017; Scholle and Ulmer-scholle, 2003). This unit can globally be
 387 interpreted as an aquatic environment with marked palustrine features. Very abundant and rounded
 388 micro- and macrocharcoal fragments suggest fires and erosion on the slopes of the catchment.

389 Detailed micromorphological analysis enabled us to discern a threefold structure within MI unit (Fig.
 390 6). MI.3 is characterized by abrupt development of palustrine conditions (very abundant organic
 391 matter) above the MII relatively dry palaeosoil. These new conditions are more probably the result of
 392 drainage deterioration and strong and permanent flooding than of a rise of groundwater-level (see
 393 unit MII features). Peak of macro- and microcharcoal (Fig. 6) and inclusion of soil aggregates from MII
 394 indicate strong and local soil erosion during this process. Water level rose during phase MI.2 and
 395 conditions became lacustrine (disappearance of pedogenic features), with strong authigenic
 396 carbonates production (abundant calcite nodules and tuffaceous concretions, and sometimes

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3 397 diatoms, see Fig. 5). Finally water level decreased slightly in MI.1, as suggested by reoccurrence of
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5 398 channels and biospheroids, more organic micromass with charcoal, and less calcite nodules and
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7 399 tuffaceous concretions. However, posteriority of these "drier" pedofeatures due to later phases of
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10 400 total emersion and erosion (not analyzed here) cannot be excluded.
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3 Figure 6. Summary diagram of main micromorphological features of NAR2 between 65 and 195 cm. Bars width indicates their relative abundance (rare, few, several /some, abundant, very abundant, see Table 3 in
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5 Supplementary Information), or alternatively their development degree. Scoria and microcharcoal are quantified using image analysis (IA). C/F: Coarse/Fine ratio, here 20 μ m.
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3.3 Geochemistry and sedimentology

The Sedimentary Units (SU) are well differentiated on the Passega (or CM) diagram of NAR2 (Fig. 8B). Most samples are poorly sorted (i.e. far from C=M line) due to common coarse particles embedded in abundant fine matrix. This is certainly due to long-term pedoturbation of most part of this low-aggradation pedo-sedimentary sequence, making it difficult to understand “pure” sedimentary processes. SUII.1, II.2-3 and II.3 probably refer to very low energy sedimentary processes (decantation phase) mixed with relatively rare and weak detrital inputs (graded to uniform suspension), likely formed under aquatic conditions. At the opposite, SUIII (III.1a, 1b and 2-3) has a CM signature implying varied processes of transport and deposition (decantation, graded suspension and rolling). Excepting sandy layers, deposits have a broadly fine but highly variable grain-size, which is consistent with a low-energy alluvial-palustrine plain with reduced aggradation, implying permanent pedoturbation and homogenization of flood deposits.

The XRF elementary signals obtained for NAR2 and 3 are globally consistent with main stratigraphic changes and with sedimentological indicators (Fig. 7A and B). Magnetic Susceptibility (MS) and D50 are interrelated and correlated with Fe, Si and Ti (except in sandy layers of NAR2), and with Fe, Zr and Rb in NAR3. Organic matter (OM) content is inversely correlated to carbonate content in both cores (see Fig. 7). Variables are well differentiated in the PCA on selected elementary signals of NAR2 (Fig. 8A), where the first 2 components count for 78.6% of the variability. The main axis (64.9%) represents the opposition between allochthonous detrital inputs (positive scores, terrigenous elements) and authigenic elements production under wet or aquatic conditions (negative scores, mainly Ca and Sr carbonates and Mn). The second axis represents the balance between siliciclastic materials (positive scores: Si, Al) and volcanic materials (negative scores: Zr, Ti). SUs are well differentiated in the distribution plot following main axes of the PCA (Fig. 8A). SUI to SUIII show mainly volcanic sediment influence, SUIII being the more detrital unit in the sequence (excepting sands). The gradual shift from SUIII to SUII.1 (from positive towards negative values of main axis) strongly suggests drainage degradation and installation of aquatic conditions.

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3 431 Five endmembers could therefore be identified depending on their geological sources and authigenic
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5 432 or allochthonous origins. A first one includes Zr and Ti, which are especially abundant in volcanic
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7 433 rocks (Mielke, 1979 ; Salminen et al., 2005) and likely come from volcanic materials of surrounding
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10 434 reliefs. The position of 20 supplementary individuals (red squares, not contributing to the PCA, see
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12 435 methods) obtained from XRF analysis of a core on volcanic-derived clays (Mayoral, 2018) confirmed
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14 436 this interpretation (Fig. 8A).

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17 437 Si, Al and Pb are more abundant in felsic materials (Mielke, 1979; Wedepohl, 1978) and are therefore
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19 438 suggestive of sedimentary inputs derived from silt-rich marls, very abundant in Limagne lowlands.
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21 439 Finally Fe and Zn, more abundant in volcanic rocks but also present in felsic materials, form together
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23 440 with Rb an intermediate endmember, indicating mixed inputs or a source from a residual terrace of
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25 441 the Allier river, which borders the northern margin of the depression (Fig. 1B and C). Ca and Mn form
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27 442 a typical chalc-manganic endmember related to wet conditions and authigenic carbonate formation
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29 443 (Salminen et al., 2005; Wedepohl, 1978). The last endmember is formed by Sr alone, isolated from Ca
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31 444 and Mn due to its higher abundance in volcanic rocks (Mielke, 1979).

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36 445 Based on these data, on geochemistry of rocks and soils from the study area, and on existing
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38 446 literature, we interpreted the local palaeoenvironmental significance of selected elementary ratios.
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40 447 Zr content is relatively high in coarse sediment as it is related to the presence of detrital heavy
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42 448 minerals (zircon, sphene), and is lower in finer sediment where heavy minerals are scarcer. By
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44 449 contrast Rb is often higher in finer fraction of sediment due to its very strong sorption by clay
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46 450 minerals (Salminen et al., 2005). In NAR2 and NAR3 cores, Zr/Rb ratio appears positively correlated
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48 451 to D50 of the sediment, both in its fine (<50um) and coarse (>50um) fractions (see Fig. 12B in
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50 452 Supplementary Information). Consequently we propose to interpret Zr/Rb as a grain-size proxy in our
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52 453 cores.

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57 454 Pb content in European soils and floodplain sediments is related to two main factors: lithology
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59 455 (natural Pb mineralisations) and anthropogenic contamination, i.e. historical mining or industrial
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3 456 activities (Salminen et al., 2005). Calcareous and volcanic rocks, such as those found in La Narse de la
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5 457 Sauvetat catchment, are not a significant source of lithogenic Pb. Additionally, considering the very
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7 458 small size of the catchment and its uncomplicated geology, lithogenic Pb fluxes can be assumed to be
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9 459 more or less constant in the sedimentary record analyzed in NAR2 and NAR3, and anomalous Pb
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11 460 enrichments are certainly of anthropogenic origin. A simple way to discriminate signal of
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13 461 anthropogenic Pb from the lithogenic Pb background is normalization using a lithogenic and
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15 462 chemically stable trace element (Arnaud et al., 2004, 2006). Therefore we propose to use Pb/Rb as a
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17 463 potential indicator of anthropogenic Pb contamination (and therefore metallurgic activity) in La
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19 464 Narse de la Sauvetat sedimentary record, especially when ratio peaks appear dissociated from
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21 465 detrital inputs proxies.

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26 466 Fe is in general terms much more abundant in volcanic than in sedimentary rocks (Salminen et al.,
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28 467 2005), and consequently also in soils developed in volcanic materials (Legrand et al., 2007).
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30 468 Geochemical studies in the Sarliève palaeolake catchment, also situated in southern Limagne and
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32 469 largely sharing lithology and superficial formations with La Narse de la Sauvetat catchment (Bornand
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34 470 et al., 1968; Bouiller, 1979; BRGM, 1973), show that local volcanic soils and rocks were Fe-enriched,
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36 471 and clearly distinguishable from Ca-enriched soils developed on Limagne calcareous bedrock
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38 472 (Fourmont et al., 2009). Within La Narse catchment, soils and fine sediment from the top of the Puy
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40 473 de Corent (*i.e.* exclusively derived from volcanic rocks. See Fig. 1), show much lower values of Ca and
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42 474 higher values of Fe (and hence significantly higher Fe/Ca ratio) than samples from NAR2 and NAR3,
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44 475 situated in calcareous lowlands (see Fig. 12A in Supplementary Information -data from Mayoral,
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46 476 2018-). Then, we propose to use Fe/Ca to trace fine detrital inputs derived from erosion of
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49 477 surrounding volcanic soils and surficial formations into La Narse Basin.
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57 479 Figure 7. A) Selected elements and sedimentological data for NAR2. Values are in 10^{-5} SI (Magnetic Susceptibility-MS-) and
58 480 in counts per second (CPS) for the XRF. B) Selected elements and sedimentological data for NAR3.

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3 481 Figure 8. A) PCA biplot of selected geochemical variables according to dimensions 1 and 2, individuals are distributed by
4 482 Sedimentary Unit. Note supplementary individuals (red squares, data from Mayoral et al., 2018). B) Passega or C-M
5 483 diagram of NAR2 with grain-size data by Sedimentary Unit. Grey area represents reference C-M diagram by Passega (1977).
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485 3.4 Malacology

11 486 Seven environmental phases were reconstructed in NAR2 (phases 2A to 2G in Fig. 9). In phase 2A
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13 487 (202-194 cm) freshwater species count 50% of the total number of individuals. In the terrestrial
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15 488 fauna, shade-demanding molluscs are scarce (Fig. 9A). In phase 2B (194-170 cm) freshwater species
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17 489 decrease to 30% while proportions of shade-demanding species increase. Whether this ecological
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19 490 group shows its highest proportions of the whole core, the species from this group are not restricted
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21 491 today to forest environments and may have lived in tall grass patches in Limagne plain. The
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23 492 proportions of freshwater species increase in phase 2C (170-158 cm) and despite a small number of
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25 493 shells, strong differences are highlighted in the ecological composition of the molluscan assemblage
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27 494 attributed to this phase with decreasing proportions of shade-demanding species (Fig. 9A). The 2D
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29 495 phase (158-142 cm) is characterized by a strong dominance of open-ground species, which represent
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31 496 60% of the total number of individuals. *Vallonia pulchella*, which lives today in wet grassland
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33 497 environments, is the most abundant species (Table 4 in Supplementary Information-SI). In addition,
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35 498 freshwater species represent only 20% of the assemblages (Fig. 9A). *Galba truncatula* is the main
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37 499 species within this group (Table 4 in SI). Its ability to survive dry episodes (Horsák et al., 2013)
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39 500 suggests a phase of contraction of the body of water in the depression and its replacement by wet
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41 501 grasslands. During the phase 2E (142-100 cm), freshwater species increase up to 60% (Fig. 9A). *Galba*
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43 502 *truncatula* and *Anisus leucostoma* dominance suggest seasonal incursions of water in the sampled
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45 503 locus (Welter-Schultes, 2012). In the terrestrial molluscan fauna, *Vallonia pulchella* is still the
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47 504 dominant species, and this taxon from wet grassland is supported by a diverse set of marshland
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49 505 species (Table 4 in SI). The phase 2F (100-80 cm) is characterized by a dramatic decrease in
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51 506 freshwater species proportions (Fig. 9A). The freshwater species that are able to survive short-term
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53 507 dry episodes sharply decrease in abundance (Table 4 in SI), which indicates a long-lasting depletion of
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3 508 the water body in the depression. In the terrestrial molluscan fauna, this environmental
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5 509 development is discernible in the decreasing proportions of marshland species (Fig. 9A) and in the
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7 510 replacement of the wet grassland species *Vallonia pulchella* by *Vallonia excentrica* (Table 4 in SI),
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9 511 characteristic of drier open-ground habitats (Welter-Schultes, 2012). Finally, the phase 2G (78-70 cm)
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11 512 is strongly dominated (more than 70%) by a diverse set of freshwater species (Fig. 9A). The main
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13 513 species of this group is *Gyraulus crista* (Table 4 in SI), which is characteristic of permanent and calm
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15 514 small water bodies with rich vegetation (Welter-Schultes, 2012).

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19 515 In the core NAR3, the full core was dedicated to malacological analysis. As a result, the volume of
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21 516 analyzed sediment was more important, which resulted in more abundant assemblages than in the
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23 517 core NAR2. However, as the volume of sediment analyzed was limited due to the core sampling
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25 518 method, some samples had to be merged to ensure a sufficient number of individuals to carry out a
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27 519 statistical analysis. Five environmental phases were reconstructed (3A to 3E). The phase 3A (201-181
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29 520 cm) is dominated by species of open-ground habitats, mostly by *Vallonia pulchella* (Fig. 9B). In the
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31 521 phase 3B (181-140 cm), *V. pulchella* is still the main species but the proportions of species living in
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33 522 marshland habitats increase, which indicates wetter environmental conditions. During the phase 3C
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35 523 (140-114 cm), marshland species show decreasing proportions while percentages of species of open-
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37 524 ground environment increase (Fig. 9B). Whether *V. pulchella* remains the most common species
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39 525 within this group, the development of *V. excentrica* reflects the presence of a distinctly drier open-
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41 526 ground habitat. In phase 3D (112-104 cm), freshwater malacofauna significantly increase up to 40%
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43 527 of the total (Fig. 9B). The dominance of *G. truncatula* within this group suggests a seasonally stagnant
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45 528 water body with a damp grassland developed in the margin according to the terrestrial fauna
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47 529 composition. Finally, phase 3E (103-84 cm) is characterized by a sharp increase in freshwater species
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49 530 up to 80-90% (Fig. 9B). The dominance of *G. crista* within this group (Table 5 in SI) reflects a quiet and
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51 531 permanent water flow with rich vegetation.
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6 533 Figure 9. Diagrams of specific composition of molluscan assemblages A) NAR2 B) NAR3. Contiguous 2cm-thick sediment
7 534 samples were grouped in bigger sets when necessary in order to reach a significant number of shells. Species are
8 535 classified by ecological affinities and by order of occurrence.

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15 538 **4-Discussion**

19 539 **4.1 Late Neolithic (end of Mid Holocene period)**

21 540 During the Late Neolithic (5000-4150 cal BP, phases N2.1 and N3.1 in Fig. 10, see also Fig. 11), after a
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23 541 lacustrine phase (see Mayoral et al. 2018), the basin was re-connected to the local drainage system
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25 542 and developed in a hydromorphic plain (Mn peak at the base of both cores, Fig. 7). Redox conditions
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27 543 were contrasted: the downstream area (NAR2) was still partly aquatic according to malacological
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29 544 assemblages, and received detrital inputs from marly slopes of the Puy de Corent (high D50 and
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31 545 CaCO₃). In the upstream sector (NAR3) higher organic matter (OM) values and malacological data
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33 546 suggest wet grasslands with more developed soils and oscillating watertable (Fig. 10 and 11). Here
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35 547 coarser detrital inputs from volcanic soils of the western catchment were predominant (higher MS,
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37 548 Zr/Rb and Fe/Ca values).

42 549 Relative openness and diversity of landscapes indicated by malacological assemblages suggest local
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44 550 transformations by Late Neolithic societies despite these wet conditions in the depression. This
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46 551 rough picture is consistent with archaeological evidence for this period: findings are very scarce at a
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48 552 regional level, however they indicate a preference for hillslopes and foothills and a reduced
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50 553 settlement density in Limagne lowlands during the Late Neolithic, maybe because of drainage
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52 554 deterioration (Ballut and Argant, 2004; Daugas and Raynal, 1989; Raynal et al., 2003; Trément, 2011).

4.2 Early to Middle Bronze Age

Early and middle Bronze Age (4150-3250 cal BP, phases N2.2-3-4 and N3.2A in Fig. 10, see also Fig. 11) are characterized by a strong increase in hydro-sedimentary activity in the basin. In detail, the period is tripartite: two high-energy alluvial phases (sands) covering the bottom of the basin (see Figs. 2 and 3), separated by a lower energy phase (sandy clays).

The first high-energy deposit was dated at 4464 ± 97 cal BP. It was associated with eroded soils from surrounding volcanic slopes (scoria and nepheline observed in thin section) and from the marly lowlands, but also with erosion of tuffaceous formations from local riverbeds, probably deposited during previous hydro-climatic stability phase. This event was followed by a low-energy hydro-sedimentary phases, dominated by fine volcanic inputs (higher Fe/Ca ratio, Fig. 10) together with an incipient soil development from c. 3850 to 3450 cal BP (weak aggregation and pedofeatures, slightly more organic matter). A second high-energy hydro-sedimentary episode occurred c. 3450 cal BP, also eroding both soils and riverbed formations.

Radiocarbon ages of these two high-energy alluvial phases, similarity with contemporaneous dynamics observed in the Rhone valley (Berger et al., 2007) and consistency with previous studies in Limagne lowlands (Ballut, 2001; Ballut and Guichard, 2005; Trément, 2011; Vital, 2004) indicate that they certainly had a climatic trigger. The first phase was likely associated with the 4.2 kyr. BP climatic event, already documented in eastern and south-eastern French regions (Brisset et al., 2013; Carozza et al., 2015; Magny, 2004). The chronological offset of c. 150-200 yr. (Walker et al., 2019) is likely due to slightly older ages provided by floated charcoal in sandy layers. The second phase was certainly linked to the middle Bronze Age climate event (so-called Lössen in the Alpine area), which implied cooler and wetter conditions between 3.5 and 3.2-3.1 kyr. cal BP in western Europe (Berger et al., 2007; Burga et al., 2001; Deák et al., 2017b; Magny et al., 2009). These two high-energy hydro-sedimentary episodes are therefore the first serious sedimentary evidence of 4.2 and 3.5 kyr. BP climate events in Limagne plain, although they have been recently documented in mountainous

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3 580 highlands of the Massif Central (Chassiot et al., 2018). The intermediary low-energy phase coincided
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5 581 with a more stable hydro-climatic period, detected in alpine lakes and glacial basins (regression
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7 582 phases) and in the Rhone valley by a general trend to pedogenesis and river entrenchment (Berger et
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9 583 al., 2007; Joerin et al., 2006; Magny, 2004; Magny et al., 2009).

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13 584 NAR3 data show that marginal areas of the basin were also affected by these phases of degraded
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15 585 hydro-sedimentary dynamics: malacological assemblages indicated a progression of marshland
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17 586 environments and biological activity decreased (fall of OM). Data from both cores clearly indicated
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19 587 wetter conditions and absence of significant anthropogenic impact on lowlands soils and vegetation.
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22 588 This situation contrasted with dryer areas of other sectors of Limagne plain where human impact was
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24 589 presumably more significant (Miras et al., 2018). Archaeological findings nevertheless remain rare in
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26 590 Limagne for this period, excepting between 3950 and 3550 BP, when the Limagne was densely
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28 591 occupied by substantial settlements (Couderc, 2019). Taken together, these data suggest a certain
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30 592 degree of adaptation of Early and Middle Bronze age societies to hydro-climatic fluctuations in
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32 593 lowlands. Nevertheless, the potential interaction of these hydro-sedimentary phenomena with
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34 594 anthropogenic impacts on soils during Late Neolithic and Early Bronze Age cannot be clearly assessed
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36 595 from the analyzed pedo-sedimentary record.

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43 597 4.3 Late Bronze Age and Early Iron Age

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49 599 The global trend during the Late Bronze Age and first century of the Iron Age (3250-2600 cal
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51 600 BP, phases N2.5A-B and N3.2B in Fig. 10, see Fig. 11) was towards a decrease of hydro-sedimentary
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53 601 activity in the whole basin. Drainage seems slightly degraded with presence of stagnant water
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55 602 especially in central lower areas of the depression (weak OM content, malacological assemblages rich
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57 603 in freshwater species). Soils were then saturated, with a massive structure, limited biological activity
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3 604 and fluctuating watertable. This phase of degraded drainage could partly correspond to the start of a
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5 605 major climate deterioration occurring at c. 2800 BP in western Europe, with cooler and wetter
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7 606 conditions prevailing until c. 2400 BP (Berger et al., 2007; Fletcher, Debret and Sanchez-Goñi, 2013;
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9 607 Holzhauser et al., 2005; Magny et al., 2009; Van Geel and Magny, 2002; Walsh et al., 2019).

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13 608 Despite these unfavorable hydrological conditions in the basin itself, a more open landscape (as
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15 609 indicated by malacology) points to clearly localized anthropogenic impact, likely connected to the use
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17 610 of fire (abundant micro- and macrocharcoal, Fig. 10), maybe for pastoral use. Additionally, the rise of
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19 611 fine volcanic sediment input (rise of Sediment Accumulation Rate –SAR– and Fe/Ca ratio, lower D50)
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21 612 suggests increased anthropogenic impacts affecting soils of the catchment slopes. This is consistent
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23 613 with archaeological data, which show development of agglomerations on the hilltops of Limagne at
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25 614 the end of the Bronze Age (3100-2750 cal BP), whereas slopes and lowlands seem devoted to
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27 615 agricultural and pastoral activities (Couderc, 2019).

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31 616 During later phases of the first Iron Age (2600-2375 cal BP, phase N2.6A and beginning of
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33 617 N3.3A in Fig. 10, see also Fig. 11) the situation was radically different: abrupt pedo-hydrological
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35 618 changes affected the basin since c. 2600 cal BP. The environment became much drier and landscape
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37 619 opened further as clearly indicated by malacological assemblages. Soils became cumulic and
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39 620 isohumic in the depression with residual hydromorphic features due to seasonal short flooding
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41 621 episodes as indicated by micromorphology and malacological assemblages. Moreover, they present
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43 622 micromorphological (microstructure, porosity, organic matter, pedofeatures, etc.), sedimentological
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45 623 (OM rate increments in both cores) and malacological (reduced biodiversity) evidences of major
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47 624 anthropogenic-induced modifications and impacts, consistent with local agricultural use starting
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49 625 from c. 2600 cal BP. Additionally, SAR rises strongly especially in lower areas of the basin with
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51 626 predominance of fine volcanic sediment, suggesting that erosion of soils of the catchment had similar
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53 627 intensity to the previous period, but became more generalized (grain-size and Fe/Ca ratio, Fig. 10).
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3 628 Taken together, these data clearly indicate a strong spatial expansion of agricultural impacts on soils
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5 629 in this catchment of southern Limagne, affecting for the first time the wet lowlands c. 2600 cal BP. It
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7 630 is noteworthy that similar phenomena are noted in the Rhone valley or in Rhineland also at the
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9 631 beginning of the Iron Age (Houben et al., 2012; Notebaert and Berger, 2014). This expansion
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11 632 necessarily implied a new technical capacity to drain and cultivate wetlands at least two centuries
12
13 633 before than usually admitted in Limagne (Trément et al., 2007a; Trément, 2011). This early drainage
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15 634 capacity certainly represented a break in the socio-environmental interaction in the Limagne
16
17 635 lowlands hitherto unsuspected, and a major step towards environmental systems anthropization.
18
19 636 Even if needing confirmation through additional investigations, this precocity is not out of place since
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21 637 drainage capacity was likely developed from the beginning of the Iron Age in central France, allowing
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23 638 hydraulic developments and small settlements on former wetlands (Bernigaud et al., 2014; Milcent
24
25 639 and Mennessier-Jouannet, 2007; Riquier et al., 2015; Walsh et al., 2019). Remarkably, the emergence
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27 640 of a proto-urban settlement including hundreds of storage pits in the neighboring Puy de Corent
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29 641 takes place only few decades (from c. 2550 cal. BP) after the beginning of impacts on soils noted at la
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31 642 Narse wet lowlands (Mayoral et al., 2018b; Milcent et al., 2014), and is maybe related to locally
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33 643 increased agricultural production.
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Figure 10. Multi-proxy synthetic diagram for NAR2 (A) and NAR3 (B) cores (MS: Magnetic Susceptibility, D50: median grain-size, SAR: Sediment Accumulation Rate, OM: Organic Matter content).

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4.4 Late Iron Age

All proxies suggest that environmental dynamics at La Narse de la Sauvetat during the Late Iron Age (2375-1980 cal BP, phases 2.6B to E and N3.3A and B in Fig. 10, see also Fig. 11) were broadly similar to the previous centuries, with soil cultivation, use of fire and probable drainage works. Increased fine sediment inputs into the basin, together with micromorphological and geochemical evidence of intensified fires and soil erosion, indicate that agricultural impact on soils of the catchment became gradually more generalized and reached a maximum between 2250 and 2150 cal BP.

From 2250 cal BP onwards and until the end of the Iron Age, micromorphological and malacological data suggest that despite generally drier soils across the basin, hydrological conditions were slightly unstable. Short floods were more frequent, even if limited to the lower part of the basin, particularly between 2150 and 2050 cal BP. The reduced energy of sedimentary inputs and a decrease in volcanic fraction indicated by sedimentological and geochemical proxies, together with a reduced accumulation rate suggest a gradually reduced connectivity with catchment slopes.

Local socio-environmental dynamics at la Narse de la Sauvetat are roughly consistent with increased anthropogenic impacts noted in previous works on Limagne. For the last centuries of the Iron Age, human impact in environmental systems became strong and generalized (Ballut, 2000; Ballut and Guichard, 2005; Trément et al., 2007a; Trément, 2011), while climatic conditions were more favorable to agricultural activities during the Roman Warm Period (Magny, 2004 ; McCormick et al., 2012). Reduction of sedimentary inputs into the basin could be connected with the emergence and development of new agricultural practices in Limagne, such as improved drainage networks or terraced fields on the slopes (Ballut and Guichard, 2005; Trément et al., 2007a; Trément, 2011). These anthropogenic modifications of hydro-sedimentary systems may have significantly contributed to contain soil erosion and hydro-sedimentary degradation.

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670 4.5 Antiquity

671 The Roman epoch (1980 to 1474 cal. BP, phases N2.6E to N2.7B and N.3.3B to N3.4B, Fig. 10, see also
672 Fig. 11) appears to be a very strong anthropogenic impact period in the basin. Soil micromorphology,
673 relatively high OM content and malacology indicate more intensive agriculture and an improved
674 drainage. Several Pb/Rb peaks in both cores (Fig. 10), not correlated with detrital inputs, indicate
675 local metallurgical activity from c. 1950 cal BP to c. 1600 cal BP. The maintained decrease of SAR in
676 the basin and the soil profile stability during the Early Roman Empire (incipient illuviation, Fig. 6) can
677 be interpreted as a strong control of hydro-sedimentary inputs. A pronounced deterioration and
678 anthropogenic erosion of volcanic soils of the catchment can nevertheless be deduced from the
679 increased number of coarse volcanic particles and the geochemical composition of fine fraction (high
680 values of Fe/Ca since c. 1800 cal BP). Impacts on soils and especially on hydro-sedimentary system
681 became more evident after 1700 cal BP, with micromorphological data suggesting more fluctuant
682 hydrological conditions and high detrital inputs from volcanic slopes (Fe/Ca, Fig.10).

683 These environmental data are consistent with local archaeological evidence, with several Roman
684 settlements (including a very extended *villa*) indicating increased human impacts in La Narse de la
685 Sauvetat basin (Simon et al., 2017), similar to the neighboring Sarliève palaeolake (Fourmont, 2006 ;
686 Trément et al., 2007a; Trément, 2011; Vernet, 2001; Vernet et al., 2005). At a regional level, human
687 impact on natural systems also became very strong during the Roman period (Ballut and Guichard,
688 2005; Berger, 2015; Notebaert and Berger, 2014). Hydro-sedimentary and soil degradation after 1700
689 cal BP could be linked to a short phase of colder and drier climate between 1750 and 1650 cal BP,
690 which was followed by relatively unstable hydro-climatic conditions (Buntgen et al., 2011; Holzhauser
691 et al., 2005). However, resilience of Late Roman Empire agrarian structures probably allowed settlers
692 to contain sedimentary inputs into the basin, or efficiently evacuate them through a drainage
693 network.

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Figure 11. Comparison of palaeoenvironmental evidence in la Narse de la Sauvetat between 5000 and 1200 cal BP (derived from core NAR2, this study) with regional archaeological data in Limagne plain and climatic changes in Western Europe. NAR2 environmental phases are from Fig. 10A. Representations of local hydrological conditions, soil erosion in the catchment and detrital inputs are qualitative (relative level or thickness according to process intensity) and based on data from Fig. 10. High-energy hydro-sedimentary episodes related to 4.2 and 3.5 kyr. cal BP climatic events are indicated (note a chronological offset of 150-200 yr. of the first episode, see the text for details). Local vegetation cover (qualitative) is represented by the proportion of shade-demanding malacological species vs. other terrestrial malacological species. Anthropogenic activities (landscape opening, use of fire, pastoral activity, agriculture and metallurgical activity) are represented by symbols. RWP: Roman Warm Period. LALIA: Late Antiquity Little Ice Age. Settlement density in Limagne is based on (1) Ballut and Argant, 2004; Couderc, 2019; Daugas and Raynal, 1989; Milcent and Mennessier-Jouannet, 2007; Raynal et al., 2003; Trément et al., 2007; Trément, 2011. Phases of climatic deterioration in Western Europe are based on (2) Berger et al., 2007; Brisset et al., 2013; Buntgen et al., 2011; Carozza et al., 2015; Fletcher, Debret and Goñi, 2013; Holzhauser et al., 2005; Joerin et al., 2006; Magny, 2004; Magny et al., 2009; McCormick et al., 2012; Van Geel and Magny, 2002; Walker et al., 2019; Walsh et al., 2019.

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711 4.6 Late Antiquity and early Middle Ages

712 The transition from Antiquity to the early Middle Ages (1500 to 1200 cal BP, N2.8A to C and
 713 N3.4A to N3.5, Fig. 10, see also Fig. 11) is characterized by a major palaeoenvironmental change at la
 714 Narse de la Sauvetat, starting from c. 1500 cal BP with sudden deposition of a black, organic and
 715 charcoal-rich layer. Based on geochemical, micromorphological and malacological data, this deposit
 716 has been interpreted as a marsh resulting from flooding of the lower areas of the depression
 717 whereas open landscape was maintained in drier peripheral areas. Detrital inputs were reduced
 718 (lower MS, low SAR), but remained relatively rich in volcanic fraction (Fe/Ca).

719 This palustrine phase was very similar to the well-known “dark layer” of the Sarliève palaeolake a few
 720 kilometers north, dated approximately between 1850 and 1750 cal BP. That layer has been
 721 interpreted as the result of introduction in hillslopes of the catchment of new pastoral practices
 722 involving fire combined with a late-Antiquity hydro-climatic degradation (Buntgen et al., 2011;
 723 Trément et al., 2007a; Trément, 2011; Vernet, 2001; Vernet et al., 2005). However, the dark layer
 724 observed at la Sauvetat has a 300-year chronological offset respect the Sarliève one: this strongly
 725 suggests that this major change had little to do with climate excursions, but was more likely due to
 726 modifications of anthropogenic activities on the catchment, implying sudden deterioration of
 727 drainage networks or even outlet modifications.

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3 728 Moreover, the strong hydro-sedimentary “crisis” sometimes noted in Limagne from 1550 or 1450 cal
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5 729 BP in previous works and often attributed to socio-climatic drivers (Ballut, 2001; Ballut and Guichard,
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7 730 2005; Trément et al., 2007a, 2007b; Vernet, 2013), is remarkably absent here. This suggests that, at
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10 731 least locally, late Antiquity landscape changes, due to modifications in anthropic activities and in land
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12 732 management, were gradual and controlled instead of abrupt and catastrophic. Spatial
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14 733 reorganizations and differential land use can explain these environmental variations at the micro-
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16 734 regional scale. Similar dynamics of land-use changes in wet lowlands during Late Antiquity or early
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18 735 Middle Ages have been identified by palaeoenvironmental research in SE France, and are likely
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20 736 connected with hydraulic systems abandonment (Berger, 1995; Durand & Leveau, 2004), but the
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22 737 question remains nevertheless obscure in Limagne and would require further investigations.

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26 738 The picture between 1400 and 1300 cal BP is less ambiguous as water level rose in the basin:
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28 739 lower areas became clearly aquatic (with in situ travertine formation) and palustrine environments
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30 740 prograded to the margins of the depression. This marked drainage deterioration is also noted in
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32 741 other Limagne marshy areas (Trément, 2011; Vernet et al, 2005; Vernet, 2013), and was followed by
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34 742 slightly dryer conditions after 1300 cal BP. Strong hydro-climatic phenomena are locally noted in
35
36 743 Limagne by scarce but reliable historical sources mentioning increased floods and seismicity (Daugas
37
38 744 and Tixier, 1975; Vernet, 2011; Vernet, 2013). These dynamics are in accord with hydro-climatic
39
40 745 degradation between 1450 and 1250 cal BP, which is well documented at western European scale
41
42 746 (Arnaud et al., 2012; Berger and Brochier, 2006; Buntgen et al., 2011; Magny, 2004; McCormick et al.,
43
44 747 2012). The influence of new forms of human management on this wetland remains nevertheless
45
46 748 difficult to assess based only on these palaeoenvironmental insights, and further research is
47
48 749 necessary to better understand socio-environmental interaction driving the early medieval landscape
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50 750 changes at la Narse de la Sauvetat.
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57 751 **5-Conclusion**

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3 753 This work used multi-proxy geoarchaeological and palaeoenvironmental analysis to reconstruct
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5 754 landscape evolution and human-environment interactions at La Narse de la Sauvetat.
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7 755 Micromorphological, geochemical, sedimentological and malacological data supported by a robust
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10 756 chronological framework allowed for the first time in Limagne lowlands a precise discussion
11
12 757 concerning the weight of anthropogenic and climatic drivers on pedo-hydro-sedimentary processes
13
14 758 and landscape evolution of the basin from Late Neolithic to the early Middle Ages.

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16
17 759 The Late Neolithic was poorly documented in the pedo-sedimentary analyzed records, but
18
19 760 nevertheless anthropogenic modifications of vegetation cover could be discerned. Until the Middle
20
21 761 Bronze Age, hydro-sedimentary dynamics in the depression were strong and clearly climate-driven by
22
23 762 the 4.2 and 3.5 kyr cal BP climate events, characterized for the first time in Limagne lowlands. The
24
25 763 first clear evidences of incipient anthropogenic impact in soils of the basin and the catchment
26
27 764 appeared in the Late Bronze Age, under slightly better hydro-climatic conditions.

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30
31 765 However the decisive phase in human impact affecting soil erosion, hydro-sedimentary system and
32
33 766 wet areas of the catchment occurred at the opening of the Iron Age. Despite probably less favorable
34
35 767 climatic conditions during some centuries after 2750 cal BP, agricultural impacts on soils of the basin
36
37 768 became evident c. 2600 cal BP and were probably accompanied by drainage works, as soil erosion in
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39 769 the catchment rose.

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43 770 Hallstatt societies seemed therefore to have acquired a first degree of emancipation from hydro-
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45 771 climatic constraints affecting these wet lowlands, crossing a major threshold in socio-environmental
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47 772 interaction in southern Limagne. This precocious forcing of soils and hydro-sedimentary system
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49 773 occurred considerably earlier than the Late Iron Age turning point (2250-2050 cal BP) usually
50
51 774 accepted in Limagne. These dynamics were reinforced during La Tène and Roman periods, and
52
53 775 impact on soils and hydro-sedimentary system expanded and deepened. However after reaching a
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55 776 peak c. 2200 cal BP the hydro-sedimentary consequences of rising anthropogenic impact appeared to
56
57 777 decrease. This is probably due to improved land management and agricultural techniques including
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3 778 hydraulics, allowing more efficient management and containment of erosion processes. Despite
4
5 779 rather favorable climatic conditions, a disruption in hydro-sedimentary system became gradually
6
7 780 discernible throughout the Roman period and especially during the Late Roman Empire. This signal
8
9 781 could be due to more unstable climatic conditions contributing to upset an anthropogenic
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11 782 environmental system with centuries of cumulative impacts.
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15 783 Sudden drainage degradation and the advent of palustrine conditions in the basin from 1500 cal BP
16
17 784 were remarkably asynchronous with other similar local dynamics. They were probably more the
18
19 785 result of modifications of land management rather than of hydro-climatic degradation that occurred
20
21 786 anyway a century later. These results go against the idea of a dramatic “collapse” of late Antiquity
22
23 787 socio-environmental systems in southern Limagne, drawing a more complex picture. They rather
24
25 788 indicate that, at least locally, their relative resilience could have allowed a fast but nevertheless
26
27 789 gradual transition to a new equilibrium in the early Middle Ages, characterized by abandonment of
28
29 790 drainage networks and occupation of lowlands by lacustro-palustrine environments under oscillating
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31 791 climatic conditions.
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36 792 Ultimately, this work confirmed that multi-proxy, high resolution analysis is the most fruitful
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38 793 approach to develop in Limagne lowlands, where the interpretation of socio-environmental
39
40 794 interaction based on palaeoenvironmental record of soils and wetlands had long been limited. The
41
42 795 obtained results, partly consistent with previous knowledge, raised specific questions due to
43
44 796 increased chronological and analytical resolution, which would be regionally addressed by further
45
46 797 multi-disciplinary research.
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22
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25 811 study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in
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27 812 the decision to publish the results.
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37 1182 **9-Supplementary information: micromorphological descriptions,**
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| cm N° | Microstr. / Porosity | C-F RD | Coarse Fraction | Micromass | BF | Org. Matter | Pedofeatures |
|-------|--|--------|-----------------|---|----------------------|--|--|
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| 6-70 | N204 Complex : subangular blocky to crumbly, spongy aggregates, poorly accommodated. Moderately separated and aggregated. Prismatic secondary structure. Abundant vughs, some polyconcave. Very abundant small channels (64-70 cm). | 1/20 | OP | Few limestone and quartz-felds. silts to fine sands, rarely basaltic. Abundant malacoremain, several ostracods. Diatoms in micromass (64-70 cm). Several biospheroids, orthic (64-70 cm). Several <i>chara</i> oogons. Several big orthic tuffaceous concretions. (70-74 cm). | SP (top) / CC (base) | Extremely abundant small to medium fragments of reddish brown tissues (64-70 cm). Abundant micro and macrocharcoal, some millimetric (64.70 cm). Very abundant amorphous OM and organic pigment. Few small bone fragments. | Very abundant calcite fine coatings and infillings of voids. Several micritic pseudomorphs of <i>chara</i> , more abundant and more microsparitic between 70 and 74 cm. Abundant and variegated tuffaceous concretions micritic to microsparitic (especially 70-74 cm), including phytoliths and diatoms. Extremely abundant small microsparitic to sparitic nodules, better developed between 70-74 cm. Very abundant big and diffuse manganic nodules, moderately to strongly impregnated. |
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| 15 | N204+N205A Subangular blocky to crumbly, well separated and aggregated. Abundant small channels (top and base), several vughs, some polyconcave. | 1/20 | OP | Few limestone silt to fine sand, few to rare quartz-felds. Few biospheroids, very abundant malacoremain, few ostracods, several <i>chara</i> oogons. | CC | Very abundant microcharcoal, several to abundant macrocharcoal. Very abundant fine OM, and very abundant and variegated remains of tissues (brown, reddish brown and black). | Abundant fine calcite coatings of voids. Abundant small sparite nodules. Few injections of beige micromass from upper levels, rich in diatoms. Very abundant big brown pedogenic aggregates, very irregular, from underlying SU. |
| 16 | | | | | | | |
| 17 | | | | | | | |
| 18 | N205B Subangular to angular blocky, well separated and aggregated. Very abundant small channels, few vughs. Secondary structure roughly prismatic. | 1/20 | OP | Rare basaltic and scoria sands, rare volcanic minerals. Several limestone sand, few quartz-feldspar sands. Very big and abundant biospheroids, some very well-rounded. Few malacoremain and rare phytoliths. | CC | Abundant microcharcoal, few macrocharcoal. Abundant reddish amorphous OM remains and pigment, one bone fragment. | Very abundant and very fine calcite coatings of voids. Several small to medium sparite nodules, some small and irregular iron impregnative nodules. Few irregular and diffuse iron hypocoatings. Abundant tubular injections of micromass from upper levels (beige and rich in diatoms, black and rich in OM and charcoal). |
| 19 | | | | | | | |
| 20 | | | | | | | |
| 21 | | | | | | | |
| 22 | N206 Subangular blocky to granular, slightly crumbly. Poorly to moderately aggregated and separated. Extremely abundant small channels (rarely bigger). Several vughs and rare chambers. | 1/20 | OP | Rare basaltic and scoria sands to granules, rare volcanic minerals and quartz fine sands. Several limestone medium to coarse sand. Abundant to very abundant biospheroids, few to several malacoremain, rare phytoliths. | CC | Abundant to very abundant microcharcoal, several macrocharcoal, one big bone fragment. Abundant fine amorphous OM, and several brownish or reddish fragments of tissues and rootlets, several reddish spores. | Abundant very fine calcite coatings of voids, several calcite nodules, irregular to rounded, disorthic to anorthic. Several small and diffuse iron impregnative nodules, rare iron quasi-coatings of big channels. Several diffuse manganic nodules, poorly to moderately impregnated, irregular or roughly dendritic. Few to several matrix injections from upper levels (beige rich in diatoms, or black rich in OM and charcoal). |
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| 25 | | | | | | | |
| 26 | | | | | | | |
| 27 | N207 Subangular to angular blocky, moderately separated and well aggregated. Secondary structure roughly prismatic. Several vughs (top) and small channels (center-base). | 1/20 | OP | Some quartz-felds. silt to fine sand, several limestone silt to medium sand. Some biospheroids, few malacoremain, rare phytoliths. | CC to SP | Abundant microcharcoal, abundant reddish organic fragments of tissues and rootlets, sometimes reddish organic pigment. Abundant fine amorphous OM. | Very fine calcite coatings of voids, several loose and discontinuous micrite infillings of fine porosity. Very rare calcite nodules, anorthic. Several diffuse manganic nodules, weakly to well impregnated, rounded to dendritic. Rare orthic microlaminated clay coatings, partly oriented, limpid to dusty. Few matrix injections from upper levels (beige rich in diatoms, or black rich in OM and charcoal). |
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| cm N° | Microstr. / Porosity | C-F | RD | Coarse Fraction | Micromass | BF | Org. Matter | Pedofeatures |
|--|----------------------|-----|----|---|--|----------|--|--|
| 1 2 3 4 5 6 7 8 9 | 112-124 N208 | | | Rare volcanic grains, very abundant silts, some carbonated fine sands, rarely coarser. Several quartz/felds. silts, rarely fine sands. Few malacoremain and biospheroids, rare phytoliths | Clayey, greyish to yellowish brown, rarely reddish, dotted by dark particles, micritisation areas (esp. 113-114 cm), and microsparite grains | CC | Abundant microcharcoals, rare macrocharcoal, abundant fine amorphous OM. Some reddish spores. Organic pigment and abundant small reddish and brownish debris | Very fine calcite coatings of voids, several micrite hypo-coatings of channels. Several to abundant micritic to sparitic irregular nodules, orthic to disorthic, unevenly developed. Some iron quasiccoatings and hypocoatings of channels. Several very small and diffuse impregnative iron nodules. Several manganic nodules moderately to strongly impregnated, rare OM-rich matrix injections from upper horizons. |
| 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 | 124-136 N209 | | | Rare medium to coarse basaltic sand, well rounded. Very abundant limestone silt to coarse sand. Several to abundant quartz/felds. Silt to fine sand. Several malacoremain, few biospheroids. | Clayey, yellowish to reddish brown, with greyish areas, dotted. Microsparite grains. | CC | Abundant microcharcoal, few macrocharcoal, abundant small fragments of amorphous OM, abundant reddish pigment, abundant small reddish brown fragments of tissues. | Abundant very fine calcite coatings of voids, rarely associated with iron diffuse hypocoatings around small channels. Sometimes partial calcite infillings. Several micritic to sparitic irregular nodules, orthic to disorthic. Several orthic manganese nodules, diffuse and weakly impregnated. Rare fragments of dusty, poorly-oriented clay coatings, anorthic. Few clusters of mite droppings, linked to organic remains. Rare inclusions of OM-rich dark matrix with microcharcoal. |
| 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 | 136-148 N210 | | | Few basaltic fine to coarse sand, rare and smaller scoria, well-rounded. Rare volcanic minerals. Very abundant limestone silts to coarse sand, abundant quartz-felds. Silt to fine sand. Few malacoremain, few to several biospheroids. | Clayery, yellowish brown, some greyish or reddish areas. Dotted by dark particles. Microsparite grains. | CC to SP | Abundant microcharcoal, one big macrocharcoal. Fine amorphous OM. Rare reddish fragments from tissues and rootlets, sometimes reddish organic pigment. Two bone fragments. | Abundant very fine calcite coatings on voids, abundant middle-sized calcite nodules, microsparitic to sparitic, concentrated c. 140-142 cm, orthic to disorthic. Several very diffuse and weakly impregnated manganic nodules, typical to dendritic, very rare ferromanganic well impregnated nodules. Some diffuse micritic or manganic hypohypocoatings of porosity. |
| 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 | 165-165 N211 | | | Few basaltic fine to coarse sand, well-rounded, and rare scoria fine sand. Very abundant limestone silt to fine sand, subangular to rounded. Abundant quartz-felds. silt to fine sand, subangular to rounded. Few biospheroid (absent at base), several malacoremain. | Clayey, yellowish brown, with greyish and reddish areas, dotted. Microsparite grains and micritisation areas (base). | CC to SP | Abundant microcharcoal, few macrocharcoal. Several fine amorphous OM and reddish organic pigment. Abundant small reddish fragments of tissues and rootlets. One bone fragment. | Abundant very fine calcite coatings of voids. Few to several micritic to sparitic calcite nodules, orthic to disorthic. Few diffuse manganic nodules, weakly to moderately impregnated. Very abundant clusters of mite droppings, associated to vegetal tissues debris. |
| 34 35 36 37 38 39 40 41 42 43 44 45 46 | 165-172 N212A | | | Several basaltic and scoria fine to medium sand, often well rounded. Abundant quartz-felds. silt to fine sand. Very abundant limestone medium to coarse sand. Rare sand-sized fragments of granite and flint. Very rare biospheroids, and several malacoremain. | Clayey, yellowish brown, greyish areas, dotted. Microsparite grains. | CC | Several microcharcoal, rare macrocharcoal. Few to several fine amorphous OM, and reddish organic pigment. Several reddish small fragments of rootlets and tissues. | Abundant fine calcite coatings of voids. Rare laminated calcite coatings of coarse particles, anorthic. Rare sparitic calcite nodules, anorthic. Abundant tuffaceous concretions remains (tubes), anorthic. Rare diffuse manganic nodules. One dusty clay coating fragment, anorthic. Some big clayey pedogenic aggregates, elongated and with diffuse borders, with striated BF (crust), anorthic. Abundant clusters of mite droppings, associated to organic debris. |

| cm N° | Microstr. / Porosity | C-F | RD | Coarse Fraction | Micromass | BF | Org. Matter | Pedofeatures | |
|--|----------------------|--|-----------------|-------------------------|---|---|-------------|---|--|
| 1 2 3 4 5 6 7 | 166-178 N212B | Single-grain (base, sand); intergrain microaggregate (middle); blocky (top). Well separated, not aggregated. | 9/10 | CP (top) /EG/ MG (base) | Sand: Several small scoria, abundant basalt, abundant quartz and feldspar, extremely abundant and coarse limestone grains, some sparite fragments. Several small volcanic minerals (olivine, pyroxene, nepheline). Few flint and rare granite grains. Several malacoremain, very abundant biospheroids well-rounded and with micrite coatings. | If present, clayey, yellowish brown, dotted, microsparite grains. | CC (top) | Rare microcharcoal, few macrocharcoal, rare fine amorphous OM. Few Reddish fragments of tissues. Few to several small to medium-sized bone fragments. | Calcite coatings of most sand grains, sometimes polyphased (pisolithe-like), anorthic. Few <i>chara</i> pseudomorphs, anorthic. Several well-rounded sparitic nodules, anorthic. Several pedosedimentary fragments of clay infillings/coatings with variegated features. Some reddish to dark brown pedosedimentary aggregates. |
| 8 9 10 11 12 13 14 15 16 | 178-186 N213 | Fissural structure to subangular blocky, very poorly separated and aggregated. Intrapedal massive, rare vughs. | 3/4 | CP /SSP | Several basaltic and scoria fine to coarse sand, well-rounded. Several volcanic minerals including nepheline. Several quartz-felds. sand. Few small fragments of flint, and rare of granite. Extremely abundant limestone fine sand to granules, several sparite fragments. Abundant fragmented malacoremain, roughly bedded. Several well-rounded biospheroids. | Clayey, yellowish to greyish brown, dotted. Microsparite grains. | CC | Abundant microcharcoal, several to abundant macrocharcoal. Rarely reddish organic pigment and fine amorphous OM. Few reddish fragments of tissues and rootlets, several bone fragments (up to 3 mm) | Rare fine calcite coatings of voids. Few small sparitic nodules, orthic. Abundant microlaminated micritic coatings of sands, pisolith-like (top). Few organo manganic nodules, strongly impregnated. Few mite droppings. Some well-rounded anorthic pedosedimentary aggregates, with variegated characteristics. Rare tube-like tuffaceous concretions, anorthic. |
| 17 18 19 20 21 22 23 24 25 | 188-195 N214 | Single-grain (top, sand), to fissural (base) Well separated, not aggregated (base) | ¾ to 1/5 (base) | MG (top)/ CP/ OP (base) | Abundant basaltic coarse sand, few scoria. Several to abundant volcanic minerals (nepheline, analcime). Several quartz/felds. fine to coarse sand, and extremely abundant limesto fine to coarse sand. Abundant sparite crystals, and some tube-like tuffaceous concretions. Rare small flint fragments. Several to abundant fragmented malacoremain, and several biospheroids, well-rounded. | If present, clayey, yellowish to greyish brown, finely dotted, microsparite grains. | CC (base) | Several microcharcoal, few to several macrocharcoal. Fine amorphous OM. Some reddish fragments from rootlets and tissues. Several small to medium-sized bone fragments. | Few fine calcite coatings of voids, few calcite nodules, some well-rounded. Microlaminated calcite coatings of some mineral or biomineral grains (orthic). Few small pedosedimentary fragments of clay coatings or infillings. Few pedosedimentary aggregates with variegated features, well-rounded. Few small and diffuse iron and manganic nodules, weakly impregnated. |

Table 3: Micromorphological description of NAR2 by thin section. C-F: Coarse-Fine. RD: Related Distribution, (OP: Open Porphyric, CP: Closed Porphyric, SSP: Single Spaced Porphyric, MG: Monic, EG: Enaulic). BF: Birrefringence Fabric (SP: Speckled, CC: Calcitic Crystallitic).

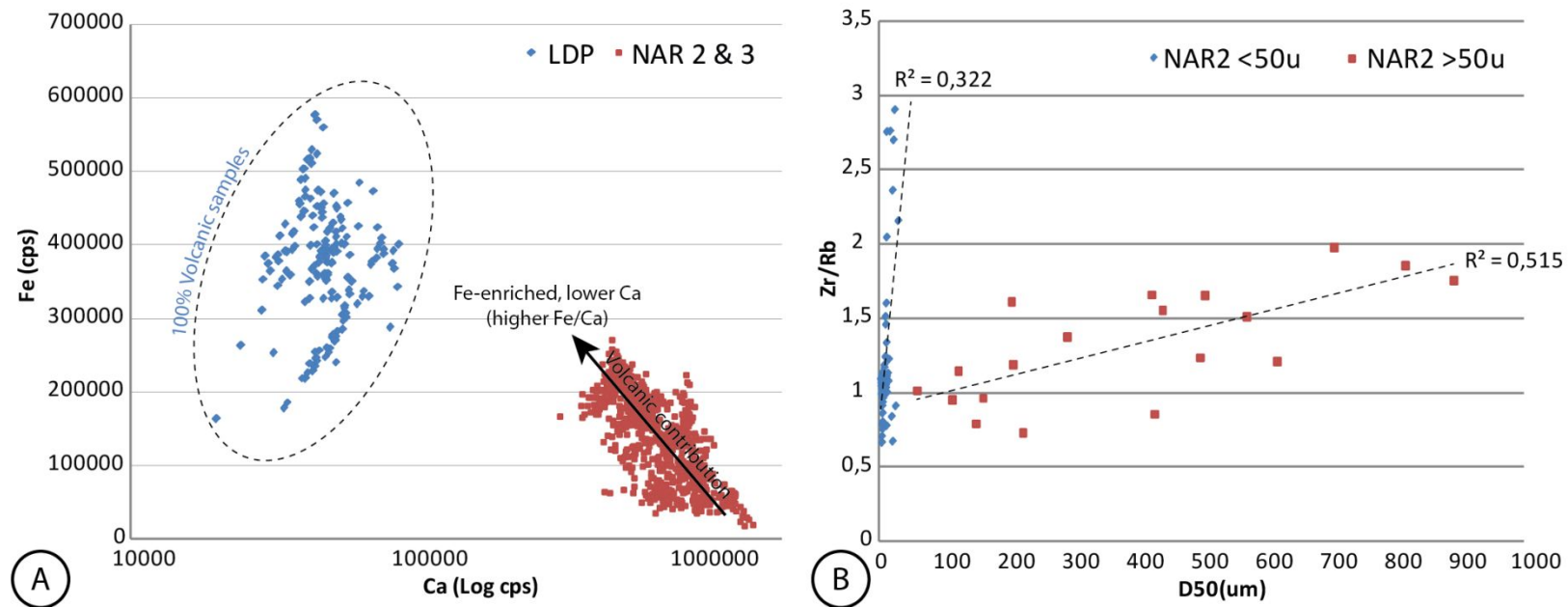


Figure 12. A) Scatterplot showing relative contents in Fe and Ca (measured by XRF core-scanner in cps, Log scale for Ca) of 100% volcanic samples (LDP blue dots, core from the summit of the Puy de Corent, lithology: basalts and scoria, data from Mayoral, 2018), vs. samples from NAR2 & NAR3 in the calcareous lowlands (this study, red dots). 100% volcanic samples have clearly higher Fe/Ca ratio. Note also the gradient in the Fe/Ca ratio for NAR2 & NAR3 samples interpreted as increased volcanic sediment content. B) Scatterplot showing relationship between Zr/Rb ratio and D50 in NAR2 samples, for two different grain-size classes. Zr/Rb is very sensitive to grain-size increase in clays and fine to coarse silts (<50um, blue dots), and moderately sensitive for very coarse silts and sands (>50um, red dots). Note that relatively low R^2 is mainly due to the reduced number of samples.

| | Sedimentary subunit | 2.24 | 2.23 | 2.22 | 2.21 | 2.20 | 2.19 | 2.18 | 2.17 | 2.16 inf | 2.16 sup | 2.15 | 2.14 | 2.13 | 2.12 | 2.11 | 2.10 | 2.9 |
|----|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|---------|---------|---------|--------|-------|-------|-------|
| | Depth (cm) | 196-202 | 194-196 | 186-194 | 180-184 | 170-178 | 164-170 | 158-162 | 154-158 | 142-154 | 132-142 | 122-132 | 114-122 | 100-114 | 90-100 | 86-90 | 80-84 | 70-78 |
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Table 4: Fauna list of malacological samples from NAR2 core. Species are classified by ecological affinities (F : forested environment; M : mesophilic species ; P : palustrine environment ; O : open environment ; A : aquatic species) and by alphabetical order.

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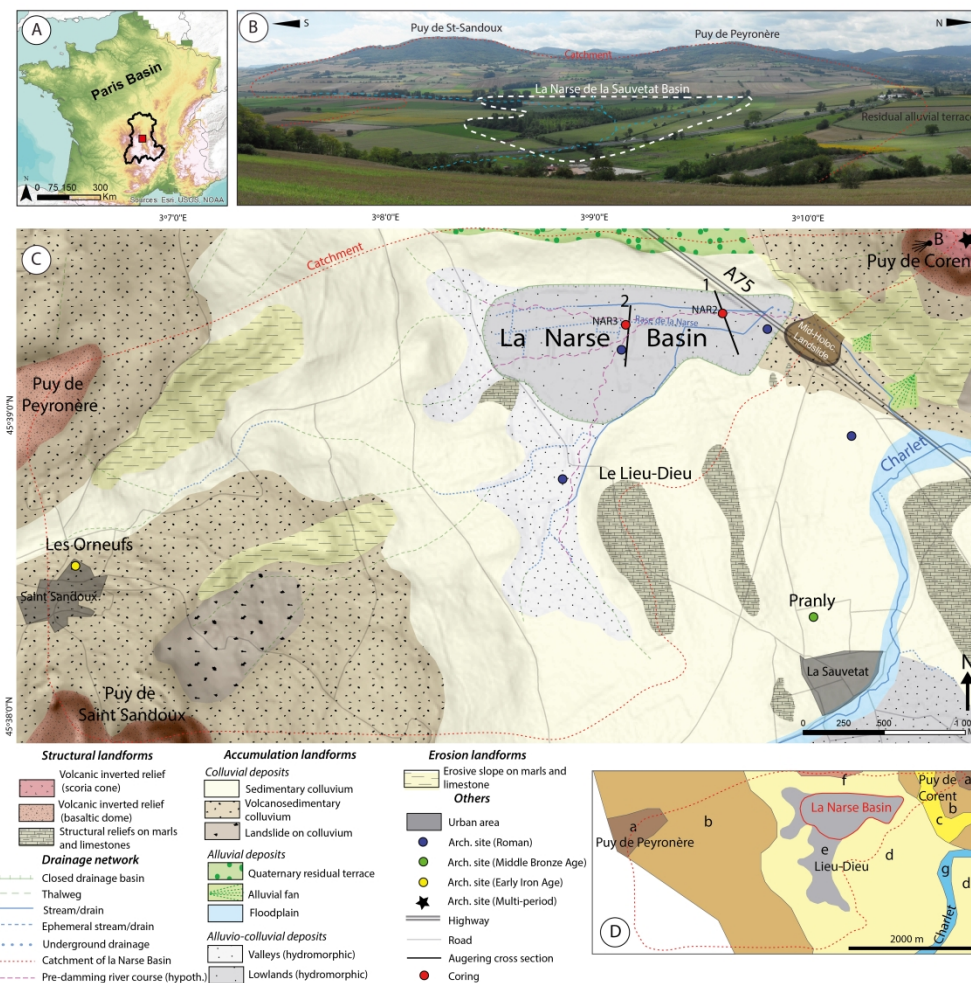
| | Sedimentary subunit | 3.13 | 3.12 | | | 3.11 | | 3.10 | 3.9 | | | 3.8 | | 3.7 | 3.6 | |
|----|--------------------------------|-----------|-----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| | Depth (cm) | 193-201 | 187-193 | 181-187 | 174-181 | 165-171 | 159-165 | 147-156 | 140-147 | 134-140 | 128-134 | 120-128 | 114-120 | 104-112 | 92-103 | 84-92 |
| 5 | <i>Arianta arbustorum</i> | | 1 | 1 | 1 | 3 | 2 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | | |
| 6 | <i>Clausilia</i> sp. | | | | | | | | 1 | | | | | | | |
| 7 | <i>Pomatias elegans</i> | | | | 1 | 1 | | | | | | 1 | | | | |
| 8 | <i>Cochlicopa lubrica</i> agg. | | | 3 | 4 | 10 | 12 | 29 | 16 | 11 | 7 | 5 | 5 | 5 | 3 | 3 |
| 9 | Slugs | 6 | 4 | 13 | 20 | 32 | 29 | 75 | 59 | 38 | 21 | 25 | 16 | 12 | 4 | 2 |
| 10 | <i>Nesovitrea hammonis</i> | | 1 | | | 2 | 1 | 4 | 2 | | | | | | | |
| 11 | <i>Punctum pygmaeum</i> | | | | 1 | | 1 | 2 | 1 | 1 | | | 2 | | | |
| 12 | <i>Trochulus hispidus</i> | | | | | | | | 1 | | | 2 | 5 | 1 | 5 | 1 |
| 13 | <i>Vallonia costata</i> | 3 | | 6 | 7 | 11 | 7 | 35 | 12 | 6 | 1 | 3 | | | | |
| 14 | <i>Vitrina pellucida</i> | | | | 1 | 1 | 1 | | | | | | | | | |
| 15 | <i>Carychium minimum</i> | | 1 | 4 | 10 | 28 | 32 | 25 | 3 | 2 | | | 4 | 16 | 1 | |
| 16 | <i>Oxyloma elegans</i> | 1 | | | 8 | 11 | 14 | 44 | 24 | 15 | 15 | 10 | 9 | 18 | 18 | 6 |
| 17 | <i>Vertigo angustior</i> | | | 1 | 4 | 9 | 16 | 4 | 1 | | | | 1 | 1 | | |
| 18 | <i>Vertigo antivertigo</i> | 2 | | 5 | 11 | 20 | 31 | 22 | 8 | 10 | 2 | 2 | 5 | 21 | 5 | |
| 19 | <i>Vertigo moulinsiana</i> | | | | | | | 1 | | | | | | | | |
| 20 | <i>Zonitoides nitidus</i> | | | 1 | 2 | 4 | 6 | 1 | | | | | | 4 | 8 | |
| 21 | <i>Helicella itala</i> | | 8 | | 1 | | 3 | 12 | 8 | 16 | 2 | 9 | 5 | 4 | | |
| 22 | <i>Pupilla muscorum</i> | 3 | 5 | 6 | 2 | 7 | 7 | 29 | 36 | 21 | 8 | 7 | 10 | 7 | | |
| 23 | <i>Vallonia excentrica</i> | | | | | | | | 15 | 8 | | | | | | |
| 24 | <i>Vallonia pulchella</i> | 20 | 55 | 73 | 102 | 100 | 126 | 202 | 252 | 182 | 44 | 23 | 104 | 95 | 18 | 15 |
| 25 | <i>Vertigo pygmaea</i> | | 6 | 4 | 8 | 17 | 19 | 20 | 29 | 22 | 4 | 6 | 23 | 11 | 2 | |
| 26 | <i>Acroloxus lacustris</i> | | | | | | | | | | | | | | 6 | 12 |
| 27 | <i>Anisus leucostoma</i> | | | | | 3 | | 2 | 1 | 2 | 1 | | 4 | 16 | 34 | |
| 28 | <i>Galba truncatula</i> | 1 | | 3 | 14 | 28 | 21 | 7 | 6 | 32 | 24 | 9 | 28 | 57 | 48 | 17 |
| 29 | <i>Gyraulus albus</i> | | | | | | | | | | | | | | 13 | 31 |
| 30 | <i>Gyraulus crista</i> | | | | 3 | 9 | 3 | 2 | 3 | 1 | 2 | | | 1 | 74 | 112 |
| 31 | <i>Hippeutis complanatus</i> | | | | | | | | | | | | | | 9 | 9 |
| 32 | <i>Lymnaea stagnalis</i> | | | | | | | | | | | | | | | 2 |
| 33 | <i>Physa fontinalis</i> | | | | | | | | | | | | | | 8 | |
| 34 | <i>Pisidium</i> sp. | 2 | 1 | 1 | 1 | 5 | 4 | 2 | | | | | 2 | 18 | 35 | 13 |
| 35 | <i>Planorbis planorbis</i> | 1 | | 1 | | | | | 1 | | | | | 13 | 26 | 26 |
| 36 | <i>Radix balthica</i> | | | | | 4 | 1 | | | | | | 2 | 18 | 27 | 22 |
| 37 | <i>Radix labiata</i> | 1 | 4 | 3 | 10 | 23 | 36 | 45 | 39 | 21 | 2 | | | | | |
| 38 | <i>Valvata cristata</i> | | | | | | | | | | | | | | 2 | 14 |
| 39 | Count | 40 | 86 | 125 | 211 | 328 | 372 | 572 | 519 | 389 | 134 | 103 | 226 | 319 | 346 | 285 |
| 40 | <i>Cecilioides acicula</i> | | | 1 | | | | | 1 | 1 | 1 | | | | | |

Table 5: Fauna list of malacological samples from NAR3 core. Species are classified by ecological affinities (F : forested environment; M : mesophilic species ; P : palustrine environment ; O : open environment ; A : aquatic species) and by alphabetical order. Grey columns indicate samples which were grouped in order to reach a number in accordance with the representativeness threshold of Evans (1972)

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Accepted Manuscript



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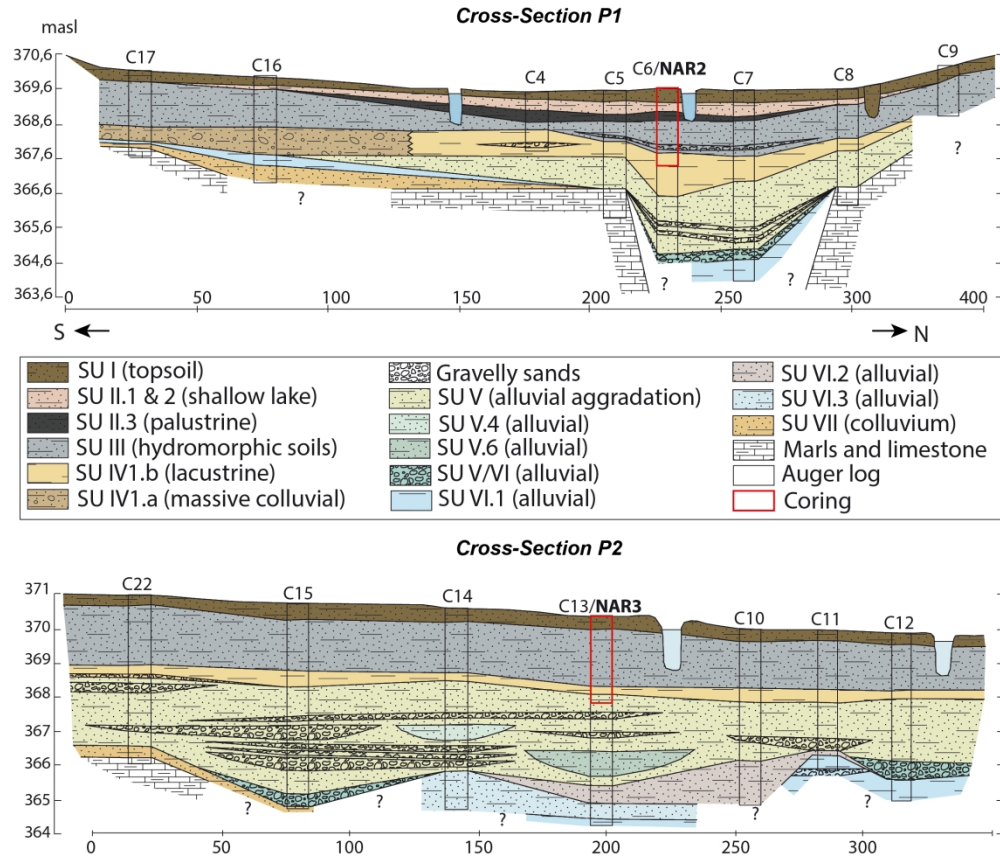


Figure 2. Selected stratigraphic cross-sections of the basin (P1 and P2, adapted from Mayoral et al., 2018) with location of cores NAR2 and NAR3 (see also Fig. 1C).

210x181mm (300 x 300 DPI)

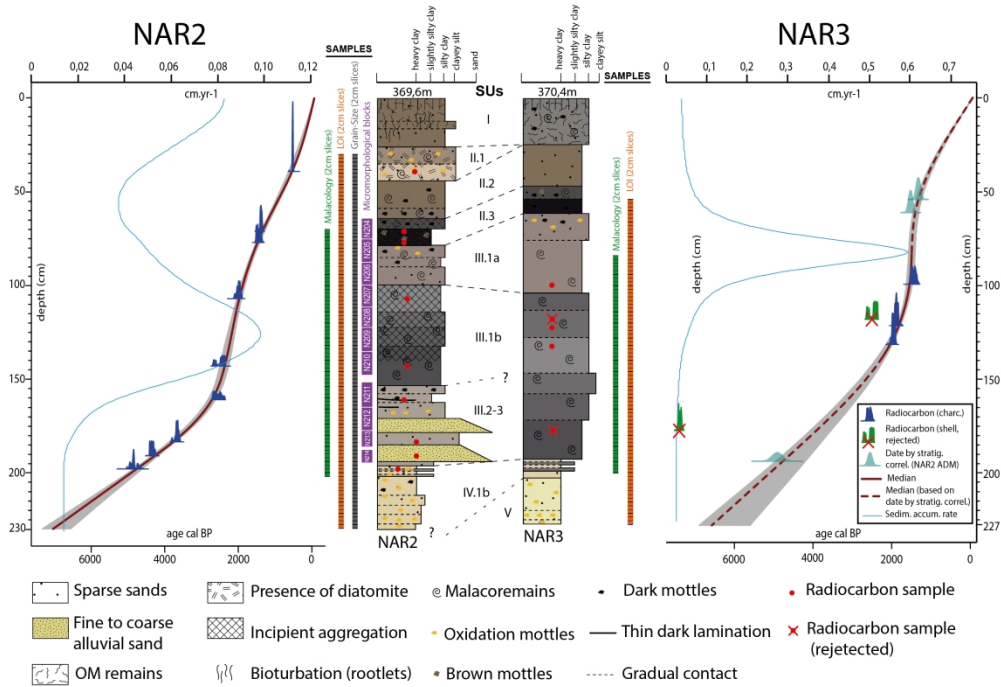


Figure 3. Litho-stratigraphy, stratigraphic correlations, sampling and age-depth model of NAR2 (left) and NAR3 (right) cores.

242x168mm (300 x 300 DPI)

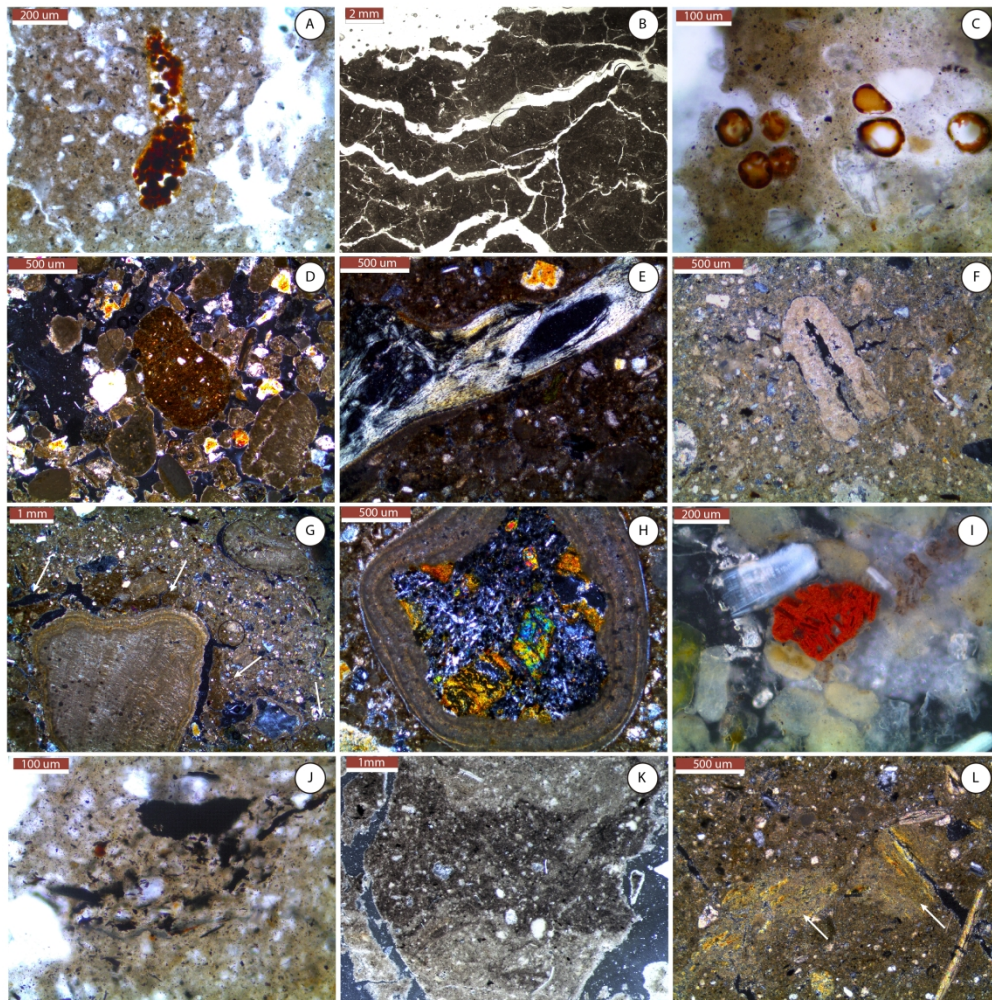


Figure 4. Selected micromorphological features of lower NAR2 (Micromorphological Units MVII to MIV, see text and Fig. 6). A) Cluster of mite droppings, microcharcoal-rich micromass (MIV, N211, PPL-Plane Polarized Light). B) Platy microstructure (MIV, N211, transmitted light). C) Spore remains (MIV, N211, PPL). D) Rounded pedosedimentary aggregate (reddish matrix), surrounded mainly by carbonated micritic sands (MV, N212B, XPL-Crossed Polarized Light). E) Bone fragment (MVI, N213, XPL). F) Fragment of micritic to micro-sparitic carbonated root concretion (MIV, N212A, XPL). G) Contact (arrows) of coarse sands with silty clays. Note the big stromatolitic/tuffaceous fragment of limestone, with a secondary microlaminated calcite coating (MV, N212B, XPL). H) Fragment of basalt with a coating of microlaminated calcite (micrite and microsparite) and rounded by transport (MVI, N213, XPL). I) Volcanic reddish scoria fragment, including translucent plagioclases (MV, N212B, OIL-Oblique Incident Light). J) Cluster of charcoal and in-situ charred remains (MIV, N211, PPL). K) Portion of dark matrix, with more abundant coarse fraction, more humic and enriched in microcharcoal, probably from a surficial soil horizon (MIV, base of N211, OIL). L) Clayey aggregates with striated B-Fabric (arrows), likely degraded fragments of slaking crust (MIV, N212A, XPL).

286x288mm (300 x 300 DPI)

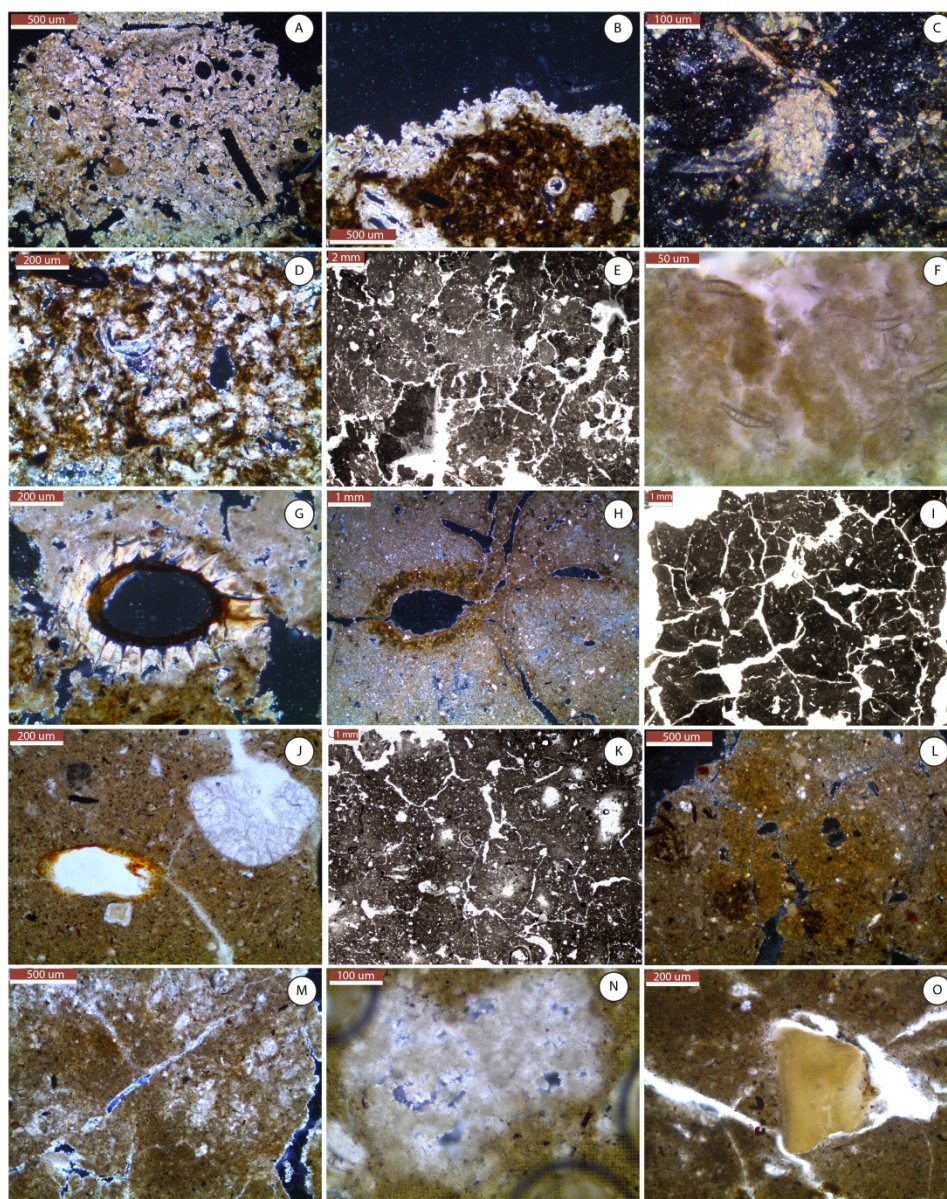


Figure 5. Selected micromorphological features from upper NAR2 (Micromorphological Units MIII to MI, see text and Fig.6). A) Orthitic tuffaceous concretion, from aggregation of smaller micritic elements and pseudomorphs (MI, N204, XPL-Crossed Polarized Light). B) Tuffaceous calcite capping. Note dark micromass, rich in organic matter (MI, N204, XPL). C) Orthitic calcite nodule in a dark crystalline to isotropic micromass (MI, N204, XPL). D) Micromass rich in calcitic grains strongly bioturbated and reorganized by biological activity (MI, N204, XPL). E) Complex microstructure, subangular with granular substructure or crumbly subangular (MI, N204, transmitted light). F) Diatoms embedded in carbonate-rich micromass (MI, N204, PPL-Plane Polarized Light). G) Characeae oogon. Note the two different types of micromass: brown, clayey, rich in organic fragments and microcharcoal (base) vs. massive micritic-microsparitic micromass (top) (MI, N204, XPL). H) Iron and micritic hypococoatings around a chamber and fissural to canalicular voids (MIII, N208, XPL). I) Subangular blocky microstructure of an organo-mineral unit (MIII, N207, transmitted light). J) Iron hypococating and biospheroid, note silty clay micromass rich in microcharcoal and small organic fragments (MII, N205, PPL). K) Granular microstructure of an organo-mineral unit, note partial collapse of porosity due to secondary clogging (MIII, N210, transmitted light). L) Silty clay matrix highly impregnated

1
2
3 by oxidized iron, and injection of matrix aggregates (rich in organic matter) from upper layers (MII, N205,
4 XPL). M) Concentration of micritic to microsparitic calcite in the matrix (and in voids), some evolving to
5 nodules (MIII, N208, XPL). N) Calcite nodule (micritic to microsparitic) in development by impregnation of
6 the matrix (MIII, N209, XPL). O) Small bone fragment embedded in a silty clay matrix with microcharcoal
7 and organic microdebris (MII, N205, PPL).

8 286x358mm (300 x 300 DPI)
9

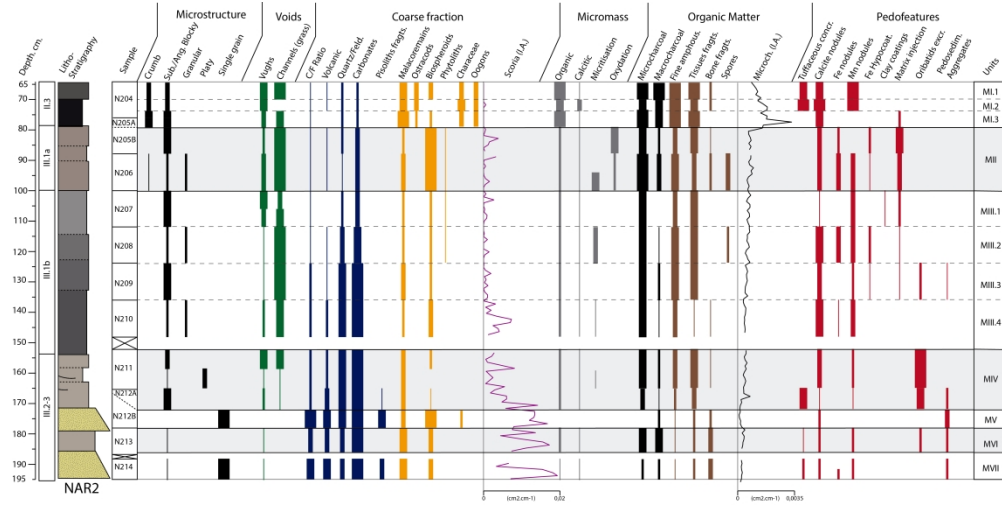


Figure 6. Summary diagram of main micromorphological features of NAR2 between 65 and 195 cm. Bars width indicates their relative abundance (rare, few, several /some, abundant, very abundant, see Table 3 in Supplementary Information), or alternatively their development degree. Scoria and microcharcoal are quantified using image analysis (IA). C/F: Coarse/Fine ratio, here 20µm.

462x232mm (300 x 300 DPI)

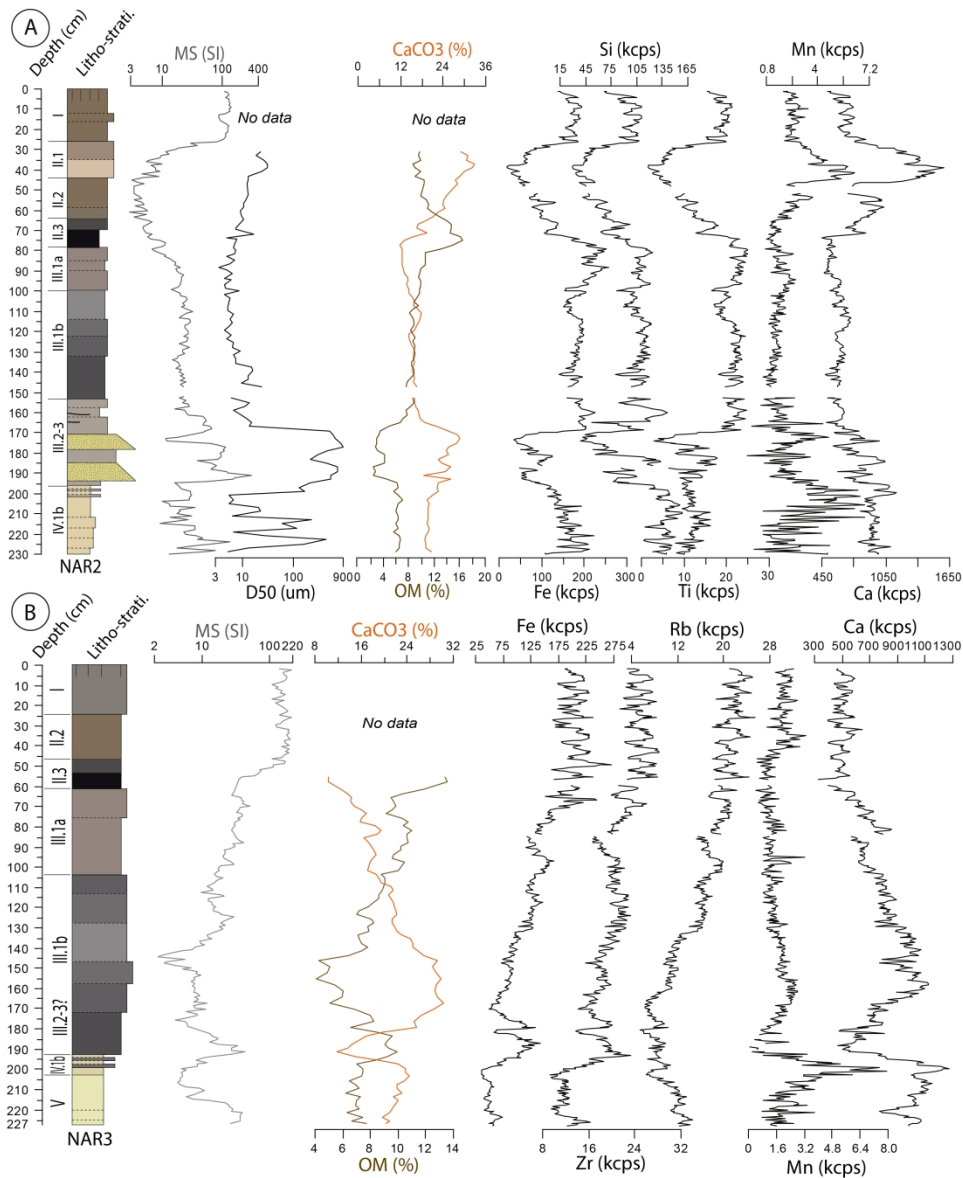


Figure 7. A) Selected elements and sedimentological data for NAR2. Values are in 10⁻⁵ SI (Magnetic Susceptibility-MS-) and in counts per second (CPS) for the XRF. B) Selected elements and sedimentological data for NAR3.

323x404mm (300 x 300 DPI)

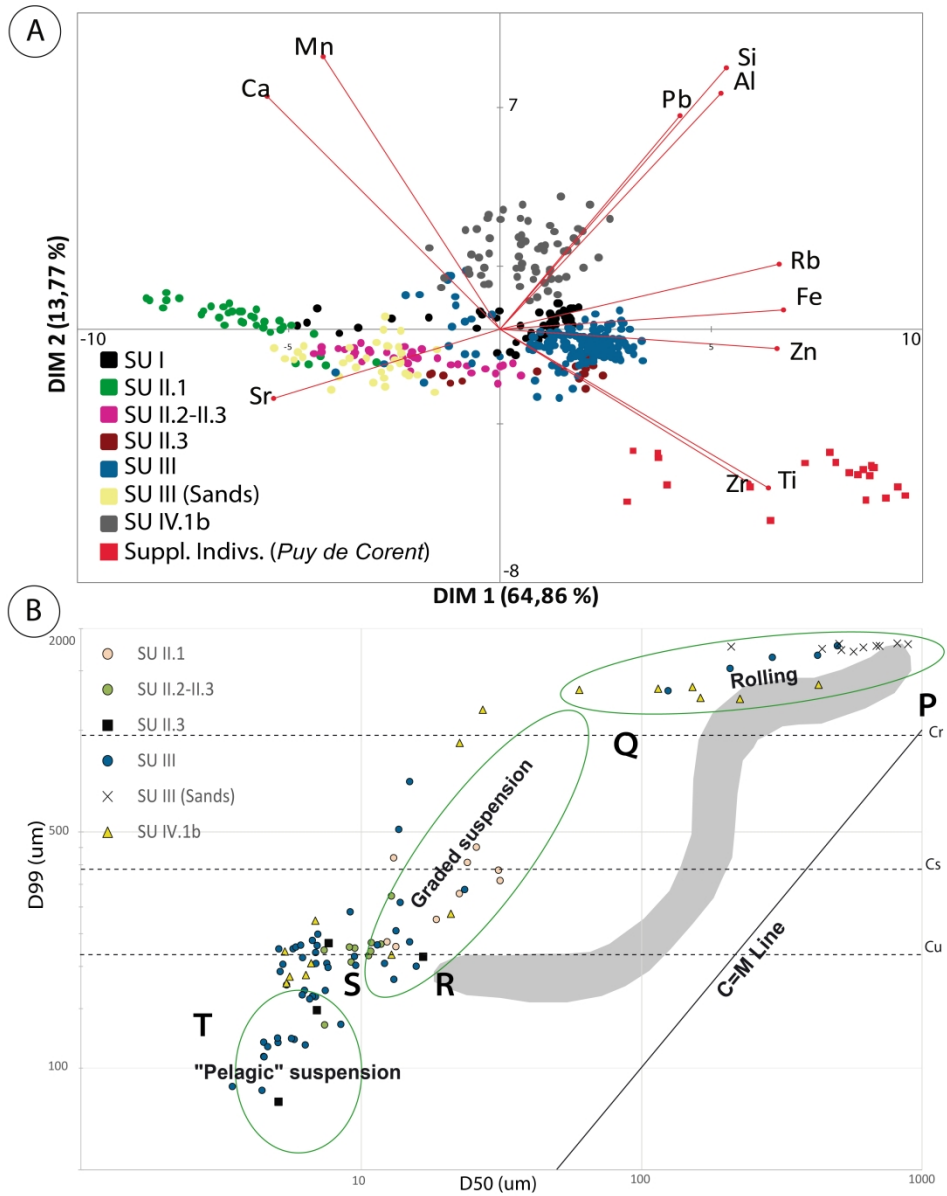


Figure 8. A) PCA biplot of selected geochemical variables according to dimensions 1 and 2, individuals are distributed by Sedimentary Unit. Note supplementary individuals (red squares, data from Mayoral et al., 2018). B) Passega or C-M diagram of NAR2 with grain-size data by Sedimentary Unit. Grey area represents reference C-M diagram by Passega (1977).

323x404mm (300 x 300 DPI)

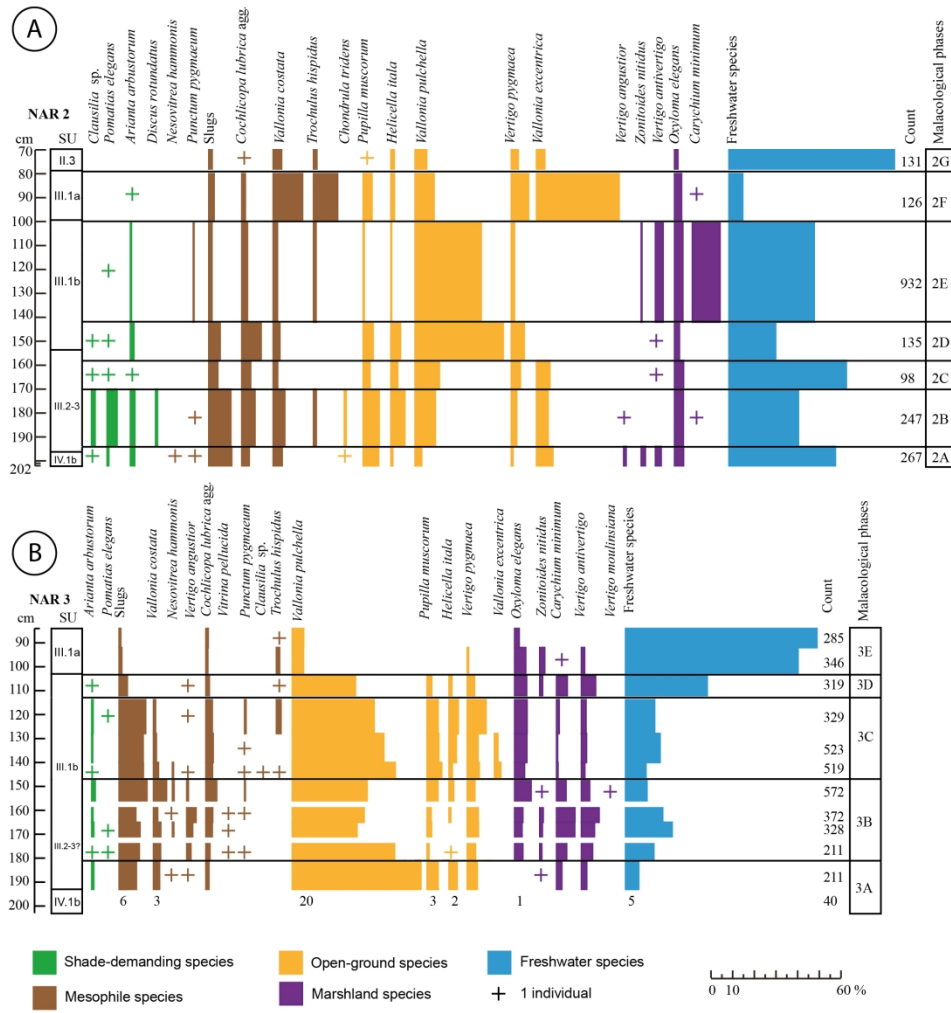


Figure 9. Diagrams of specific composition of molluscan assemblages A) NAR2 B) NAR3. Contiguous 2cm-thick sediment samples were grouped in bigger sets when necessary in order to reach a significant number of shells. Species are classified by ecological affinities and by order of occurrence.

210x216mm (300 x 300 DPI)

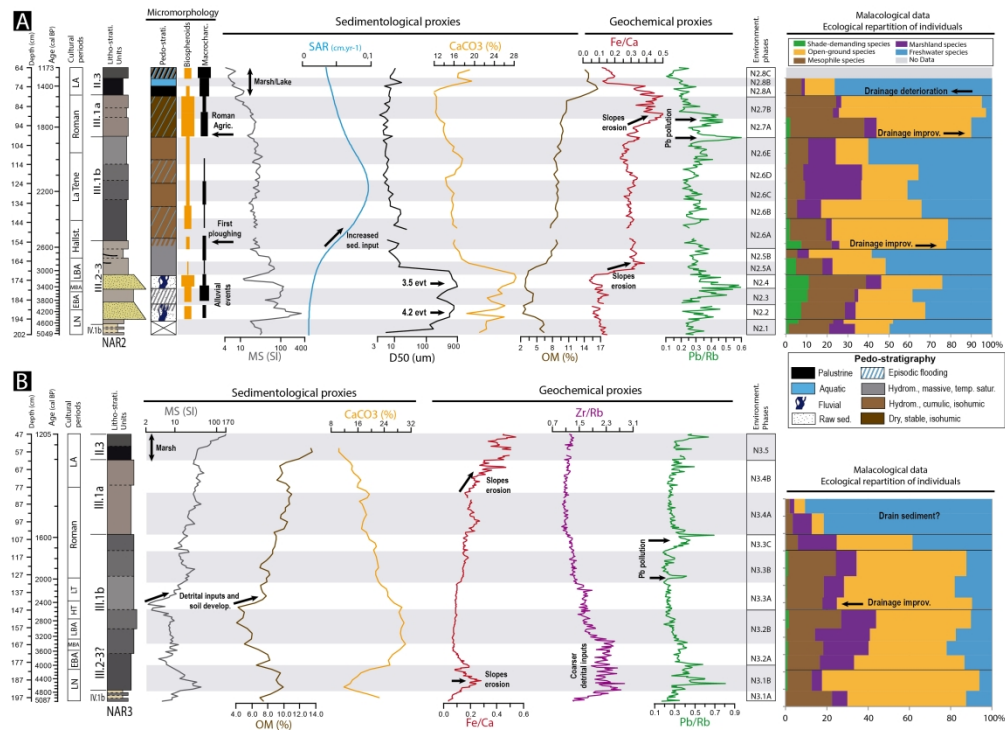


Figure 10. Multi-proxy synthetic diagram for NAR2 (A) and NAR3 (B) cores (MS: Magnetic Susceptibility, D50: median grain-size, SAR: Sediment Accumulation Rate, OM: Organic Matter content).

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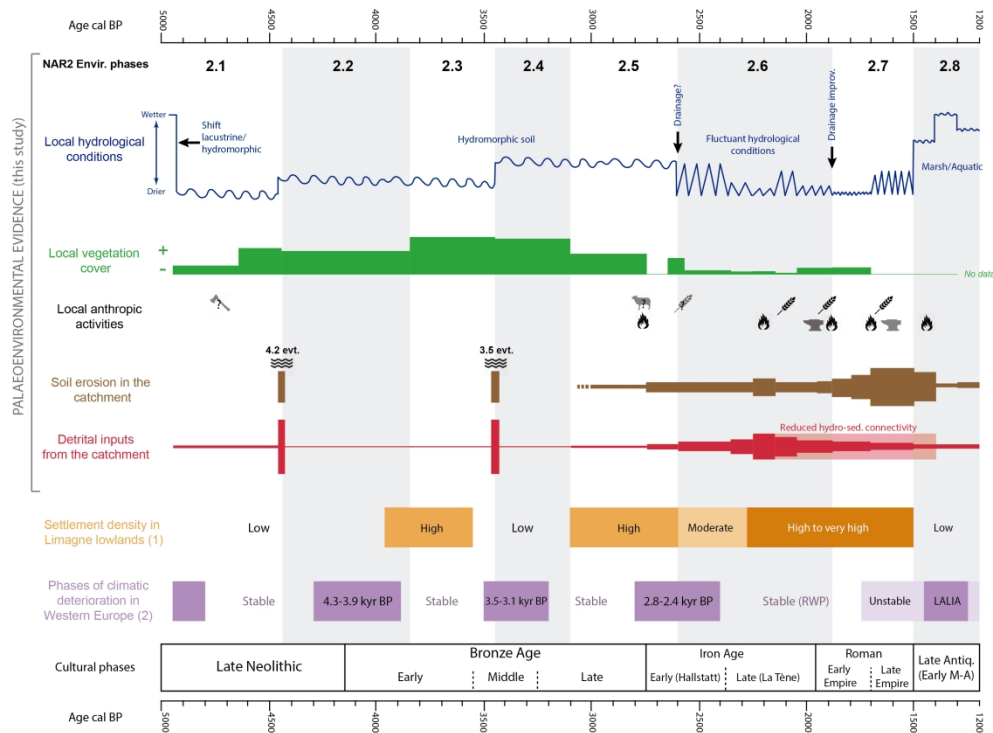


Figure 11. Comparison of palaeoenvironmental evidence in la Narse de la Sauvetat between 5000 and 1200 cal BP (derived from core NAR2, this study) with regional archaeological data in Limagne plain and climatic changes in Western Europe. NAR2 environmental phases are from Fig. 10A. Representations of local hydrological conditions, soil erosion in the catchment and detrital inputs are qualitative (relative level or thickness according to process intensity) and based on data from Fig. 10. High-energy hydro-sedimentary episodes related to 4.2 and 3.5 kyr. cal BP climatic events are indicated (note a chronological offset of 150-200 yr. of the first episode, see the text for details). Local vegetation cover (qualitative) is represented by the proportion of shade-demanding malacological species vs. other terrestrial malacological species. Anthropic activities (landscape opening, use of fire, pastoral activity, agriculture and metallurgical activity) are represented by symbols. RWP: Roman Warm Period. LALIA: Late Antiquity Little Ice Age. Settlement density in Limagne is based on (1) Ballut and Argant, 2004; Couderc, 2019; Daugas and Raynal, 1989; Milcent and Mennessier-Jouannet, 2007; Raynal et al., 2003; Trément et al., 2007; Trément, 2011. Phases of climatic deterioration in Western Europe are based on (2) Berger et al., 2007; Brisset et al., 2013; Buntgen et al., 2011; Carozza et al., 2015; Fletcher, Debret and Goñi, 2013; Holzhauser et al., 2005; Joerin et al., 2006; Magny, 2004; Magny et al., 2009; McCormick et al., 2012; Van Geel and Magny, 2002; Walker et al., 2019; Walsh et al., 2019.

282x207mm (300 x 300 DPI)

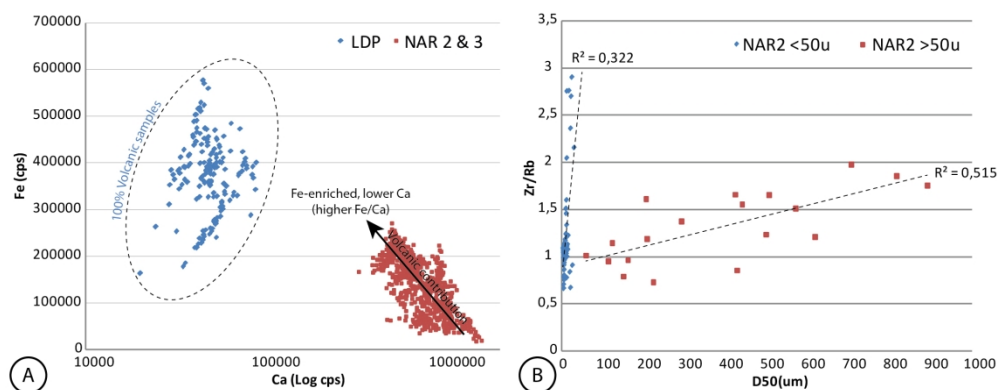


Figure 12. A) Scatterplot showing relative contents in Fe and Ca (measured by XRF core-scanner in cps, Log scale for Ca) of 100% volcanic samples (LDP blue dots, core from the summit of the Puy de Corent, lithology: basalts and scoria, data from Mayoral, 2018), vs. samples from NAR2 & NAR3 in the calcareous lowlands (this study, red dots). 100% volcanic samples have clearly higher Fe/Ca ratio. Note also the gradient in the Fe/Ca ratio for NAR2 & NAR3 samples interpreted as increased volcanic sediment content. B) Scatterplot showing relationship between Zr/Rb ratio and D50 in NAR2 samples, for two different grain-size classes. Zr/Rb is very sensitive to grain-size increase in clays and fine to coarse silts (<50um, blue dots), and moderately sensitive for very coarse silts and sands (>50um, red dots). Note that relatively low R2 is mainly due to the reduced number of samples.

185x73mm (300 x 300 DPI)