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The Roman Water Management of Arles as Read in Aqueduct Carbonate Archives

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ABSTRACT

This article reconstructs the complex history of modifications made to the Roman aqueduct of *Arelate* (Arles), by studying carbonate incrustations in its channels. These deposits, precipitated by flowing water, have preserved an archive of the aqueduct's life-cycle in their stratigraphy, fabric and stable isotope composition. Two tributaries, from Caparon and Eygalières, converged in a basin before an arcade bridge, from which a single channel continued to Arles. Originally, the Caparon branch alone supplied Arles with water from the south side of the Alpilles hills, the basin acting as a header basin before the arcade. Later, the Eygalières branch from the north side of the Alpilles was joined to the basin. The Caparon branch was then diverted to power water-mills at Barbegal, changing the basin's function from convergence back to a header basin. After some decades, the Eygalières branch was also used to supply the mills, changing the basin into a distribution structure. From Arles, lead pipes laid across the bed of the Rhône also supplied water to the Trinquetaille quarter. Major cleaning of the aqueduct in the early fourth century is also identified. Anthropogenic carbonates can therefore provide crucial information on the provenance of water and alterations to ancient aqueducts.

1 | Introduction

The Roman city of *Arelate*, one of the most important urban centres in Roman Provence, featured a complex water management history including multiple aqueduct branches delivering water to the city, inverted siphons beneath the Rhône River, and later the addition of the first industrial water-mill complex on a ridge at Barbegal to the north-east of the city (Figure 1) (Heijmans and Sintès 1994; Heijmans 2004; Rothé and Heijmans 2008; Leveau et al. 2019). Frequently modified, this system operated for over four centuries, from the start of the first millennium CE until at least the beginning of the fourth, and possibly the fifth century CE. While the architectural remains of this water system are well documented (Grenier 1960; Leveau et al. 2019; Fabre et al. 2023), its functioning, management, sustainability and adaptations in response to environmental, political and socio-economical changes remain largely unexplored. In this study, we attempt to reconstruct the long activity over at least four centuries of the water system in a framework of changing environment, political power and socio-economic circumstances by analysing carbonate deposits formed by flowing water inside aqueduct channels and a basin. *Arelate* serves as an excellent case study of the transition of a small Roman provincial city into a late antique imperial residence with a renovated water supply network, in contrast to nearby ancient cities of Nîmes and Fréjus where people abandoned maintenance of their aqueducts during the crisis of the third century. Numerous instances of human intervention for sustainable water use are captured in aqueduct carbonate, highlighting the versatility of this material for interdisciplinary research. The analysis of aqueduct carbonate provides insight into human strategies for ensuring a sustainable water supply and adapting it to changes in water demand, availability, quality and the political and economic circumstances. Our study demonstrates for the first time that the water management of the Roman aqueduct of *Arelate* covers four to five centuries, spanning the system's initial construction to its transition into the late antique period.

The findings of this work significantly contribute to our understanding of the urban development of Arles and activities of Barbegal and its connection to the city and to Roman Provence. Therefore, we trust that the results of this paper are of interest to historians of the ancient economy and urbanism and specialists in ancient water management. The methods used include careful and strategic multi-sampling of parts of a water supply system, and stratigraphic correlation using optical microscopy, stable isotope and trace element analysis, which can in principle be applied to any ancient water supply system to unravel its maintenance and reconstruction history.

The modern city of Arles, originally a Celtic trading hub, was established as a Roman colony by Julius Caesar in 46/45 BCE. *Arelate* in those days was a moderately sized provincial city with a major river port on the Rhône but endowed with a very large territory and important enough to have its own long aqueduct system (Heijmans and Sintès 1994; Fabre et al. 2023). The Emperor Constantine himself stayed at *Arelate* between 308 and 310 CE, and from 395 CE it became the residence of the Praetorian Prefecture of the Gauls, and thus the effective capital of Gaul and Hispania (Heijmans 1999, 2004). *Arelate* also flourished in the fifth and sixth centuries but power changed hands; in 476 CE, the city was captured by the Visigoths, who continued to maintain its importance, as did the Ostrogoths, who possessed the city from 508 till 536 CE, but after it was delivered to the Franks, it gradually fell into decline (Heijmans 1999, 2004).

The Roman aqueduct of *Arelate* was supplied by water sources in and near the Alpilles massif to the north-east (Figure 1a,b) (Grenier 1960; Blanchet 1999, 2001; Leveau 1995, 2018; Leveau et al 2019; Fabre et al. 2023). As a small range of limestone hills, the Alpilles can only support minor springs, prompting the successive construction of two aqueduct branches. The original and shorter Caparon branch, with a total length of 11 km, tapped several sources to the south of the massif, while the longer and younger Eygalières branch, with a minimum length of 37.5 km, supplied *Arelate* with water from the north side of the same range. The two branches joined in a basin on the south side of the hills, referred to here as the 'Bassin des Arcs' (Figure 1e). From this point, a single conduit, which we refer to as the 'Arles city conduit', carried water to Arles over 12.5 km. The combined length of the three sections of the aqueduct is 61 km, with an estimated maximum total discharge of 54,400 m^3 per day (Leveau et al. 2019; Terraz et al. submitted). The Caparon and Eygalières branches had a maximum possible discharge of 21,600 and 32,800 m^3 per day, respectively, when new, but these volumes were significantly reduced over time by carbonate deposition (Fabre et al. 2023; Terraz et al. submitted). The aqueducts were mostly built as masonry channels (Figure 3a), with several short tunnels and small bridges, a two-storey bridge across the depression immediately south of the Alpilles, and probably a large bridge before its entrance to the city (Figure 1b).

The initial construction of the Caparon branch can be dated to 3 BCE (Paillet 2011), based on milestones found along the *Via Aurelia* crossing this branch at Paradou (Figure 1c). An elevated road bridge was built here to let the *Via Aurelia* pass over the Caparon branch, while the slope of the aqueduct was steepened to let the road pass above it, suggesting that road and aqueduct were constructed simultaneously (Figure 1g) (Paillet 2011; Leveau 2018; Fabre et al. 2023). At least four sources with side aqueducts tapped small aquifers in the Cretaceous limestone and Miocene sandstone molasse to feed the Caparon branch. Aqueducts derived from the Entreconque and Mas de la Dame springs were joined by a branch from the Sainte Berthe spring north of Manville to reach a convergence basin measuring 2.7×2.5 m at a site called 'la Burlande' in Paradou (Figure 1b,c) (Leveau 2018). Here, a branch from the Arcoule spring to the north joined the basin. From the Burlande basin, the Caparon branch ran for over 5.6 km towards the Bassin des Arcs (Figure 1b).

The Eygalières branch tapped water from the north side of the Alpilles, but the exact location of its sources is unknown (Figure 1a,b) (Fabre at al. 2023). The aqueduct can be traced eastward as far as Mas Crema south of Mollégès, at 55 m a.s.l., where the aqueduct probably tapped local funnel-shaped springs called 'laurons' (Figure 1a,b) (Giudicelli et al. 1980; Fabre et al. 2023). These laurons are supplied by mixed water from the Alpilles and from the Durance River water table in the coarse sediment of an alluvial fan which filled the depression between the Alpilles, the Durance and the Petite Crau ridge of Saint-Rémy-de-Provence (Fabre et al. 2023). The aqueduct passed into a tunnel below the Petite Crau and contoured the Alpilles on their west side to join the Bassin des Arcs from the west (Figure 1b).

An important water-powered structure later added to the Arles water supply system was the water-mill complex of Barbegal, the earliest known truly industrial mill complex of antiquity (Benoit 1940; Leveau 1998; Wilson 1999; Guendon 2005; Sürmelihindi et al. 2018, 2019, 2020; Passchier et al. 2020, 2024). This complex was fed by aqueducts of the Arles water system, as described below (Figure 1d,e).

West of Arles, a Roman aqueduct system whose destination is unknown exists near the town of Bellegarde. This aqueduct could theoretically have supplied water to *Ugernum*, Roman Beaucaire, or to the quarter of Arles lying across the Rhône on the west bank, presently known as Trinquetaille, and even to Arles itself (Figure 1a). The aqueduct takes its water from the Laval spring west of Bellegarde and runs through the village from west to east for 5.3 km to a basin at Valescure (Figure 1a). From this point, a short series of arches was discovered running

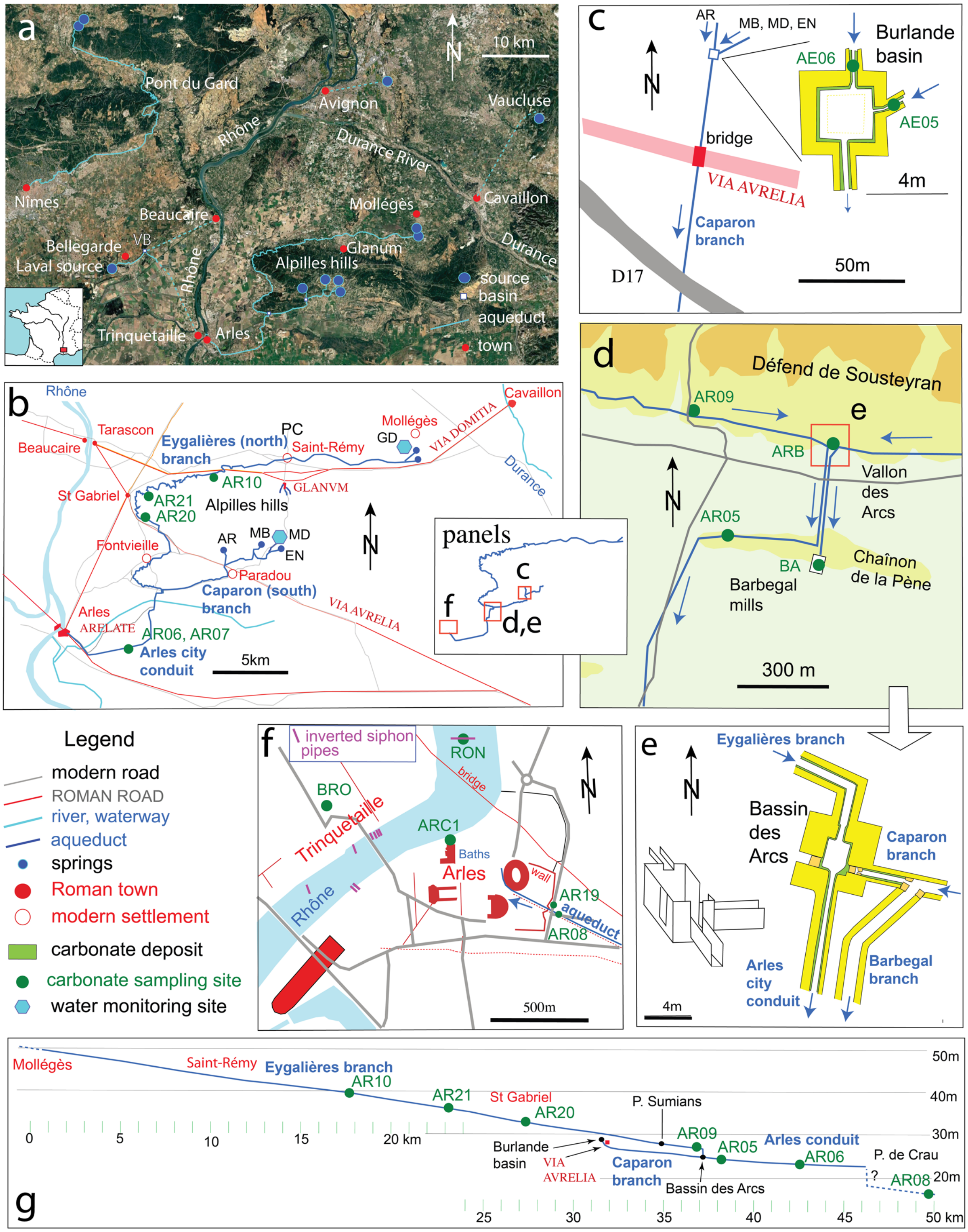

FIGURE 1 | (a) Aqueducts and major springs along the lower Rhône River, as mentioned in this paper. (b–f) Organisation of the aqueducts and water structures of Arles. (b) Location of the aqueducts of Arles and locations and sources mentioned in the text. Sites of carbonate sampling, with sample numbers, in green. (c) Structure and surroundings of the Burlande basin. (d) Junction of the aqueducts of the Arles water system and the Barbegal mills. (e) Structure of the Bassin des Arcs. (f) Track of the Arles aqueduct and inverted lead siphon pipes in Arles. (g) Profile of the aqueduct after Fabre et al. (2023). ARB refers to all samples taken in the Bassin des Arcs, BA all samples from Barbegal. BRO and RON, location of sampled lead pipes; AR, Arcoule spring; EN, Entreconque spring; GD, Grand St Didier spring; MB, Mas Sainte Berthe spring; MD, Mas de la Dame spring; PC, Petite Crau de Saint-Rémy; VB, Valescure basin.

towards Arles, but all traces vanish for the final 10 km (Fabre 2011a). Finally, several large-diameter lead pipes were found under the riverbed of the Rhône in 1570 and 1822 (Figure 1d) (Cochet 1993; Hansen 1992) and again recently, showing that several inverted siphons existed below the Rhône River between Arles and its Trinquetaille quarter on the west side of the river (Long et al. 2013, 152) (Figure 1a,d). The question is whether these inverted siphons supplied the western quarter with water from the Arles aqueduct, as is generally assumed (Cochet 1993), or if they supplied Arles with water from the Bellegarde aqueduct. This is archaeologically crucial, as the latter scenario would imply an increased water demand due perhaps to a rise in population, a drier climate, or the construction of more public water works such as fountains, nymphaea, or baths that could not be satisfied by the Arles aqueduct alone. In this paper, we demonstrate how carbonate deposits can reveal the functioning of the Arles water supply and its transformation in late antiquity, addressing questions related to a changing level of urbanisation, the local society and economy, politics and the long-standing question of the city's connection to the mill complex of Barbegal.

2 | Aqueduct Carbonate Studies

Roman water supply systems are the largest engineering structures remaining from antiquity, and one of the greatest technological achievements of the Roman Empire (Aicher 1995; Ashby 1935; Hodge 1992; Viollet 2007). These spectacular structures can be studied from their architectural remains and from literary sources to draw conclusions about their construction, maintenance and restructuring, but unfortunately, much of their structure is buried and hard to access (Hodge 1992) and little is said in ancient sources on how they functioned or how they were maintained (Deming 2020). Fortunately, aqueduct carbonate survived in many ancient aqueducts to be used as archives. It has long been documented that ancient water systems are encrusted with these anthropogenic deposits (Adolphe 1973; Carlut et al. 2009), but only in the last decades, an effort has been made to investigate them with the modern petrographic and geochemical methods used in the study of speleothems, travertine and riverine tufa, such as SEM/EDS, stable isotope analysis, and trace element investigations (Benjelloun et al. 2023; Sürmelihindi et al. 2021, 2023; Sürmelihindi & Passchier 2023). Such studies show that aqueduct carbonate is different from speleothems, travertine and tufa in fabric and geochemistry, having developed from large volumes of permanently running water in regular-shaped channels in a dark environment and subject to frequent human intervention. The last factor implies that they can be used to understand how ancient water supply systems worked and were sustained and maintained, with downstream samples informing about conditions in upstream sections, even if these are buried or destroyed. Although our team and other scientists have investigated several Roman aqueducts, these were mostly single lines for provincial Roman cities. This study uses modern analytical techniques on carbonate to reconstruct the development of a complex, long-lived, multi-branch aqueduct system of an important ancient city, whose aqueducts were transformed through the centuries.

3 | Materials and Methods

This study is based on carbonate samples that we collected at several sites along the Arles aqueduct system by chisel, angle grinder, or drill corer as part of an on-going research project on aqueducts in Provence and the mills of Barbegal (Supporting Information S1: Appendix A1 and A2). This was expanded for the present work by our re-excavation of the Bassin des Arcs and the bras mort in October 2023. We excavated the basin under the supervision of Philippe Leveau using an excavator and by hand, and 17 new samples were taken from the basin and connected channels. We prepared thin sections and polished slabs of all samples. Optical microscopy was used to identify the carbonate fabric in thin section. The polished slabs were first analysed for stable oxygen and carbon isotope composition, which was followed by trace elements measurements and stratigraphic cross-correlation of samples. Oxygen and carbon isotope analyses were carried out at the University of Innsbruck. Polished slabs of the samples were micromilled at 0.2 mm intervals along a trace 3–5 mm wide and parallel to the lamination. The sample powders were analysed using a semi-automated device (Gasbench II) linked to a ThermoFisher Delta V isotope ratio mass spectrometer. Isotope values are reported relative to Vienna PeeDee Belemnite (VPDB). Long-term precision is better than 0.1‰ for both $\delta^{13}C$ and $\delta^{18}O$ (Spötl and Vennemann 2003). Water samples were analysed in the water chemistry laboratory of the JGU Mainz. Laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) measurements of trace element distribution were performed using an ArF Excimer laser system (ESI NWR193) with an output wavelength of 193 nm coupled to an Agilent 7500ce ICP-MS. Details of the instrumentation and analytical parameters are described elsewhere (Passchier et al. 2016).

4 | Results

4.1 | Water Analyses

The original water sources for the Arles aqueduct remain unknown, as no water-collecting structures have been discovered. Based on the location of the most upstream remnants of the aqueduct and the positions of existing springs, however, the approximate site of the sources was estimated (Fabre et al. 2023). The Caparon branch used at least four small springs along the southern side of the Alpilles (Figure 1b). The Eygalières branch, in its final and longest form, probably carried water from two or more springs in the marshy area near Mollégès (Figure 1a,b). We identified two springs that still flow year-round at or near the sites where the aqueduct probably captured water, tapping into the same aquifers: the Mas de la Dame spring on the Caparon branch (43° 44.272′ N, 4° 49.475′ E) and the Grand St Didier spring on the Eygalières branch (43° 47.374′ N, 4° 55.331′ E) (Figure 1b). Both springs, which may have been used by the Roman aqueducts, were monitored over a 2-year period, taking monthly water samples and measuring temperature, conductivity, pH, and carbonate hardness (Figures 1b and 2a–c). Water samples were analysed for stable isotopes of oxygen, hydrogen and dissolved inorganic carbon (DIC), as well as trace elements (Figure 2a,b). For comparison, the water composition of the Laval spring (43° 45.386′ N, 4° 29.055′ E) associated with the Bellegarde aqueduct was also analysed (Figures 1a and 2a–c).

The stable isotope and trace element composition of the springs on the north and south side of the Alpilles is very different (Figures 1a and 2), with very low $\delta^{18}O$ and δD values on the north side (Grand St Didier), and much higher values on the

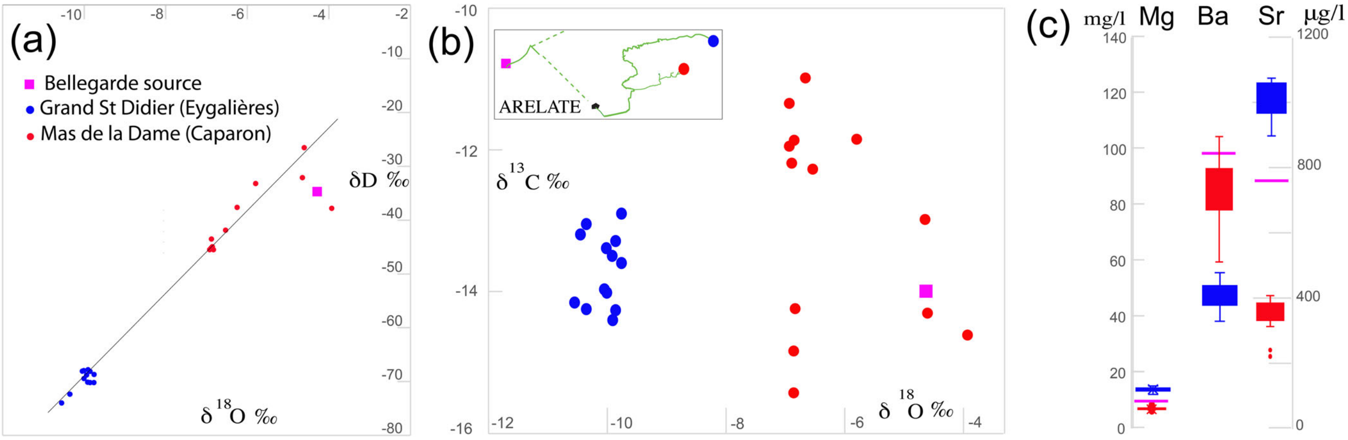

FIGURE 2 | (a–c) Hydrochemical data of two springs, Grand St Didier and Mas de la Dame, on the north and south side of the Alpilles, respectively (Figure 1b), and for the Laval spring of the Bellegarde aqueduct (Figure 1a). Values and sampling dates are given in Supporting Information S1: Appendix 3.

south side (Mas de la Dame). The Grand St Didier spring is one of the 'lauron' springs of the Mollégès plain, which represents a mixture of water from the Durance River, with an Alpine signature, and karst water of Mesozoic limestones of the Alpilles (Fabre et al. 2023). These springs do not lie at the foot of the hills but in the plain to the north of them. The springs of the southern Alpilles, like Mas de la Dame, have isotopic signatures more characteristic of typical karst springs. The Laval spring of Bellegarde also fits into this pattern but drains Pliocene and Pleistocene sediments (Figure 2a–c) (Fabre 2011b). The chemical composition of the water of these three springs is also different, especially with regard to Mg, Ba and Sr (Figure 2c).

4.2 | Carbonate Deposits

Aqueduct carbonate was sampled at several sites along the branches of the Arles aqueduct system and on the Bellegarde aqueduct (Figure 1a,b). In this study, we focus on the Eygalières branch and the Arles city conduit which mainly supplied *Arelate* with water through the interaction of the various aqueducts near the Bassin des Arcs. We present the bulk carbonate composition of the Bellegarde aqueduct deposits, and the possible link to Arles, but not details of this aqueduct's carbonate stratigraphy.

In the Caparon branch (Figure 1b), the first thin deposits become visible after several kilometres downstream of the springs, while deposits up to 18 cm thick are present in and around the Burlande convergence basin (Figure 1c). These deposits are mostly microsparitic and well layered. In the final stretch of the Caparon branch, between the Burlande basin and the Bassin des Arcs, deposits are porous, micritic and poorly layered, and cover the walls and the vault of the aqueduct, showing that it ran full (Leveau et al. 2019; Sürmelihindi et al. 2020). This change in the nature of the deposits from dense microsparitic to porous and micritic carbonate with increasing distance from the springs is attributed to a decrease in slope (Figure 1g) (Fabre et al. 2023) and the mode of use of this section of the aqueduct: it has been proposed that for a period of time, its downstream part served as a reservoir for the mill at Barbegal, with porous carbonate forming in a relatively stagnant water body (Leveau et al. 2019; Sürmelihindi et al. 2020).

In the Eygalières branch, no carbonate was observed upstream of Saint Rémy-de-Provence (Figure 1b), and the first carbonate we could sample was at Dalméran (sample AR10: Figure 1b). Aqueduct carbonate increases progressively in thickness from this point downstream, with maximum thickness in some tunnels along the NW corner of the Alpilles, and generally exhibits high porosity and poorly visible layering. At Pont de Roux (sample AR09: Figure 1d), however, the carbonate fabric is more sparitic and well layered and represents the longest and most complete section of deposit in the Eygalières branch (Figure 3a).

The Bassin des Arcs, where the Caparon and Eygalières branches meet, contains deposits with traces of human intervention that hold the key to understanding the various modifications and adaptations made to the Arles aqueduct system and the reason for them, as outlined below (Figures 1e and 3b–f).

South of the Bassin des Arcs, two adjacent aqueduct bridges cross the 'Vallon des Arcs', the western one carrying the Arles city conduit, and the eastern one supplying the Barbegal watermills (Barbegal aqueduct: Figure 1d). In the Arles city conduit (Figure 1d), carbonate deposits are rather solid on the Chaînon de la Pène stretch, just downstream of the bridges (sample AR05: Figure 1d), but are more porous in the gently dipping last section before the city (AR06) and at its entrance into the city (sample AR08: Figures 1f and 3g). This could be explained by the low velocity of water because of the gentle slope in this part of the aqueduct (Figure 1g).

Fragments of aqueduct carbonate deposits (sample ARC1: Figure 3i) were used as aggregate in concrete to form the roof of the caldarium of the so-called 'Baths of Constantine' in Arles, built in the late third or early fourth century (Figures 1f and 3h) (Heijmans 2004). These fragments were removed from the Arles city conduit as part of a renovation of the aqueduct that was evidently contemporary with the construction of these public baths. A carbonate fragment (AR07) with a similar stratigraphy to that of ARC1 was found outside a manhole shaft of the aqueduct in the Crau plains east of Arles (Figure 1b;

FIGURE 3 | Field observations of the Arles water structures. (a) Typical masonry channel section of the Eygalières branch, at the sampling site of AR09. (b) The Bassin des Arcs, looking south. (c) The Bassin des Arcs showing the feeding and outgoing aqueducts, looking south. (d) View of the 'bras mort', looking north. Clastic sediments were removed, exposing the bottom deposits of unit I and I*, and side deposits of units I*, IV and V. (e) Unconformity at the entry of the Caparon branch into the Bassin des Arcs, looking south, location given in (b). (f) Interpretive drawing of (e). An angular unconformity of unit V covers the partly breached wall that blocked the Caparon branch, and the sediments of units III and IV. (g) Arles city conduit close to where it enters the city of *Arelate*, at the sampling site of AR08. (h) Caldarium of the 'Baths of Constantine', Arles. Aqueduct carbonate fragments were used in the concrete of the vault of the caldarium, arrowed. (i) Masonry block fallen from the roof of the caldarium, consisting mostly of fragments of aqueduct carbonate embedded in mortar, arrowed. Sample ARC1 was sampled from this block. Photos (b) and (c) Philippe Leveau; other photos Cees Passchier. AC, Arles city conduit; BB, Barbegal branch; BM, bras mort; CB, Caparon branch; EB, Eygalières branch.

Supporting Information S1: Appendix Figures A2). This fragment had been removed from the aqueduct channel at around the late third century, since this carbonate stratigraphy no longer exists in the channel itself, where only porous deposits are now present. This suggests that the fragments in the roof of the baths came from this section of the Arles city conduit.

Several sections of large diameter lead pipes found under the riverbed of the Rhône in 1822 (Figure 1f, RON) (Cochet 1993) are on display in the Musée Départemental Arles Antique. Very thin deposits (less than 1 mm) of carbonate were sampled in these lead pipes, and in a lead pipe from a Roman house in Rue de Brossolette in Trinquetaille (BRO.87.00.17, found in 1987) (Figure 1f, BRO). These thin crusts provided sufficient material to obtain individual stable isotope measurements.

4.3 | Bassin des Arcs

The most important water structure of the Arles aqueduct system is the Bassin des Arcs at the junction of the Caparon and Eygalières branches and the start of the Arles city conduit, which underwent frequent transformations (Figures 1e, 3b–d and 4). The basin has dimensions of 1.9 × 2.7 m and is 1.6 m deep (bottom at 24.38 m ordnance datum [NGF]) and has four openings and connections to aqueduct branches. The Caparon branch entered from the east, 17 cm above the bottom of the basin (Figures 3b and 4a) (24.55 m NGF; Leveau 1995, 2011; Guendon 2005). The Eygalières branch, which came from the west, made a sharp turn to flow into the basin from the north, 1.47 m above the bottom of the basin, with a cascade (25.85 m NGF; Figures 1e, 3b,c and 4a) (Leveau 1995). The exit towards the Arles city conduit lies in the south wall of the basin, slightly above the level of the Caparon branch (24.64 m NGF; Figure 4a,b) (Leveau 2011). To the west is a drainage opening, blocked at some stage by a wall. The Arles city conduit runs from the basin over the western bridge across the Vallon des Arcs and on to the city (Figure 1d), while the eastern bridge, which served the Barbegal water-mills, was built later and was connected to the Caparon branch by a jogged leg (Figures 1e, 3c and 4b). In this later phase, the entire flow of the Caparon branch was used to power the mills, and the short section of the Caparon branch between this jog and the basin was closed off by two walls built on top of the original carbonate deposits on the floor of the aqueduct channel, one at the basin side and one at the jog site, so that it no longer functioned to transport water to the city (Figure 4b). This section is referred to as the 'bras mort' ('dead-branch'; Figure 3d) (Guendon 2005).

Carbonate deposits in and around the Bassin des Arcs serve as key elements to determine the changing function of the basin and changes in the water supply of the different aqueducts and the two bridges across the Vallon des Arcs. The basin was excavated first in 1989–1991 (Leveau 1995), and the carbonate deposits of the basin were first studied and published by Guendon (2005). We were able to resample and study the basin in more detail and use different techniques during our re-excavation in October 2023. Figure 4c shows cross-sections of the basin and the carbonate stratigraphic packages around the basin and inside the adjacent aqueducts. Figure 5 shows the microstratigraphy of individual samples, with enlargements in Supporting Information S1: Appendix Figure A2. Locations are given in Figures 1e and 4b. Six main stratigraphic units are identifiable in the Arles city conduit, numbered I–VI; cross-correlation with the two aqueduct branches shows that units I and I* represent water from the Caparon branch, and units II–VI represent flow from the Eygalières branch (Figure 5).

In the Eygalières branch at Pont de la Roux *c.* 500 m before the basin (sample AR09: Figure 1d), approximately 19 cm of carbonate is present in the channel. It consists of stratigraphic units II–VI (Figure 5) with an alternation of distinct microsparitic and micritic laminae (Supporting Information S1: Appendix Figure A4a,b) that can be cross-correlated with samples up- and downstream. The deposits can be divided into two main parts: a dense, well-layered and dominantly microsparitic part; units II–V with thin micritic laminae; and a porous, poorly laminated top; unit VI (Figure 5). Unit VI is almost structureless and perhaps missing minor stratigraphy at the top due to erosion. Some units are further subdivided into *a* and *b* since part of them is missing at some sites. Sample AR09 from Pont de la Roux was chosen as a reference sample, as it is the most complete, and is compared with samples from the exit

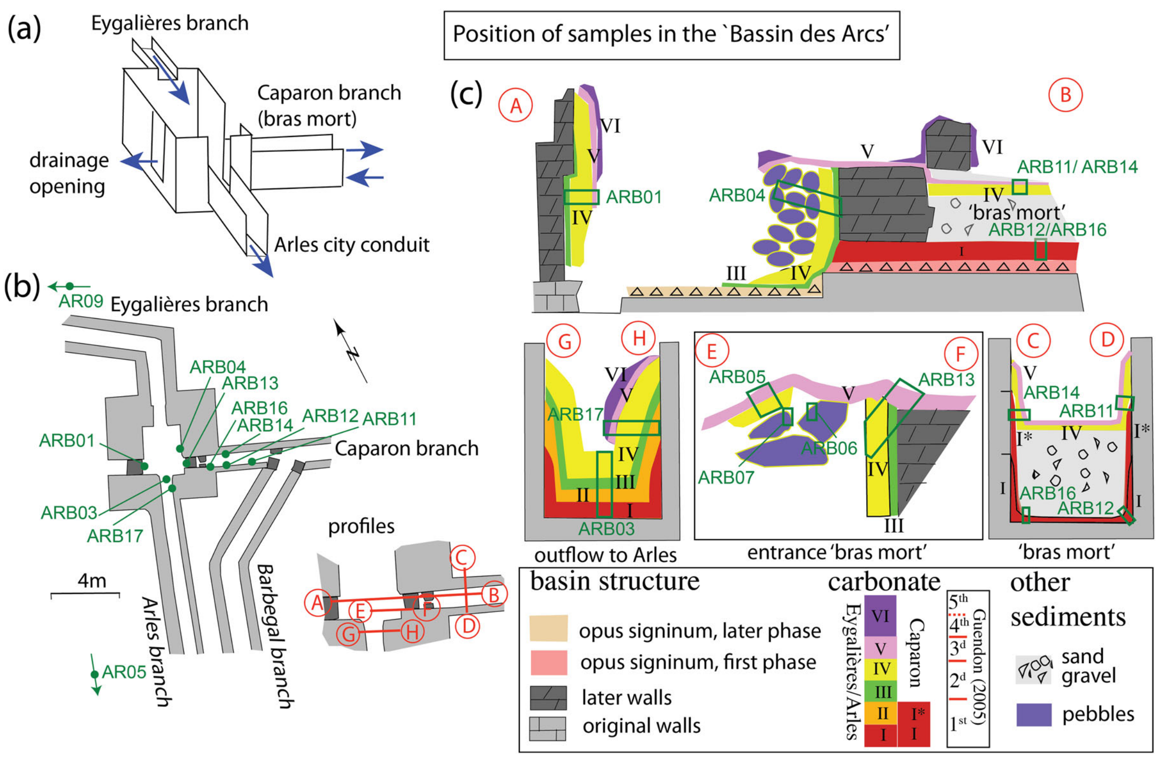

FIGURE 4 | Position of samples taken in and around the Bassin des Arcs. Cross-sections modified after Guendon (2005). (a) 3D diagram of the basin, looking N. (b) Map of the basin and attached channels, with sampling sites of carbonate marked. Traces of cross-sections of (c) shown at right. (c) Cross-sections of the basin with carbonate deposits. Colours indicate stratigraphic packages. The stratigraphic subdivision of Guendon (2005) is shown related to our stratigraphy in the legend.

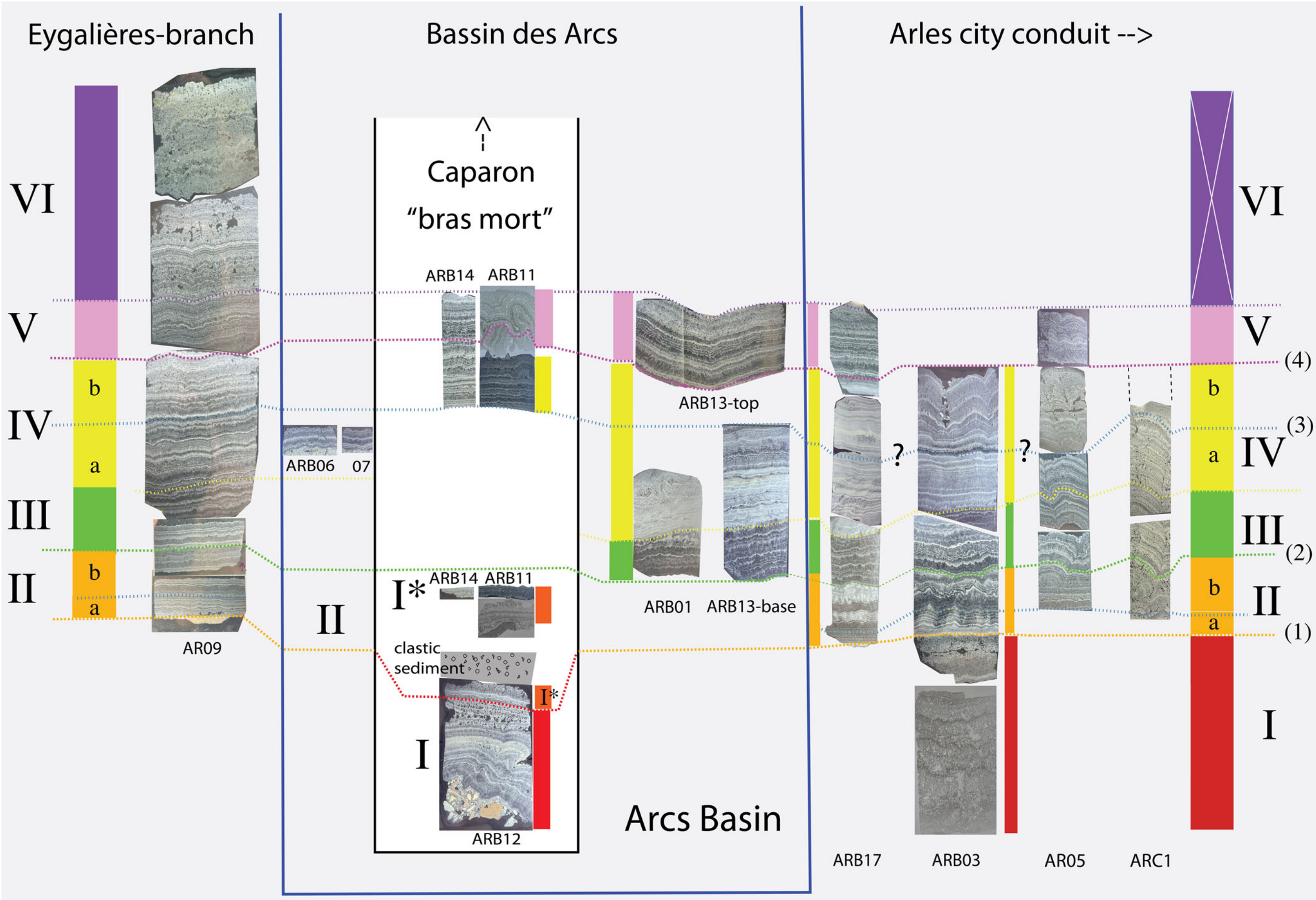

FIGURE 5 | Microstratigraphy of the carbonate deposits from aqueducts of the Arles system and around the Bassin des Arcs. Images show thin sections in plain polarised light. Hypothetical reconstruction of the depositional history on the right with notes (1–4): (1) Eygalières branch starts; (2) start of Barbegal, Caparon branch diverted; (3) first diversion of Eygalières branch water to Barbegal; (4) wall of the 'bras mort' trimmed, more water from the Eygalières branch sent to Barbegal.

of the Bassin des Arcs (ARB03, ARB17) and the Arles city conduit (AR05) (Figure 5). Sample ARB03, at the exit of the basin, preserves a lowermost layer of carbonate, unit I, with a microfabric dominated by algal filaments in porous, poorly laminated micrite, very different from the upper deposits (Figure 5; Supporting Information S1: Appendix Figure A4c). Sample ARB17, from the wall of the Arles city conduit above the channel bottom sample ARB03, lacks these basal deposits of unit I, probably because the water level was initially low (Figures 4c and 5). However, deposits of the Caparon branch in the 'bras mort' and further east contain the same deposits of unit I.

The stratigraphy of sample AR05, downstream of the basin on the Arles city conduit (Figure 1d), is similar to that of AR09, but the lower part of unit II (IIa in Figure 5) and part of IVa are missing, while V is the last recognisable unit (Figure 5). However, unit IIa is present in samples ARB03 and ARB17 at the exit of the basin to the Arles city conduit, showing that the Bassin des Arcs simply transferred water from the Eygalières branch to the Arles city conduit. Missing layers in AR05 may have been locally removed, since the ARC1 sample from the Bath of Constantine also lacks both unit I and unit IIa. Most likely, this cleaning operation was done along the last stretch of the Arles city conduit at the same time. The last deposits of Unit VI of AR09 cannot be found in either the Bassin des Arcs or in the Arles city conduit and therefore must have been removed almost everywhere. Hence, sample AR09 is the most complete and serves as a master sample for our study.

Several carbonate samples were taken in the Bassin des Arcs itself (ARB01, ARB04, ARB13) and in the so-called 'bras mort' (ARB11, ARB12, ARB14) (Figures 4b and 5, Supporting Information S1: Appendix Figure A2). In the basin itself, no deposits older than unit III are present (Figures 4 and 5), which can be explained by cleaning, deepening of the basin, and the application of a new layer of *opus signinum* to the bottom of the basin just before deposition of unit III (Guendon 2005). At the same time, the Caparon branch was blocked by walls and the 'bras mort' was created, probably associated with the building of the deviation to the Barbegal mills (Leveau 1995). An as of Trajan in mint condition, dated 103–111 CE, was found in the mortar of the freshly laid floor of the basin predating carbonate unit III, and indicates a *terminus post quem* for this reconstruction work (Leveau 1995; Leveau et al. 2000, page 419 monnaie n°4).

Carbonate deposits in the Bassin des Arcs are unusual, in that they show considerable variations in density, with units III and V consisting of dense sparitic calcite and deposits of unit IV consisting of white porous micritic calcite with remains of biofilms (Figure 6; Supporting Information S1: Appendix Figure A2). A deposit of clastic sediment including large pebbles of Mesozoic limestone up to 0.4 m in diameter, and of fragments of older basin- or aqueduct carbonate, was found in the basin, covering the top part of unit IV and being covered by unit V (Figure 4c). Each pebble is coated by a thin veneer with part of stratigraphy IV (samples ARB06, ARB07), indicating that they were deposited in the basin late during the deposition of unit IV (Figure 4c; Supporting Information S1: Appendix Figure A2-2).

The 'bras mort' of the Caparon branch contains at its base initial deposits of the Caparon branch, predating the construction of the walls that close it off at both ends (Figure 3d, ARB12, ARB16 in Figure 4c) (Guendon et al. 1991; Guendon 2005). These deposits are in two layers. The lower layer (I) covers the walls until 0.47 m from the bottom, while the upper layer (I*) covers the walls up to a height of 0.9 m, indicating a significant rise in water level in the Caparon branch (Figure 4c, section c–d). These deposits were covered by the walls closing off the 'bras mort' and by sand and gravel between the two walls (Figure 4c, section c–d). These clastic sediments were then in turn covered by new carbonate deposits consisting of the top of unit IV (IVb) and unit V (ARB11 and ARB14 in Figure 3d), indicating that at this stage, water from the Eygalières branch was diverted to Barbegal. This new carbonate also covers the older, thin carbonate film (unit I*) that was deposited high on the walls of the channel, predating the clastic sediment filling (Figure 4c, section c–d). Unit I* has similar composition and microfabric to unit I, but is of the same age as unit II of the Eygalières branch since it predates unit III.

The walls that closed off the 'bras mort' were lowered at a later stage to let water flow from the Bassin des Arcs to Barbegal. This happened first during deposition of unit IVb since deposits of this unit are present in samples ARB11 and ARB14 in the 'bras mort' (Figures 4c and 5; Supporting Information S1: Appendix Figures A2–3). Later, the top of the breached walls was further lowered and covered by unit V in a roughly hewn angular unconformity that affects the wall and units III and IV that covered the wall on the basin side (Figures 3e–f and 4c).

4.4 | Stable Isotope and P (Phosphorus) Profiles

The stable isotope composition of carbonate deposits was measured in nine samples along the aqueducts of the Arles water system (Figure 6). A full profile representing units II–VI was measured for AR09 from the Eygalières branch, the most complete sample, while partial profiles were measured for other representative samples. The stable isotope profiles show a distinguishable and prominent periodicity, and comparison of isotopic profiles from different samples was used to confirm and partly justify the correlation of microstratigraphic units based on correlation of the visible layering. Notably, unit III can be traced from the Eygalières branch (AR09) through the basin (ARB13) to the exit of the Bassin des Arcs (ARB03), and in the deposits from the roof of the 'Baths of Constantine' (ARC1) (Figure 6).

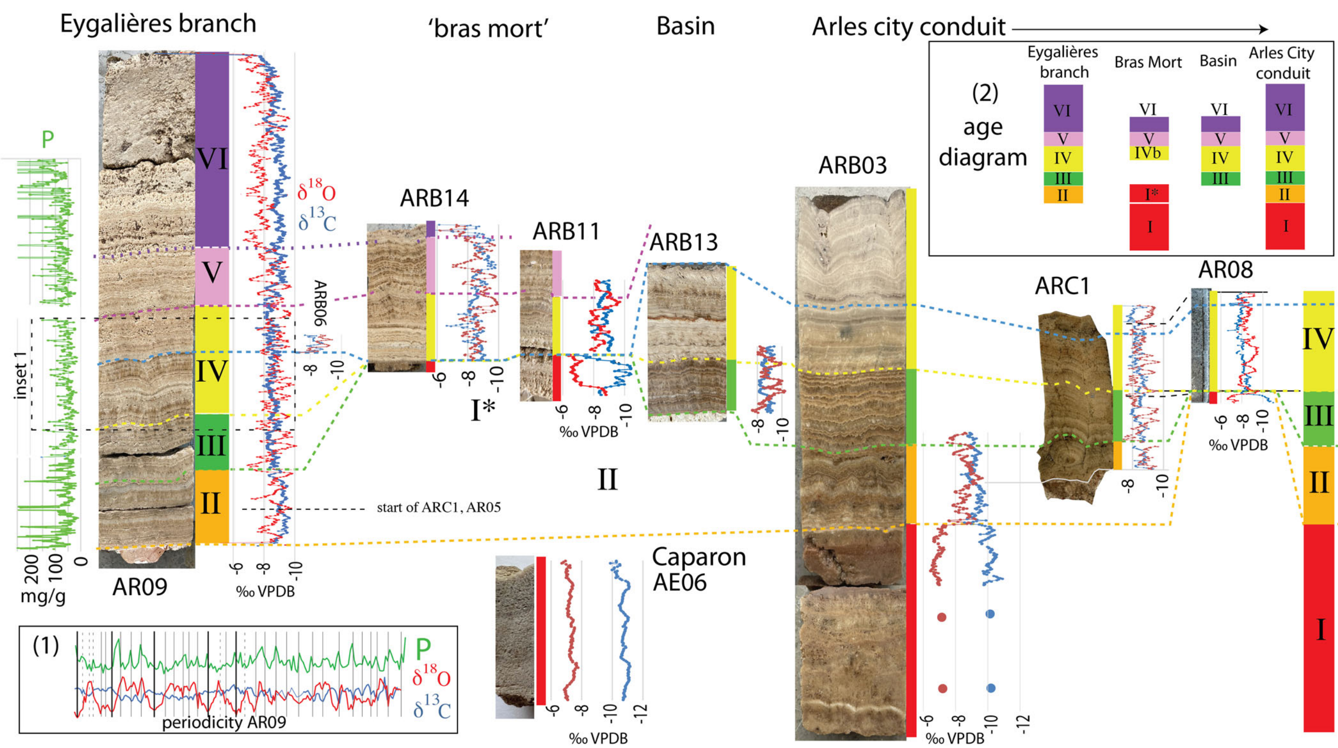

FIGURE 6 | Polished carbonate samples and stable isotope profiles for the Eygalières branch (AR09), Caparon branch (AE06) and selected samples from the 'bras mort', the 'Bassin des Arcs' and from the Arles city conduit, including a sample from the roof of the Baths of Constantine (ARC1). The profile for phosphorus (P) is shown for parts of AR09. Inset (1) shows short- and long-term periodicities in values of $\delta^{18}O$, $\delta^{13}C$ and *phosphorus* for the central sector of AR09 (units II–VI). Inset (2) shows the relative age of stratigraphic units in each branch. Enlarged images of samples in Supporting Information S1: Appendix Figure A2.

The periodicity of $\delta^{18}O$ in AR09 shows peculiar, irregular and long-term cycles throughout the sample, and together with $\delta^{13}C$, sometimes more regular short-term cycles, where these short cycles have the same length for both isotopes (Figure 6, inset 1). Trace element measurements of P (Phosphorus) in AR09 show a comparable short-term regular periodicity (Figure 6, inset 1). These short-term regular periodicities in P, $\delta^{18}O$, and $\delta^{13}C$ may represent annual variations in temperature of source water, rainfall, and degassing rate, water temperature and residence time in the aqueduct channel (Figure 6) (Sürmelihindi, Passchier, Baykan, et al. 2013, Sürmelihindi, Passchier, Spötl, et al. 2023; Sürmelihindi & Passchier 2023).

Besides the periodic variations in stable isotope values, the absolute values of $\delta^{18}O$ and $\delta^{13}C$ are significantly different for the lower (units I and I*) and upper parts (units II–VI) of the stratigraphy. Units I and I* have more positive $\delta^{18}O$ and more negative $\delta^{13}C$ than upper units and are similar to $\delta^{18}O$ and $\delta^{13}C$ of carbonate in the Caparon branch, represented by the lower part of ARB11 and the upstream sample AE06 from the Burlande Basin (Figures 1c, 6 and 7d).

To reveal the significance of differences in stable isotope composition between the different branches of the Arles aqueduct and the Bellegarde aqueduct, we plotted $\delta^{18}O$ versus $\delta^{13}C$ for the different branches in Figure 7b–d. Carbonate from the Eygalières- and Caparon branches, the Arles city conduit, and the Bellegarde aqueduct all show distinct values. Figure 7e compares mean stable isotope values of carbonate from the Arles aqueduct system with values from other Roman aqueducts in southern France.

5 | Discussion

5.1 | Water and Carbonate Stable Isotopic Composition

The stable isotope and trace element composition of water of the two monitored springs reflects the different characteristics of two aquifers (Figure 2). The Mas de la Dame spring of the Caparon branch is fed by karst water from the Alpilles, while the Grand St Didier spring of the Eygalières branch is fed by mixed water from the Alpilles karst system and the Durance River, which derives most of its water from high catchments in the Western Alps (Figure 1b) (Fabre et al. 2023). This is supported by the observation that carbonate from the Eygalières branch shows a more negative $\delta^{18}O$ signature than most other aqueducts in southern France (Figure 7e): it is comparable only with values from Vaison-la-Romaine, an aqueduct with springs derived from high-altitude catchments of the Mont Ventoux. The difference in source water composition is reflected in the stable isotope composition of carbonate deposits in each aqueduct branch (Figure 7b), and this makes it possible to determine the origin of the water supplied to the city of Arles and its western quarter of Trinquetaille.

Samples from different parts of the Arles water system show systematic variations (Figure 7c,d). Samples from the Barbegal water-mills overlap with the values of both the Eygalières (e.g., AR09) and the Caparon branches (e.g., AE05) (Figure 7c,e), indicating that the mills were supplied by both sources during parts of their history. Samples from the Eygalières branch and the Arles city conduit (AR10, AR09, ARB03, AR08) show $\delta^{13}C$ values that increase from the upstream (AR10) to the downstream (AR08) samples, owing to progressive carbon dioxide degassing along the aqueduct line (Figure 7d) (Sürmelihindi, Passchier, Baykan, et al. 2013). Samples ARB03 and AR08 show an overlap with values of the Caparon branch (Figure 7d, inside dashed polygon), but this relates to unit I in the lowest part of their stratigraphies.

The irregular, long-term cycles in $\delta^{18}O$ in sample AR09 (Figure 6, inset 1) may be related to original variations in water composition, for example, due to variable contributions of water from the Durance and local karst water on long-term timescales (Figure 1a,b), but also to long-term climatic trends.

Since the difference in spring water composition is reflected in the stable isotope composition of the carbonate deposits in each aqueduct branch (Figure 7b), we can propose a hypothetical detailed reconstruction of changes in the water management of the Arles aqueduct system over time. The Bassin des Arcs was a key location for this reconstruction.

5.2 | Management of and Modifications to the Arles Aqueduct

Based on the carbonate microstratigraphy presented in Figures 5 and 6, nine operational stages can be distinguished in the Bassin des Arcs and connected aqueduct branches (Figure 8), with details being still further explored.

The oldest carbonate (unit I) is present in both the Caparon branch ('bras mort', ARB12, ARB16) and the Arles city branch (ARB03) (Figure 5) showing that initially the Caparon branch was the only source of the Arles city conduit (Figure 8a). The Eygalières branch was not yet connected to the Bassin des Arcs, and the basin acted as the header tank for the Vallon des Arcs bridge. The tank was of the classical type, built of large ashlars, with an outlet on the west side to enable water flow over the bridge to be shut off in times of maintenance. Porous micritic carbonate, rich in algal filaments, was deposited (unit I), representing the water composition of the Caparon springs and low flow discharge and flow speed (Supporting Information S1: Appendix Figure A4c).

Carbonate of unit II forms the first deposits in the Eygalières branch and covers the deposits of unit I in the Arles city conduit (samples ARB03, AR05) (Figures 5 and 6). This implies that the Eygalières branch was connected to the north side of the basin in a second phase (Figure 8b). The branch entered the basin at a much higher elevation than the Caparon branch, dropping water into it from a height of 1.5 m above the floor. The addition of the new branch was associated with a rise in water level in the basin and in the Caparon entry, visible in the 'bras mort' where younger deposits (unit I*) reach higher on the wall (Figures 4c, 5 and 6) (Guendon 2005). These unit I* deposits, with the same composition as unit I, must therefore be of the same age as unit II in the other channels. The header tank was

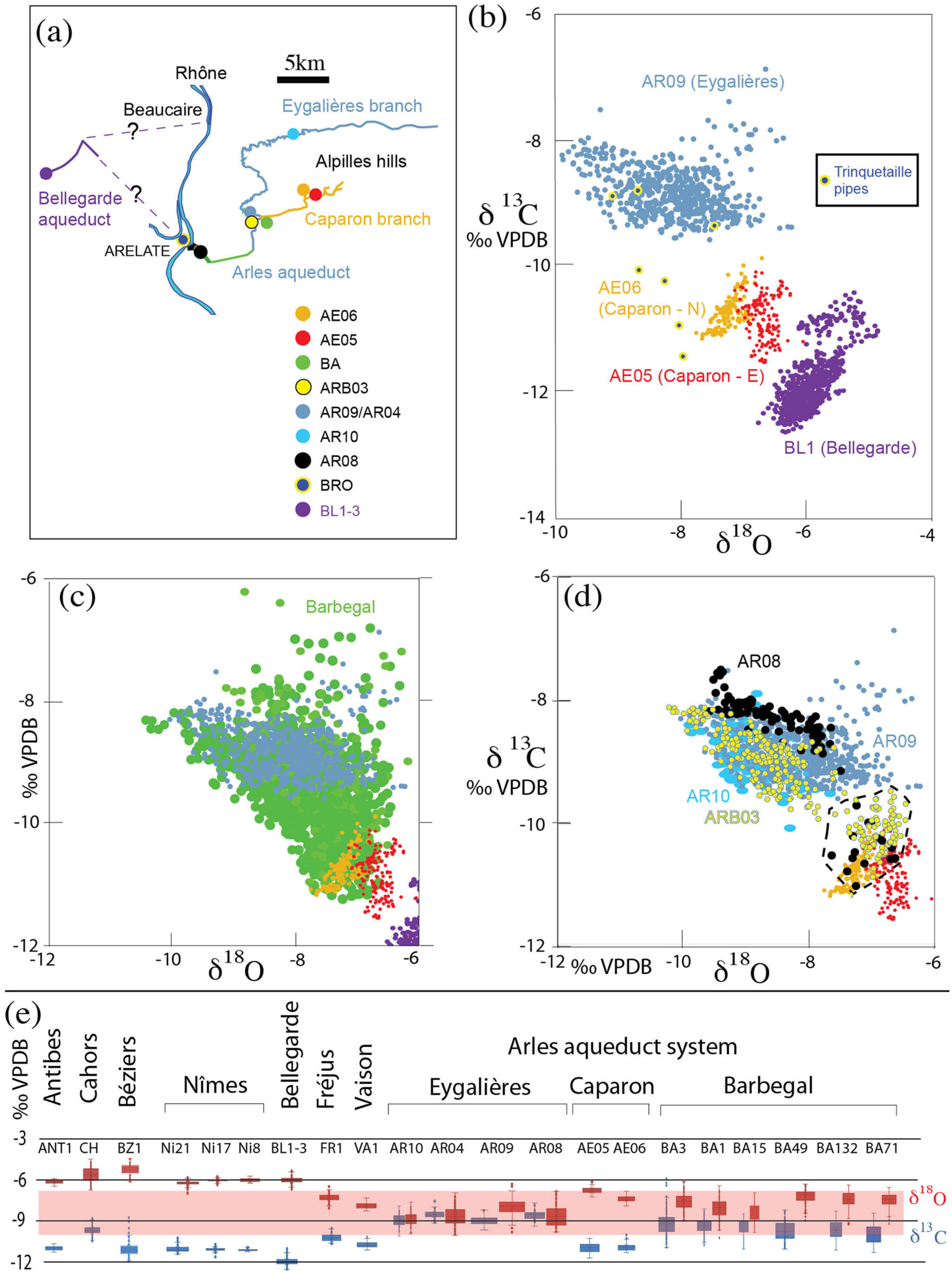

FIGURE 7 | (a) Location of carbonate samples analysed. (b) $\delta^{18}O$ – $\delta^{13}C$ values of samples analysed from various components of the Arles aqueduct system and Bellegarde. (c) The same diagram with superimposed values of carbonate from the Barbegal mill complex (green). (d) Upper part of the same diagram as (b) with results from samples of the upstream Eygalières branch (AR10), the start of the Arles city conduit at the basin (sample ARB03), and the entrance to the city of Arles (AR08). The dashed polygon outlines the composition of unit I deposits at the base of samples ARB03 and AR08, which are thought to have formed from water of the Caparon branch. (e) $\delta^{18}O$ and $\delta^{13}C$ values of samples analysed from the Arles aqueduct and from other aqueducts in southern France. The red bar shows the $\delta^{18}O$ value range of the Eygalières branch.

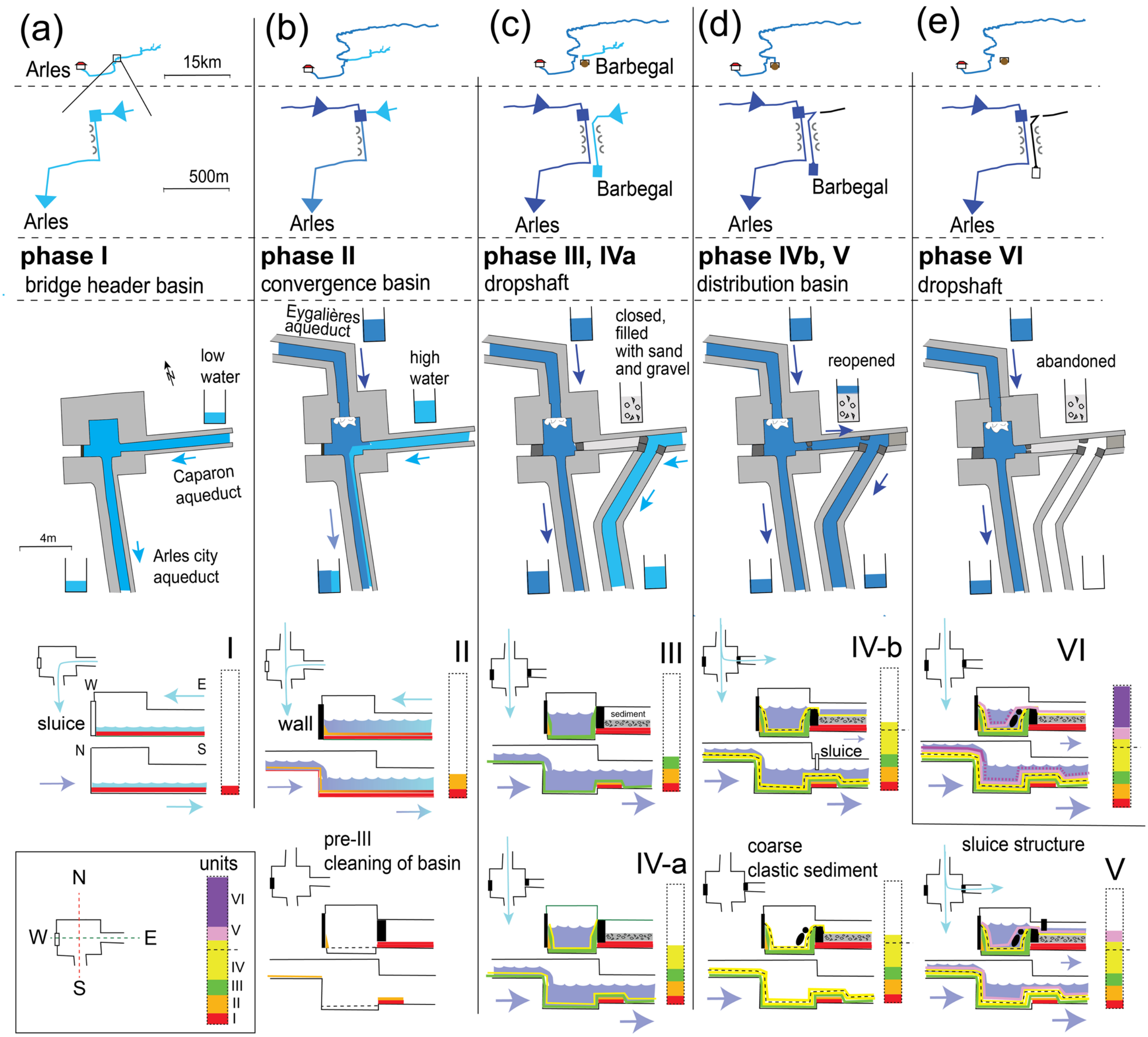

FIGURE 8 | (a–e) Transformation of the aqueduct of Arles and the Bassin des Arcs. The top part of the diagram shows a plan view of the water supply system. The lower part of the diagram shows carbonate deposits in cross-sections of the basin and adjacent aqueducts. Two orthogonal cross-sections are shown for the basin in each phase. Colour codes refer to the stratigraphic packages of samples in and around the basin, with some minor simplifications. Basin and channel dimensions are not to scale.

therefore transformed into a convergence basin for the two aqueducts (Figure 8b). The rise in water level was due to the added discharge of the Eygalières branch but may have been aided by a modification in the Arles city branch, since a higher water level reduced the danger of erosion of the basin by the cascading water from the Eygalières inlet. The idea that the Eygalières branch was attached to the basin in a secondary phase is also supported by the unusual placement of its entrance, with a considerable height difference compared to the Caparon branch and an unusual arrangement, bending sharply to enter from the north (Figures 3b,c and 4b). The geometry of the basin and the linked aqueducts, therefore, suggests that its use as a convergence basin was an improvised modification of a header tank to a bridge.

Although the Caparon and Eygalières branches supposedly both contributed to the water supply of Arles during deposition of unit II, we found no evidence for the mixing of water of different composition from both branches in the stable isotope and trace element composition of the carbonates, when comparing samples AR09 (Eygalières branch) and ARB03 (Arles conduit) (Figure 6).

In the next stage, a drastic series of modifications was made (Figure 8c): the basin was made 10 cm deeper, deposits of unit I and II were removed from the walls and bottom, the bottom was replastered, and the western outlet and the inlet of the Caparon branch were walled up (Figures 4c and 8c). In other words, the Eygalières branch was now the only aqueduct supplying the city of *Arelate*, and the basin was transformed from a convergence basin into a header tank for the aqueduct bridge and an effective dropshaft for this aqueduct. The Caparon branch was now diverted across a new, parallel arcade over the Vallon des Arcs to power the Barbegal water-mill complex. Following this modification, a distinct sparitic carbonate layer (unit III) was deposited on the bottom and walls of the basin, including the wall closing off the Caparon branch and the former western outlet opening (samples ARB03, ARB13) (Figures 5, 6 and 8c).

Previous studies related the construction of the Barbegal mill complex and the deposition of unit III to an extension of the Eygalières branch from springs in the vicinity of Fontvieille to the Laurons of Mollégès (Leveau 1995; Sürmelihindi et al. 2020; Fabre et al. 2023). However, we see no change in stable isotope or trace element composition in the carbonates of the Eygalières branch between units II to III (Figure 6). Moreover, unit II is already present in the upstream samples AR20 and 21 (Figure 1b,g; Supporting Information S1: Appendix Figure A2-1). It is therefore more likely that the Mollégès springs supplied the Eygalières branch from the very start of its operation.

The prominent sparitic carbonate unit III is followed in the basin by more micritic deposits of unit IV (Figures 5, 6 and 8c). At some stage during the deposition of unit IV, the wall across the 'bras mort' to the Barbegal mills was breached to let water from the basin run towards Barbegal, reversing the direction of flow in the 'bras mort' and turning the Bassin des Arcs into a distribution basin (Figure 8d) (Guendon 2005). This is known because upper deposits of unit IV (unit IVb) are found at the base of the stratigraphy on top of the sandy deposits in the 'bras mort' (samples ARB11, ARB14) (Figures 4c and 5). At the same time, a sluice gate was installed at the exit of the basin towards Arles (Figure 8d-IVb) (Guendon et al. 1991; Guendon 2005). Towards the end of the deposition of unit IV, clastic sediment including large stones was deposited in the basin, filling up the SE corner (Figure 8d). Most of these stones are rounded limestone pebbles, covered with a thin layer of carbonate that seems to be part of the stratigraphy IV (Figures 4c and 6; ARB06). It is unclear whether these sediments were deposited in the basin by a natural event due to flooding or damage to the channel upstream or by human intervention, for example, as rip-rap to prevent erosion. Next, the wall separating the basin and the 'bras mort' was lowered further by at least 15 cm (Guendon et al. 1991), probably to increase water flow towards the mills. This was done by rough and irregular chiselling, leaving a ragged edge for the water to flow over (Figure 3e,f). Water then flowed across the barrier, depositing the prominent sparitic layer V (Figures 3e,f, 6 and 8d). Two blocks, part of a small arch, were placed in the 'bras mort' during deposition of unit V to narrow the channel and to regulate and reduce its water flow to some extent (Figures 3d and 8d-V) (Guendon et al. 1991; Guendon 2005). The stratigraphy of unit V was recognised in the 'bras mort' (ARB11, ARB14), in samples from the basin (ARB13, ARB05) (Figure 4c) and in sample ARB17 taken from the wall of the Arles city conduit, at the exit of the basin (Figure 5). This shows that water was still flowing towards both Barbegal and Arles at this stage. The sluice gate that operated at the exit of the basin towards Arles in stage IV was removed, and its grooves were covered by deposits of unit V (Guendon et al. 1991).

The final chapter of the aqueduct's operational history was the deposition of porous carbonate, initially still layered with some microsparite but later porous, micritic and structureless (unit VI) (Figures 5, 6 and 8e). This change in the carbonate fabric reflects poor maintenance of the channel structure which finally led to the abandonment of the entire system. Deposits of unit VI have so far been recognised in the Eygalières branch (AR09, AR21; Figure 5) and in the Arles city conduit (sites of AR06 and AR19) (Figure 1; Supporting Information S1: Appendix Figures A2–4). These late deposits are hard to interpret and are easy to erode, being soft and friable. Flow to Barbegal had possibly stopped at this stage (Figure 8e), and the basin was once again a header tank and dropshaft but no deposition of unit VI was found here.

5.3 | Reconstruction of Changes in the Arles City Conduit

Carbonate slabs that were found to be reused as aggregate in the roof of the 'Baths of Constantine' in Arles (ARC1) contain unit III and parts of units II and IV (Figure 5). A sample of carbonate (AR07) found beside an access shaft to the Arles city conduit in the plain to the east of the city (Figure 1) seems to have similar stratigraphy to ARC1 (Supporting Information S1: Appendix Figures A2–5), suggesting that carbonate slabs for the roof of the baths were quarried from the Arles city aqueduct here, probably in an effort to clean the aqueduct in preparation for its rehabilitation as a water supply to the new 'Baths of Constantine'. AR07 (Supporting Information S1: Appendix Figures A2–5) contains some additional, younger layers, indicating that the stratigraphy of ARC1 is incomplete. The aqueduct below the access shaft where the fragment was found seems to contain only porous micritic carbonate (AR06), probably of unit VI, confirming this hypothesis.

5.4 | Other Water Elements

The stable isotopic composition of carbonate deposits in the lead pipes found in the bed of the Rhône at Arles (Figure 1g, RON) and from the Roman house in Rue de Brossolette in Trinquetaille (Figure 1g, BRO) corresponds to the water from the Eygalières branch and possibly the Caparon branch of Arles, and not to the Bellegarde aqueduct (Figure 7b). This means that this inverted siphon below the Rhône River provided Trinquetaille with water from the Arles aqueduct and did not flow in the other direction. This had already been suggested (Cochet 1993; Leveau 2011) but can now be confirmed with our carbonate analyses. Although no remains of an aqueduct connection have been found, the Bellegarde aqueduct may still have supplied other parts of the Trinquetaille quarter with water. If any anthropogenic carbonate is found in future on the west bank of the Rhône or in siphon pipes from the river, the geochemical characteristics of carbonate derived from the three main water supply branches, presented in Figure 7, could serve to test this hypothesis.

5.5 | Possible Age of the Carbonate Deposits and Their Removal

The dating of the events described above is partly constrained by archaeological documentation. Since it is suggested that the Caparon branch of the original Arles Roman aqueduct system was built around 3 BCE (Paillet 2011; Fabre et al. 2023), it provides an Augustan date for the base of unit I of the carbonate deposits and the functioning of the Caparon branch, the original supplier to the Arles city conduit. A further date is suggested by the 'as of Trajan' found below deposits of unit III, implying a *terminus post quem* for these deposits of 103–111 CE, and an earliest possible date for the start of operation of the Eygalières branch and the mills of Barbegal. Further coins of Antonine date were found in unit IV in the basin, while the sandy deposits of the 'bras mort' contained ceramic fragments datable to the first century (Leveau et al. 2000; Leveau 2011). A single coin of Constantius II (348–351 CE) found in the basin shows that it was still active in the mid-fourth century (Leveau 2011). Since deposits of units II–IV (Figure 6) are present in the samples that we found in the roof of the 'Baths of Constantine', built in the late third or early fourth century (Heijmans 2004), these deposits must be older. However, the samples are probably incomplete and may have included younger units as seen in AR07. As we discovered these pieces of aqueduct carbonate in the concrete of the baths, we associate them with the rehabilitation of the aqueduct for the public water works in the city and suggest that the 'Baths of Constantine' must have been supplied by aqueduct water, although the connection to the aqueduct has not yet been found. The importance of Arles as an imperial residence in the fourth century and later as Praetorian Prefecture of the Gauls (from 395 CE onwards) suggests that the aqueduct remained in service for over 400 years.

At present, no absolute ages have been established for the carbonate deposits in the aqueduct branches, but stable isotope and phosphorous (P) profiles (Figure 6) show a periodicity that is interpreted to be annual, providing a tool to assess the age of the events sketched above. Up to ~160 cycles in P and $\delta^{18}O$ could be counted in the deposits of AR09, significantly fewer than the active period for the aqueduct suggested by our data presented here. Combining archaeological data and our carbonate findings, we nevertheless attempt to introduce a dating for the management of the Roman and late antique aqueduct of Arles.

Counting cycles of $\delta^{18}O$ and P periodicity, sample AR09 shows a minimum of 16 and a maximum of 24 cycles in unit II; 12-18 cycles in unit III, 18–40 cycles in units IV; 14–18 cycles in unit V, and 40–67 cycles in unit VI (Figure 6). $\delta^{18}O$ and P profiles could not be analysed all the way to the preserved top of sample AR09 because of its porosity, and the sample may have lost material at the top, so that the number of years represented by unit VI remains uncertain.

If unit III started late in the reign of the Emperor Trajan or early in the reign of Hadrian, the Eygalières branch would have started operating at the end of the first century CE. This leaves less than a century for the sole operation of the Caparon branch (represented by unit I) to supply Arles if it started operating in 3 BCE. The small number of cycles counted in units III and IV suggests that the first opening of the wall between the basin and the Barbegal mills already took place in the middle or late second century CE and the lowering of the wall at the onset of unit V in the late second century. The base of deposits VI could then date from the first half of the third century.

The Barbegal mill complex continued in operation until at least the early third century, using water from the Caparon and later the Eygalières branches (Figure 8c). After the abandonment of the mill complex, other activity was suggested on the site until the mid-fourth century (Leveau 1995; Leveau et al. 2000). The youngest coins found at the site are from 348/351 CE, and it has been suggested that activity ceased after the revolt of Magnentius in 353 CE (Leveau et al. 2000). Some carbonate fragments derived from wood of the Barbegal mills confirm a stable isotope signature of the Eygalières branch (Figure 7c).

Since the 'Baths of Constantine' must have been supplied by the aqueduct, their period of use might correspond to an extended unit VI, but this is uncertain and not proven by archaeological survey. Restoration of the aqueduct fits well with the prosperous period at Arles under the Emperor Constantine (Loseby 1996; Underwood 2019). The aqueduct could then have functioned for another 100–130 years, at least until the mid-fifth century, when a large *natatio* was added to the Baths. We believe that the use of the aqueduct came to an end at the latest with the Franks and Burgundians invading southern Gaul (Heijmans 2004).

5.6 | Reasons for Modification

Based on the established course of events, we can make some deductions about the reasons for the modifications observed. Arles was originally provided with water only by the Caparon branch in the Augustan period, and the Eygalières branch was added nearly a century later. The main reason to add the Eygalières branch was probably increased water demand in Arles and the construction of public buildings, including baths, by the late first century. Since the four inverted siphons in the Rhône, with a considerable water demand, date from the late first-/early second century (M. Heijmans, Ph. Leveau, pers. comm.), the need to supply the Trinquetaille quarter may have been an additional reason for the reconstruction. Moreover, the water supply of the Caparon branch was probably not satisfactory, as its quantity fluctuated during the dry Provençal summers (Guendon 2005; Leveau 2011, 2018).

In the early second century at the latest, the Caparon branch was disconnected from the city supply and was used to supply the newly constructed Barbegal water-mill complex. Presumably, it was realised that the abundant flow of the Eygalières branch, which was more reliable during the summer, was sufficient to supply the city. However, later, the Eygalières branch had to supply both to the city and the mill complex.

6 | Conclusions

The water management of Arles over the course of the Roman period shows a complex history of adaptations and maintenance, as indicated by the analysis of carbonate microstratigraphies within its water supply system. This leads to the following conclusions:

1. The stable isotope and trace element composition of aqueduct carbonate from the channels of the two main branches of the Arles aqueduct system (Eygalières and Caparon), and the Bellegarde aqueduct differ significantly, reflecting the different composition of their water sources. These differences allow reconstruction of the modifications made to the components of the Arles aqueduct system, their relative timing, their relation to the water-mills of Barbegal, and their connection to the ancient urban centres of Arles and Trinquetaille.
2. In its original form, the Arles aqueduct, built in 3 BCE, was supplied solely by the Caparon branch, while the Eygalières branch was added only in the late first century CE, due to increasing water demand.
3. In the early second century CE, the Caparon branch was detached from the Arles water supply system and used to supply the newly built mills of Barbegal, probably due to the low and irregular discharge of the Caparon branch springs, while the discharge of the Eygalières branch was decided to be sufficient to supply the city of Arles.
4. After some decades, water from the Eygalières branch was led to the Barbegal mills as well as to Arles.
5. Stable isotope analysis shows that Trinquetaille was supplied with water through lead pipes laid across the bed of the Rhône from the Arles aqueduct. There is no evidence that the Bellegarde aqueduct supplied either Trinquetaille or Arles with water.
6. The aqueduct of Arles underwent a significant rehabilitation programme in the late third or early fourth century, shown by aqueduct carbonate deposits reused as aggregate in the vaulted roofs of the Baths of Constantine in Arles. No comparable late antique cleaning or maintenance programme is known from nearby aqueducts in Provence, such as Nîmes, Béziers, or Fréjus. The crucial factor at Arles seems to be the imperial interest in the city in the early fourth century and the ambitious building programmes initiated by the Emperor Constantine.
7. Carbonate deposits in aqueduct systems with multiple water sources can help to reconstruct complex histories of use if the water sources used are sufficiently geochemically distinct. In any case, aqueduct carbonates are promising archives to understand functioning and sustainability of ancient water systems.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.