PNAS RESEARCH ARTICLE | SOCIAL SCIENCES
EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES

Seeing Roman life through water: Exploring Pompeii's public baths via carbonate deposits

Gül Sürmelihindi[a,b,1,2], Cees Passchier[b,1], Monika Trümper[c], Thomas Heide[c], Christoph Spötl[d], Denis Scholz[b,1], Michael Weber[b,1], and Friedrich Hawemann[b,1]

Affiliations are included on p. 10.

Edited by Panagiotis Karkanas, American School of Classical Studies at Athens, Athens, Greece; received July 9, 2025; accepted November 23, 2025

The ancient city of Pompeii, destroyed by the eruption of Mt. Vesuvius in AD 79, shows technological improvements to its water supply after becoming a Roman colony. Its inhabitants relied on wells for their water supply prior to the installation of a Roman aqueduct. Carbonate incrustations deposited in various components of the city's hydraulic infrastructure, including the aqueduct, its water towers, the well shafts, and pools of the public baths. The stable isotope and trace element composition of these carbonates differ markedly between structures supplied by wells and those fed by the aqueduct, reflecting the contrasting origins of their source waters. While the aqueduct was fed by karst springs, the wells tapped into highly mineralized groundwater from volcanic deposits. These geochemical distinctions allow for a detailed reconstruction of Pompeii's water management system, particularly the transition from well- to aqueduct-based water supply. The periodicity of $\delta^{13}C$ variations in carbonate crusts sampled from well, pools, and drainage channels of the Republican Baths offers insights into the operation and maintenance of the facility. $\delta^{13}C$ values show a sharp drop from wells to bathing pools, suggesting contamination by human waste and implying that the bath water was not regularly replenished in the Republican Baths.

Pompeii | anthropogenic carbonate | Roman aqueduct | ancient water management | baths in classical antiquity

Significance

Anthropogenic carbonate deposits from the baths and aqueduct of Pompeii provide insights into water use and changing operational conditions of Roman public baths. Bathing facilities were originally supplied by deep wells, which relied on water-lifting devices to meet demand. These mechanisms underwent a series of modifications and technological improvements before being replaced by an aqueduct in the first century AD. The microstratigraphy and geochemical signatures of carbonate incrustations preserved in wells, baths, and the aqueduct provide valuable information about the hygienic conditions of the baths, technological improvements, and the transition from water-lifting to gravity flow. Anthropogenic carbonates serve as key archives for reconstructing Roman bathing conditions and ancient water management systems, highlighting their significance as elements of cultural heritage.

Public baths were an important aspect of Roman culture, and bathing culture evolved with the growth of the Roman Empire and its wealth. This development can be traced especially well in the ancient city of Pompeii (Fig. 1 *A* and *B*) which was destroyed by the eruption of Mt. Vesuvius in AD 79. The entire water system of Pompeii as it existed in AD 79 was frozen in time by the eruption and can now be studied in detail. The aim of our study was to investigate how the development and management of the Republican and other public baths in Pompeii evolved during the city's transition from Greek to Roman culture by analyzing carbonate deposits within their water supply systems.

Pompeii, founded in the 6th century BC, lacked a substantial natural water resource and originally organized its water needs by rainwater storage in cisterns, and the use of wells (1–5). Public bathing facilities and industrial complexes used well shafts up to 40 m deep with water-lifting machinery to reach the groundwater level 20 to 37 m below the surface (5, 6) (Fig. 1*C*). The city's water supply improved significantly with the connection to an aqueduct constructed during the Augustan Period (27 BC to AD 14) (Fig. 1 *A* and *C*). A catastrophic earthquake in AD 62 and several minor earthquakes preceding the eruption of Vesuvius (7, 8) caused extensive damage to buildings, while the aqueduct and the urban water supply system were either not severely affected by these events or were repaired immediately afterward (9, 10).

Previous archaeological studies of the remains of the Pompeii water supply system have revealed many details of its purpose and functioning (2–6). The complexity of the system prompted questions regarding Pompeii's bathing culture, the management of the three major public baths (Republican, Stabian, and Forum Baths), and the reasons behind technological innovations such as the shift from wells to an aqueduct.

Water in the well shafts, the baths, and the aqueduct of Pompeii deposited calcium carbonate with alternating layers of different chemical and isotope composition, calcite crystal size, and shape. Such differences between layers reflect seasonal changes in temperature and chemical composition of the water as well as biological activity (11). Analysis of such carbonate deposits within man-made structures can therefore provide valuable information on the provenance of water, and on changes in water quality and quantity over time (11). Carbonate deposits also record evidence of anthropogenic changes within a water supply system (11). Consequently, an archaeological approach that examines the

The authors declare no competing interest.

This article is a PNAS Direct Submission.

[1]Present address: Institute for Geosciences, University of Mainz, Mainz 55128, Germany.

[2]To whom correspondence may be addressed. Email: surmelih@uni-mainz.de.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2517276122/-/DCSupplemental.

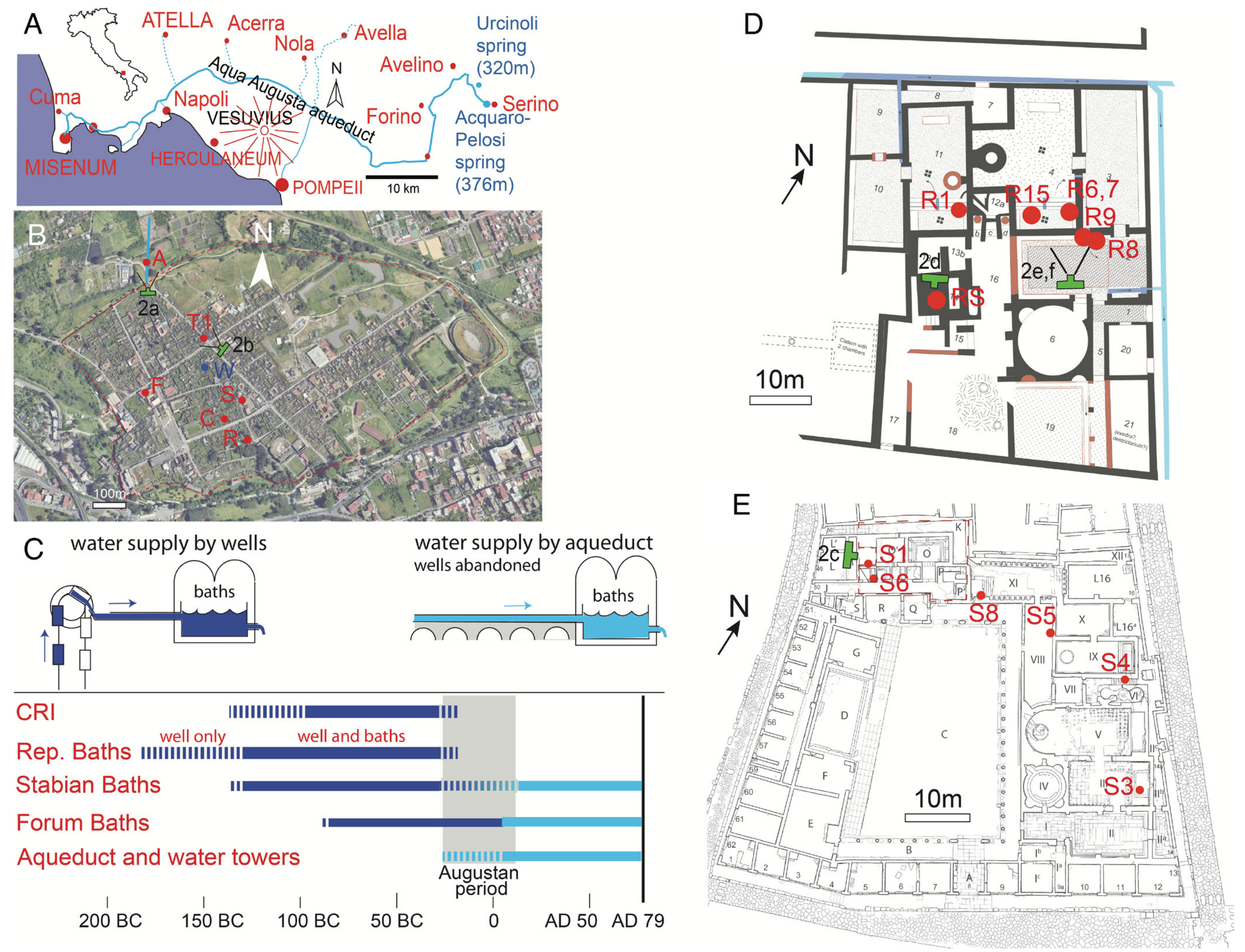

Fig. 1. (*A*) Simplified map of the area near Pompeii and Mount Vesuvius with other ancient cities in connection to the possible water sources. (*B*) Aerial photograph showing the location of the studied water structures in the ancient city of Pompeii; C—CRI (VII 14.5, 17-19); R—Republican Baths (VIII 5.36); S—Stabian Baths (VII 1.8); F—Forum Baths (VII 5.24); A—aqueduct; T1—investigated water tower; W—sampled well; (*C*) time line of the water structures discussed in this paper, with the transition from the use of wells to the aqueduct; (*D*) plan view of the Republican Baths with sampling sites; (*E*) ground floor of the Stabian Baths, with sampling sites. (*D*) after (15), (*E*) after (13).

properties of calcium carbonate deposits in ancient water distribution systems can be used to reconstruct the history of such systems—particularly public baths—revealing aspects of their maintenance and the adaptations made during their period of use.

In this paper, we combine geochemical data on carbonate deposits and archaeological observations on the ruins of the water structures to reconstruct the history of the water supply of the baths of Pompeii between 130/120 BC and AD 79. Our aim was to investigate how bathing standards and ancient water management evolved over time within four distinct historical phases: from the 2nd century BC to 80 BC when Pompeii was inhabited by the Samnites, who were familiar with Greek culture; after 80 BC when Pompeii became a Roman colony; during the reign of the Emperor Augustus (31 BC to AD 14), a period marked by extensive monumentalization, including the construction of the aqueduct; and after the earthquake of AD 62.

Water Structures of Pompeii

The water supply system of Pompeii was investigated by obtaining carbonate deposits from water structures in public baths and a private house, their supplying deep wells, the aqueduct, and one of its water towers. These structures have the following characteristics.

Stabian Baths and Adjacent Structure. The Stabian Baths (site VII 1.8) were built after 130 to 125 BC and were active until the city was destroyed in AD 79 (12, 13) (Fig. 1 *B*, *C*, and *E*). Originally, a large deep well in the northwest corner provided groundwater to the baths (Figs. 1*E* and 2*C*). This well was equipped with a water-lifting system consisting of a treadwheel and two bucket chains (6) (Fig. 3*A*). These filled two small basins that, in turn, supplied a large water reservoir on the roof of the baths (Fig. 3*A* and *SI Appendix*, Fig. S1*C*). The water was then directed to the water-consuming rooms of the bath complex via lead pipes. Due to capacity limitations of the well, the Stabian Baths only had pools in the hot rooms (caldarium) of the two bathing sections for men and women (Fig. 1*E*). Wastewater was disposed of through drains that passed the other rooms of the bathing sections, the apodyterium (changing room) and the tepidarium (warm room). During the Augustan Period (27 BC to AD 14), the baths were connected to a newly constructed urban water system, which was probably fed by the "Aqua Augusta" or Serino aqueduct, a 145 km long aqueduct network that supplied

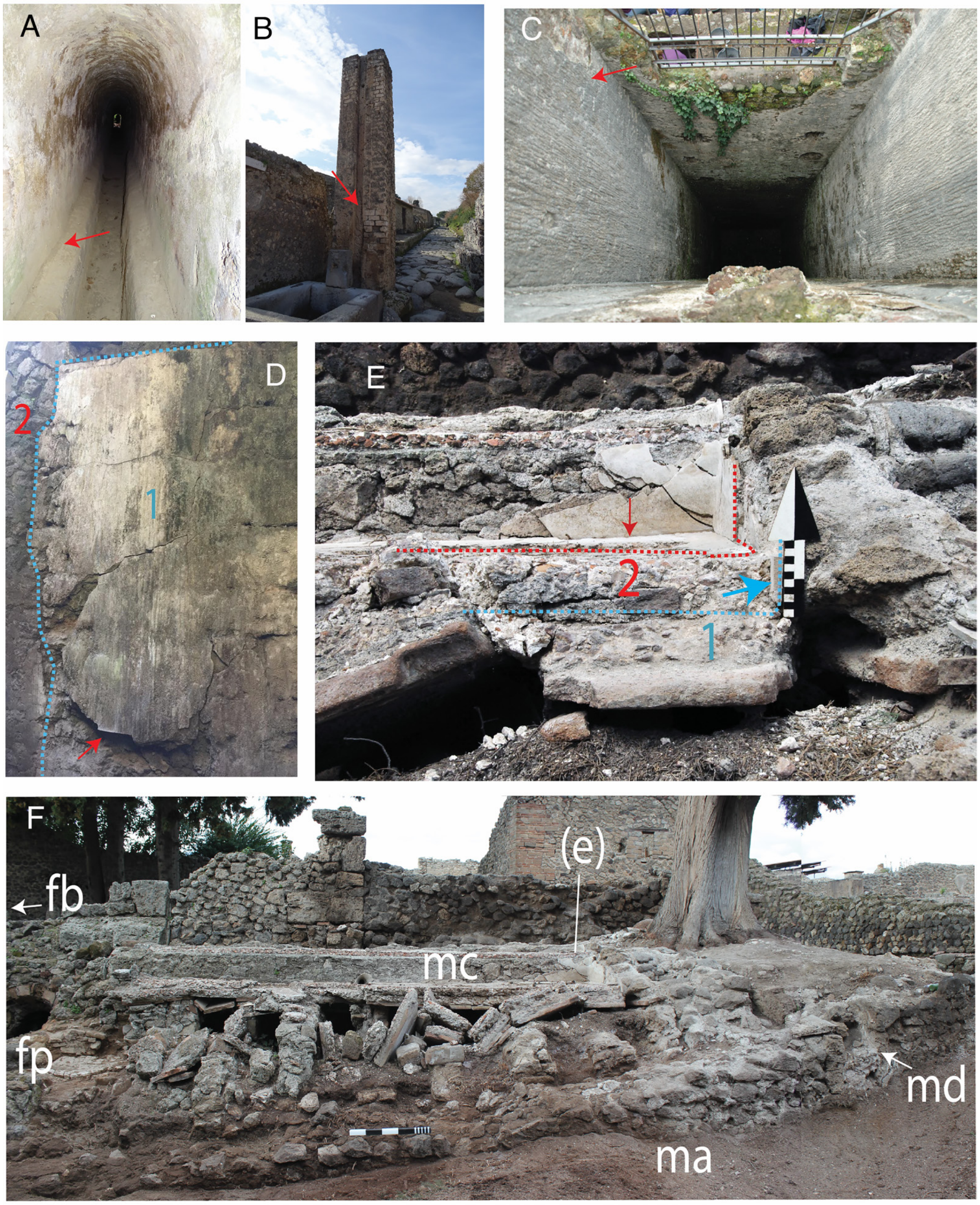

Fig. 2. (*A*) Aqueduct of Pompeii, near its entrance into the castellum aquae. Thin carbonate deposits are present on the walls (arrow - sample A). (*B*) Pressure tower of the aqueduct water system. Leakage carbonate is present in the vertical gutter on front of the tower (arrow—sample T1). (*C*) Well shaft of the Stabian Baths covered by carbonate deposits (arrow—sample S1). (*D*) southern wall of the well shaft of the Republican Baths with two phases of modifications and thick carbonate deposits of Phase 1. Arrow—sample RS. (*E*) Eastern part of the men's caldarium hot pool showing two phases of modification. Blue arrow—sample R7; red arrow—R6. Blue and red dotted lines show start of carbonate deposition of Phases 1 and 2; (*F*) Overview of men's caldarium of the Republican Baths, looking north. fb—women's bath; fp—praefurnium (heating structure); mc—men's caldarium hot pool and position of (*E*); md—drainage pipe of men's baths (sample R9); ma—men's apodyterium (dressing room).

several cities in the Vesuvius area with water (8, 14) (Fig. 1 *A* and *C*). This development provided a more abundant and permanent water supply. Additional pools and basins were added and the number of bathers increased significantly.

In the Stabian Baths, calcium carbonate crusts are preserved on the walls of the well, where they are about 1 cm thick (Fig. 2*C* and *SI Appendix*, Fig. S1*D*), and in the two small reception basins of the water-lifting machine, with a thickness of about 2 to 3 cm (Fig. 3*A*). Carbonate samples were taken in the well shaft (S1), from the southern reception basin (S6), from leakage deposits below a lead pipe running along the east wall of service room VIII (S5), in the pool of the men's tepidarium (S3), in the bronze heating device of the women's baths (S4), and from a drainage channel on the floor of the women's baths (S8) (Figs. 1*E* and 3*A* and *SI Appendix*, Fig. S2).

A large private house west of the Stabian Baths, the Casa della Regina d'Inghilterra (CRI, site VII 14.5) (Fig. 1*B*), includes a deep well of similar size and age as the Stabian Baths where two bucket chains operated by a treadwheel filled two small basins (*SI Appendix*, Fig. S1 *A* and *B*). The original context and function of the well cannot be determined. The well was probably in use from the late second or early first century BC till AD 4 in the Augustan Period (Fig. 1*C*). A sample (E3) was taken from the walls of the western reception basin of the water-lifting machine (*SI Appendix*, Fig. S2).

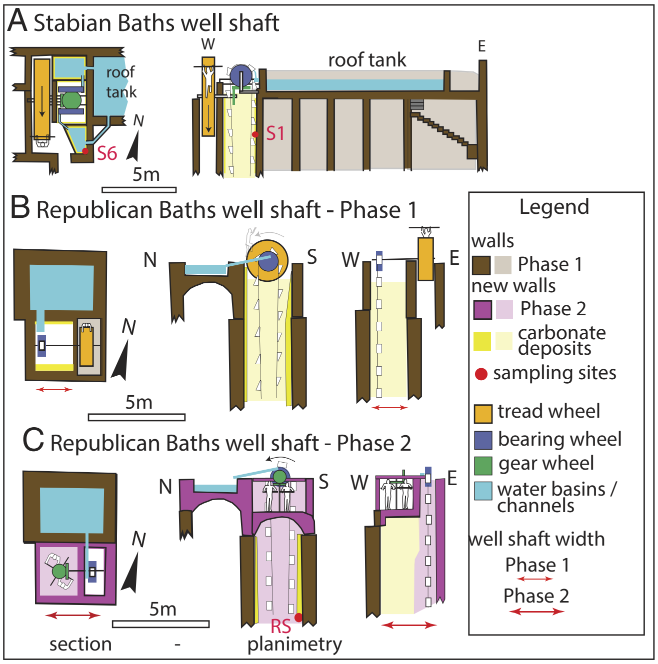

Fig. 3. Water-lifting installations in the studied bathing facilities. Simplified after (5). Two phases of construction are shown for the Republican Baths. Carbonate deposits are shown where covering the back wall. (*A*) Stabian Baths. (*B*, *C*) Two phases in development of the Republican Baths.

Republican Baths. The Republican Baths (site VIII 5.36) were built after 130/120 BC and were abandoned around 30/20 BC (15) (Fig. 1 *B–D*). They are poorly preserved since they were largely dismantled in antiquity and overbuilt by the garden peristyle of a neighboring house (Fig. 1 *B* and *D*). The baths integrated a preexisting large deep well (5, 6, 15) dating to the 3rd or early 2nd century BC (Fig. 1*D*). A water lifting mechanism (Fig. 3 *B* and *C*) was installed in the well shaft to serve the baths. The well and this mechanism went through two phases of transformation as discussed below (5, 6). Carbonate deposits were collected from the well shaft (RS) (Figs. 2*D* and 3 *B* and *C*), the pool in the men's caldarium (R6, R7), the pool in the women's caldarium (R1), and from the drains of the men's bathing section (R8, R9) (Fig. 2*F* and *SI Appendix*, Fig. S2). In the hot pool of the men's caldarium, dense carbonate deposits were found covering sidewalls and a first (R7) and overlying second (R6) cement floor of the pool (Fig. 2 *E* and *F* and *SI Appendix*, Fig. S2). R11 was found on the floor of the baths, R9 in the drain of the men's baths, and R8 covered the wall below the exit of this drain.

Forum Baths. The Forum Baths (site VII 5.24), built after 80 BC, were originally also supplied by a well with a water-lifting device that included a tread wheel and two bucket chains (6, 16), and later by the aqueduct in the Augustan Period (Fig. 1 *B* and *C*). Fragments of anthropogenic carbonate deposits were used as building material (spolia) in the wall of the well, when the well was transformed into a cistern in the Augustan Period (*SI Appendix*, Fig. S1*F*). Samples were taken from two of these carbonate spolia (F1, F2) (*SI Appendix*, Fig. S2). They show alternating microsparite and sparite with crystal fans (*SI Appendix*, Fig. S3-F1). Their microfabric and geochemical composition are similar to those of the reception basin (S6) of the Stabian Baths but their stratigraphy differs. The samples are probably derived from a reception basin of the water-lifting machine of the Forum Baths.

The Aqueduct and Water Towers. The aqueduct of Pompeii (Figs. 1*B* and 2*A*) entered the city at its highest point on the north side, but its course outside the city is still unknown (8, 17). The aqueduct supplied baths, fountains, industrial facilities, and some private houses in the city with water through a network of lead pipes. The pipes were connected to 14 water towers (Fig. 2*B*) that were evenly distributed on the city's sloping terrain and served to maintain water pressure within the distribution network (2, 4, 18). Carbonate was collected from the side wall of the aqueduct (A—Figs. 1*B* and 2*A*), and from overflow deposits on the pillar of a water tower next to insula VI 16 (T1—Figs. 1*B* and 2*B* and *SI Appendix*, Fig. S2).

Results

Carbonate deposits in the water supply systems and public baths of Pompeii were deposited from water originating either from local wells tapping the groundwater, or from the aqueduct. Since we do not have access to water from the Roman period, we sampled present-day groundwater in Pompeii, and from the springs that are thought to have supplied the aqueduct, bearing in mind that both water sources may have changed since Roman time. Especially the Pompeii aquifer may have been altered by the AD 79 eruption.

Water Composition. We sampled groundwater in Pompeii to compare its composition to that of the springs of the Aqua Augusta aqueduct 35 km to the NE. Since most wells in Pompeii are presently either dry or contaminated, we could only sample groundwater in a deep well in the house of N. Popidius Priscus (site VII 2.20). This well was covered and inside a building (Table 1). For water of the aqueduct, we provide measurements and published data (19) for the Acquaro-Pelosi springs, which originally fed the Aqua Augusta and probably Pompeii (8, 14, 17). The water composition of these springs is clearly very different from the groundwater in Pompeii (Table 1). Notably, total dissolved solids of the groundwater are significantly lower in the Acquaro-Pelosi springs. In fact, the groundwater in Pompeii reaches mineral concentrations close to what is considered unhealthy for human consumption (1, 20). This difference is attributable to the underlying geology: the Pompeii groundwater interacts with eroded volcanic lavas and pyroclastic deposits (21, 22), whereas the aqueduct springs are fed by a karst aquifer (4, 8, 19).

Carbonate Deposits. Although the bedrock of Pompeii consists of volcanic pyroclastic material and not limestone (22), the groundwater can deposit calcium carbonate from dissolved calcium from the volcanic rocks, and high concentrations of dissolved CO_2. Most carbonate samples from Pompeii are poorly laminated crystal fan and clotted peloidal boundstones and cementstones, commonly columnar with variable porosity (23) (Fig. 5*A* and *SI Appendix*, Figs. S3 and S4). Samples from the wells (RS, S1) have a smaller crystal size than samples from the reception basins (S6 and probably F1) (*SI Appendix*, Fig. S3). Samples R6 and R7 from a pool in the Republican Baths stand out by their white color and compact microsparitic (5 to 15 µm) fabric with crystal fans, with regular fine lamination, in contrast to deposits of the well (RS). The latter are irregularly layered cementstones with alternating micritic (<5 µm) fabric and sparitic (>15 µm) crystal fans, porosity, and numerous included fragments of volcanic origin (*SI Appendix*, Figs. S3–S5). Aqueduct carbonate (A) has a laminated tabular base layer, followed by microsparitic columnar stromatolitic boundstone with high porosity (*SI Appendix*, Figs. S3*A* and S4 *A–C*).

Table 1. Water chemistry data from a well in Pompeii, from the south slope of Mt. Vesuvius and the coastal plain near Pompeii (26) and from the karst springs of the Aqua Augusta (our data and ref. 19)

Site	Provenance	Sample	pH	Cond.	T	Chloride	Nitrate	Sulfate	Na	K	Ca	Mg	$\delta^{18}O$	δD	$\delta^{13}C$
Pompeii groundwater				µS/cm	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰	‰	‰
Well in house VII II.20	This study	PM2	6.8	1023	16.2	52	87.1	73.1	44	83	69.5	30.2	−6.12	−37.5	−0.61
S-Flank Mt Vesuvius	(26) Tables 1,2	10	6.3	2020	18.2	178	n.d.	180	144	220	150	112	−5.78	−36.8	0
S-Flank Mt Vesuvius	(26) Tables 1,2	11	6.1	2900	16.8	318	n.d.	109	213	227	367	261	−6.1	−36.7	n.d.
S-Flank Mt Vesuvius	(26) Tables 1,2	12	6.8	1478	17.1	167	n.d.	172	92	156	138	74	−6.47	−37.3	1.5
Springs of Aqua Augusta															
Aquaro-Pelosi	(19) Table 2.1.1	May 05	7.3	370	11	10.95	7.07	8.83	6.25	3.6	63.6	12.2	n.d.	n.d.	n.d.
Aquaro-Pelosi	(19) Table 2.1.1	Jun 05	7.5	336	12	7.61	2.56	5.34	5.16	3.05	56.1	13.6	n.d.	n.d.	n.d.
Aquaro	This study	Feb 25	7.4	408	12.9	7.5	1.6	5.1	6.5	3.5	66.9	13.4	−4.01	−31.7	−13.3
Pelosi	This study	Feb 25	7.4	391	12.8	6.7	2.2	4.0	5.0	2.8	59.9	12.5	−4.09	−32.0	−13.5

Note: This table represents modern water composition. This compositon may be different from that in Roman time for the same locations.

Carbonate deposited from drainage (S8, R9, R11) consists of clotted peloid micrite and microsparite, while that formed from leakage water (T1, S5) is a microbialite with clotted peloid micrite and microsparite (23) (*SI Appendix*, Fig. S3). All samples, especially those from the well shafts, are contaminated by detrital inclusions of volcanic origin and detrital quartz. Based on SEM-EDS and optical analysis, the detrital volcanic components included pyroxene, hornblende, fayalite, Fe-oxide, feldspar, feldspathoids, and vesicular glass (*SI Appendix*, Figs. S4 and S5). These inclusions occur isolated in the carbonate fabric but occasionally form lenses or fill porosity between columnar structures.

Stable Isotopic Composition. The stable isotope values of O ($\delta^{18}O$) and C ($\delta^{13}C$) in the carbonate deposits provide pivotal information about the provenance and contamination of water (11) (Fig. 5*D* and *SI Appendix*, Fig. S6). Carbonate samples from the investigated large wells and their reception basins (F1, F2, S1, RS, and E3) have comparable $\delta^{18}O$ values, slightly less negative than those of the aqueduct carbonate (Fig. 5 *C* and *D*). $\delta^{13}C$ values of all wells are significantly higher than those of the aqueduct, while the water tower (T1) has slightly higher $\delta^{13}C$ values than the aqueduct (A) (Fig. 5*D*).

The stable isotopic composition of carbonate deposits in the water system of the Stabian and Republican Baths shows systematic changes through the water system, from well to drainage (Fig. 5*D*). In the Republican Baths $\delta^{18}O$ becomes more negative from the well to the heated pools. In the drainage of the Republican Baths, the $\delta^{18}O$ values are slightly less negative than in the pools (Fig. 5*D*). There is a clear systematic decrease in $\delta^{13}C$ from the well (RS) to the heated pools (R1, R7, and R6) to the drainage of the Republican Baths (R11, R9, and R8).

In the Stabian Baths $\delta^{18}O$ was slightly higher in the transport system (S6, S5) compared to the well (S1) (Fig. 5*D*). In the drainage sample (S8) $\delta^{18}O$ and $\delta^{13}C$ are low. The stable isotope profiles that could be measured in the thicker samples of the Stabian, Republican, and Forum Baths show a strong periodic cyclicity in $\delta^{13}C$, and to a lesser extent in $\delta^{18}O$ (Figs. 4 and 5*C*). R1, S3, and S4 were very thin samples for which only a single stable isotope value could be measured (Fig. 5*D*).

Trace Elements. Fig. 5*B* shows selected trace element concentrations for samples of the aqueduct systems (A, T1), the Republican (RS, R7, R6, and R9), Stabian (S1) and Forum Baths (F1), and the CRI (E3). Additional trace elements are shown in *SI Appendix*, Fig. S7 and Table S1. In general, Sr is lower in the aqueduct and related water tower deposits than in samples in the baths derived from groundwater. Sr, Mg, and P are enriched in drainage deposits in R9 and S8 of the Republican and Stabian Baths (Fig. 5*B* and *SI Appendix*, Fig. S7). Elements typically associated with pyroclastic or clay particles such as Al, Fe, and Lanthanides are higher in the aqueduct, on the water tower and in the well shaft of the Republican Baths compared to the other groundwater-derived deposits (Fig. 5*B* and *SI Appendix*, Fig. S7). Zn and Pb are enriched in the Republican Baths. Zn gradually increases in R6. Pb shows significantly enhanced values in the water tower compared to the aqueduct, with high initial values that decrease with time (24). Similar decreases in Pb with time are seen in the pools and drainage of the Republican Baths (Fig. 5*B*). Mg is higher in bathing structures than in well shafts and aqueduct-derived water. Sr and Mg show a pronounced periodicity in the aqueduct and a clear but less pronounced periodicity in R7 and R9 of the Republican Baths.

Th–U Dating. The operating age of the Pompeii baths is relatively well constrained by archaeological data, with an uncertainty of 30 to 50 y (Fig. 1*C*). Th–U dating of three samples S1, F2, and R7 (*SI Appendix*, *Supplementary Information Text* and Fig. S8) gave uncorrected ages ranging from 2.75 to 3.96 ka, which are substantially older than their possible ages. This is, however, not surprising because the carbonate is substantially contaminated with detrital Th associated with volcanic particles and clay minerals (*SI Appendix*, Figs. S4 and S5), as evident from the very low ($^{230}Th/^{232}Th$) activity ratios ranging from 2.15 to 3.77. This results in apparently older ages (25). For ($^{230}Th/^{232}Th$) activity ratios <20, a correction for detrital contamination must be performed. Using the assumption that all three samples were affected by the same detrital component and considering the estimated operating ages of the individual baths given above, we calculated corrected ages of 71 BC for S1 and R7 and 35 BC for F2 (*SI Appendix*, Table S2). These mean ages fit the archaeological age range (Fig. 1*C*).

Discussion

The microstratigraphy and geochemical signatures of carbonate incrustations in ancient water systems such as those of Pompeii, provide valuable insights into the provenance of water in different parts of the system and its temporal variations, the dynamics of

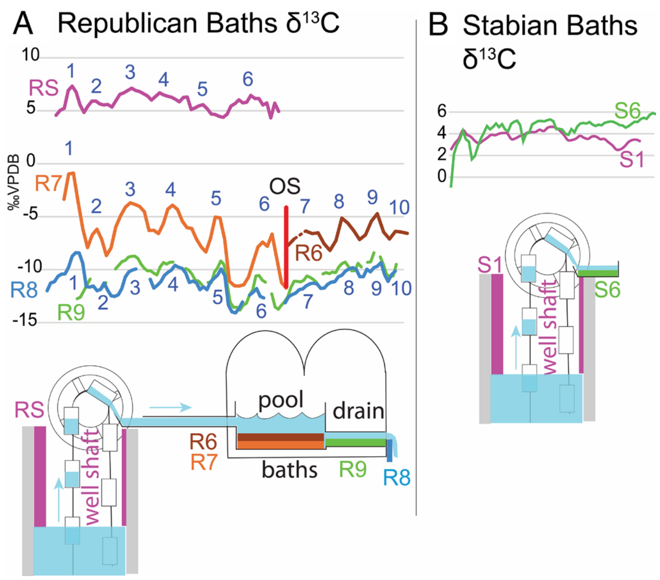

Fig. 4. $\delta^{13}C$ profiles of carbonate samples from different parts of the water system of (*A*) the Republican and (*B*) the Stabian Baths, showing interpreted correspondence. Sketches below the stable isotope diagrams illustrate the environment for each of the graphs shown. Diagrams are not to scale. Detailed stable isotope profiles and corresponding thin section images are given in *SI Appendix*, Fig. S3.

water transport, the operation of public baths, levels of heavy metal contamination, and the overall hygiene of the supplied water (11, 24), as outlined below.

Tracing the Waters of Pompeii. Analytical data of sampled groundwater in the wells of Pompeii could be supplemented by analytical data of groundwater north of Pompeii (26). Groundwater flow maps in ref. 26 suggest that their water samples 10 to 12 are relevant for the present composition of groundwater in Pompeii. The values from these points correspond well with our analysis of the water sample from Insula VII (Table 1). $\delta^{18}O$ and δD values of modern groundwater in Pompeii are in the range of western Mediterranean precipitation, while the $\delta^{13}C$ values are high and in the range of −0.6 to 2‰ (Table 1). These relatively high $\delta^{13}C$ values are probably due to influx of volcanic CO_2 along faults close to Pompeii (26, 27). The elevated $\delta^{13}C$ values of carbonate from the wells stands out from that of other aqueduct carbonates in the Mediterranean (*SI Appendix*, Fig. S6*B*), possibly indicating that $\delta^{13}C$ values were also high in the well water of Roman Pompeii, possibly due to contributions of volcanic CO_2, although the aquifer may have been different before the AD 79 eruption. $\delta^{13}C$ values may have increased further before carbonate deposition by rapid degassing, when groundwater was lifted in buckets and poured into open air basins (Fig. 3).

The slightly higher $\delta^{18}O$ values of carbonate of four investigated wells and reception basins (samples F1, F2, S1, RS, and E3) compared to those of the aqueduct (A) can be explained by the vertical isotopic lapse rate of $\delta^{18}O$ due to the higher elevation of the spring supplying the aqueduct (380 m) compared to Pompeii (42 to 30 m, Figs. 1*A* and 5*D*) (28). $\delta^{18}O$ and $\delta^{13}C$ values of aqueduct carbonate are comparable to carbonate deposited from other karst spring that fed Roman aqueducts (11) (*SI Appendix*, Fig. S6*B*) and published values of the Aqua Augusta aqueduct at Ponte Tirone east of Pompeii (PT in Fig. 5*D*) (8).

Carbonate samples from the aqueduct water system and the well of the Republican Baths contain volcanic particles, visible in thin section and by SEM (*SI Appendix*, Figs. S4 and S5), which explain the relatively high concentrations of Al, Fe, and Lanthanides compared to samples from other wells and baths (Fig. 5*B* and *SI Appendix*, Fig. S7). As Sr values are significantly lower in the aqueduct and the investigated water tower than in the wells (Fig. 5*B*), high Sr and $\delta^{13}C$ values can serve to distinguish structures fed by the aqueduct or by the wells, bearing in mind that such values can be altered by microbial activity, organic matter, and/or degassing.

Although the aqueduct was used to supply the Stabian and Forum Baths, as shown by the presence of lead pipes transporting water to the buildings (5, 6), few carbonate deposits were left in the operational part of the Forum and Stabian Baths shortly before the eruption due to ongoing rehabilitation work after the AD 62 earthquake (6). The only significant carbonate deposit derived from aqueduct water found in the baths is drainage sample S8 of the Stabian Baths. The other samples found in the Stabian Baths were from then-abandoned parts of the groundwater supply network such as leakage water on a wall (S5) and the basins of the water machine (S6). The Republican Baths predate the aqueduct and therefore provide no material related to the aqueduct.

Origin of the Pompeii Aqueduct Water. Ohlig (29) claimed that Pompeii's aqueduct was built after 80 BC and was first supplied by water from near the town of Avella, to be connected to the Aqua Augusta aqueduct in the Augustan Period (Fig. 1*A*). This hypothesis was mainly based on a difference in trace element composition between thin, oldest carbonate deposits that occurred high on the channel walls, and later lower deposits which indicate reduced water discharge (29). This reduction in discharge may have been due to ground motion prior to the eruption (17). Other authors (8, 17) rejected the idea of an aqueduct from Avella and suggested a source from the Aqua Augusta aqueduct or from springs on Vesuvius from the start. The stable isotope composition of carbonate in the aqueduct (Fig. 5*C*, sample A), including the oldest carbonate deposits, does not correspond to carbonate derived from a source in volcanic rocks like the wells in Pompeii and could indeed correspond to the Aqua Augusta: $\delta^{18}O$ and $\delta^{13}C$ values of (A) are similar to those at Ponte Tirone on the Aqua Augusta, with $\delta^{13}C$ values slightly higher in the Pompeii aqueduct, which can be attributed to CO_2 degassing along the way (Fig. 5*D*-PT). The deviant trace element composition of the thin first carbonate layer of the aqueduct described in ref. 29 can be attributed to contamination from the plaster on which the carbonate was deposited, as also observed in other aqueducts (11). The same applies to the low stable isotope values of carbonate adjacent to the plaster (Fig. 5*C*, sample A).

Water Transport and Use. A comparison of stable isotope and trace element compositions in carbonate deposits from the aqueduct, water distribution systems, wells, pools, and drainage structures in the public baths of Pompeii provides insights into changes in water composition during its movement through the different systems. These different geochemical signatures allow for the reconstruction of water provenance, the identification of contamination sources, and an assessment of human activity and adaptive practices within the bathing complexes to meet increasing demand.

Carbonate from overflow deposits on a water tower (T1) fed by the aqueduct shows a cyclicity and an increase in $\delta^{13}C$ values compared to the aqueduct, (Fig. 5*C*) that can be attributed to the exposure of the overflow carbonate on the towers, which would have promoted microbial activity, photosynthesis, and enhanced CO_2 degassing, processes known to elevate $\delta^{13}C$ and introduce more pronounced cyclic variation (11). Unexpectedly, no corresponding variation is observed in $\delta^{18}O$ values, which is notable

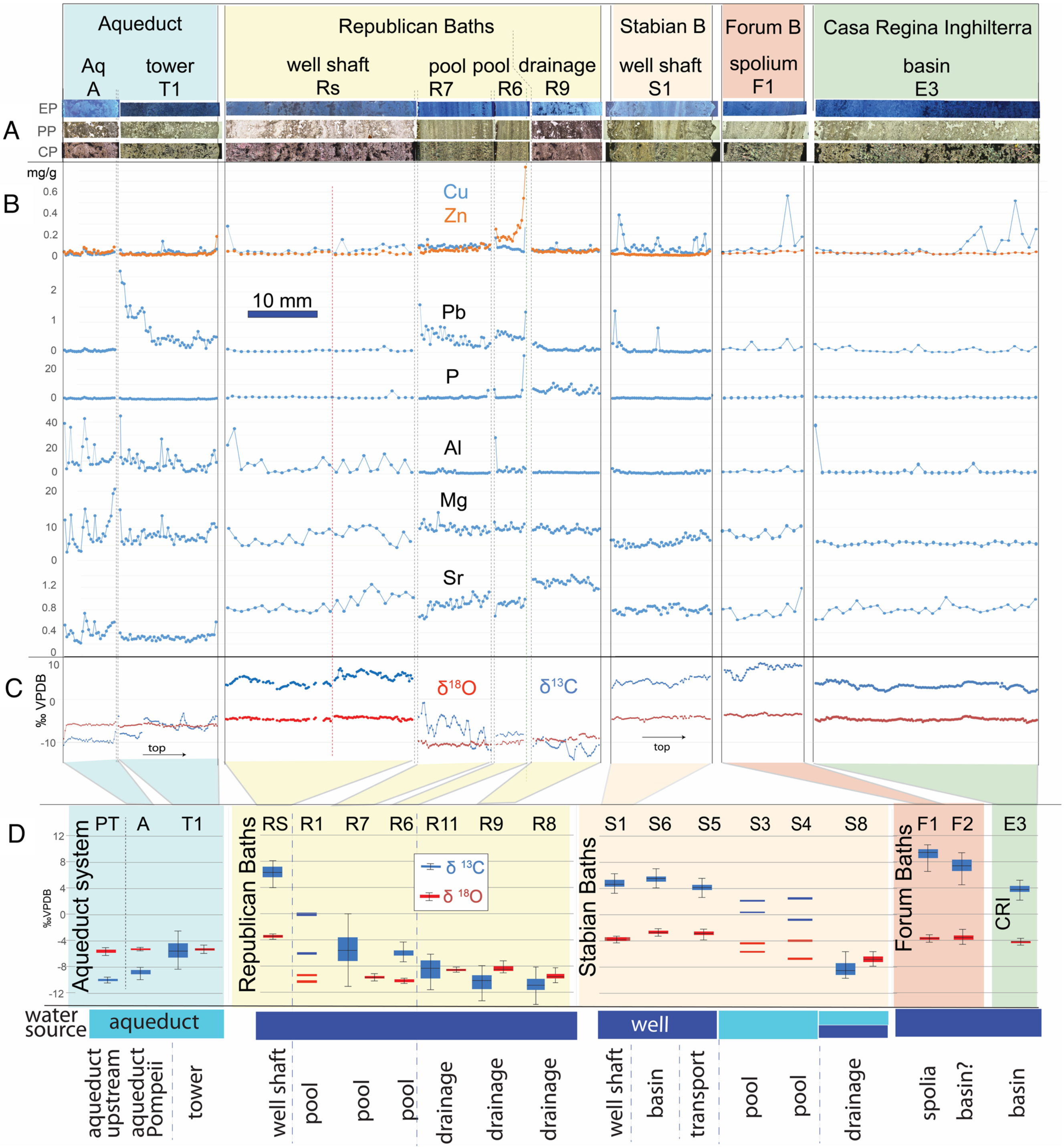

Fig. 5. (*A*) Thin section profiles in plane-polarized light (PP), cross-polarized light (CP), and epifluorescence (EP) of samples of selected Pompeii water structures. (*B*) Trace element and (*C*) stable isotope profiles for the same sections. (*D*) Box and whisker plots of stable isotopes for all samples studied. Abbreviations at the top refer to sample names. The blue horizontal bars shows archaeologically attested water source. PT are values from the Aqua Augusta aqueduct at Ponte Tirone from ref. 8.

given that evaporation would be expected to affect both isotopes under open-air conditions.

The Republican Baths. Carbonate from the Republican Baths shows a strong decrease in δ^{18}O and δ^{13}C from the well to the pools (R1, R6, and R7) and subsequently to the drainage (R8, R9, and R11) (Figs. 4*A* and 5*D*). The decrease in δ^{18}O can be attributed to heating of the water, since δ^{18}O values show an inverse correlation with temperature due to the temperature-dependent kinetic isotopic fractionation (11, 30). Mg values also increase in the same samples (Fig. 5*B*), also altered due to the temperature effect (11). The high δ^{13}C values of the well carbonate (RS) can probably be attributed to high δ^{13}C values of the well water (−0.6 to 1.5‰ in modern groundwater, Table 1) combined with enhanced CO_2 degassing during water-lifting activity and deposition of splash water on the shafts of the well in open-air depositional conditions. The marked decrease in δ^{13}C values from the wells to the pools and to the drainage system could be explained by equilibration with atmospheric CO_2, or the introduction of organic carbon, which is low in ^{13}C. Atmospheric CO_2, however, had δ^{13}C values between −6.5‰ and −6.2‰ in Roman time (31), insufficient to explain the observed drop. Given that the lowest $\delta^{13}C$ values were observed in drainage water, the introduction of organic carbon from microbial activity and human waste (e.g., sweat, sebum, urine, bathing oil) is probably the main cause of the observed decrease (32–34). P is enriched in drainage deposits of the pools (R9), probably related to the same organic contamination (Fig. 5*B* and *SI Appendix*, Fig. S7). In conclusion, the water in the heated pools of the Republican Baths shows clear evidence of contamination from human activity, suggesting that it was not replenished regularly. This is consistent with the limitations at that time, as the wells of the baths, operated by water-lifting machines, could refresh bath water only once per day, assuming operation occurred exclusively during the daytime (6).

The Stabian Baths. Operation of the Stabian Baths was more complex than the Republican Baths since they were first served by a well and later linked to the aqueduct (12, 13). Carbonate from the remains of the older, well-fed water network show $\delta^{18}O$ and $\delta^{13}C$ values comparable to the well of the Republican Baths (Fig. 5*D*), but show much lower values in the drainage deposits. These low values can be attributed to a large component of aqueduct water, and possibly the presence of organic carbon in wastewater, as in the Republican Baths. High P values (S8) support this (*SI Appendix*, Fig. S7).

Heavy Metal Pollution. Heavy metals in calcite (Fig. 5*B* and *SI Appendix*, Fig. S7) such as Cu (S1, S8, F1, and E3), Pb (R7, R6, T1, and S8), and Zn (R6, R7, and S8) can be derived from volcanic sources, fresh hydraulic plaster, from boilers made of bronze and lead, and from lead waterpipes, where these elements represent a contamination of the drinking water (24, 35). The elevated Pb levels observed in the Republican Baths samples (R6 and R7) indicate that the lead was introduced through the piping system in the bathing complex, as these levels are absent in samples from the well (RS) (Fig. 5*B*). In the aqueduct-related system, there is a strong increase in Pb-level from the aqueduct to the water tower T1 due to the use of lead pipes in the city water supply system, and a decreasing trend in T1 with time that can be attributed to the gradual encrustation of the pipes by carbonate, reducing the lead pollution level (24) (Fig. 5*B*). A similar decrease of Pb with time can be seen in R7 and R6 and to some extent in R9 of the Republican Baths (Fig. 5*B*).

Development in the Republican Baths. Three phases of use can be reconstructed for the well that supplied the Republican Baths (5, 6, 15). In the earliest phase, predating the construction of the baths (Phase 0), the well was likely used by the general public, with water being drawn using a winch-operated rope and bucket system. With the construction of the Republican Baths (Phase 1, Fig. 3*B*), the well was integrated into the facility, and water extraction was mechanized through the use of a single treadwheel-operated bucket chain, capable of supplying approximately 0.9 m^3/h. Leakage water from buckets led to the formation of carbonate encrustation on the shaft walls, with deposits thicker on the south side and thinner on the north. This asymmetry suggests that the buckets were raised on the south side and lowered on the north side (Fig. 3*B*). In Phase 2, the well shaft was enlarged toward the east, and a vault was built over the western part (Fig. 3*C*). The bucket chain was repositioned toward the newly constructed eastern section and operated more efficiently by a capstan-and-gear mechanism installed atop the vault, increasing the water supply to as much as 3.2 m^3/h (Fig. 3*C*). Surprisingly, only very thin carbonate deposits are present on the new part of the well. This may indicate a technological improvement, where this new bucket chain of Phase 2 spilled less water than its predecessor, or was in use for a relatively short period of time, as discussed below.

In the baths, two phases of use could be distinguished, with reconstruction of the heating facilities of the baths, the installation of new hot water boilers and reconstruction of the heated pool in the men's caldarium during Phase 2 (5, 6) (Fig. 2*E* and *SI Appendix*, Fig. S1 *E*–*K*). $\delta^{18}O$ values slightly decrease in carbonate from Phase 1 (R7) to Phase 2 (R6) in this pool (Fig. 5*D*), probably indicating hotter water, while Zn and Pb levels increase (Fig. 5*B*) showing the effect of renovation included new heating devices and another plumbing system, increasing metal contamination.

A cross-correlation of $\delta^{13}C$ cyclicity of carbonate in the different structures of the baths reveals up to ten matching cycles (Fig. 4*A*). In the heated pool of the men's caldarium, cycles 1 to 6 represent the first phase of use of the pool (R7), which align with the last deposits of Phase 1 of the well (cycles 1 to 6 of the top of sample RS; Fig. 4*A*). Older deposits in the well (Fig. 5 *C* and *D* and *SI Appendix*, Fig. S3) predate those in the men's pool. These older deposits may represent phase 1 predating restructuring of the pool, or even Phase 0 of the well. Carbonate of the men's pool's second use phase (R6) with cycles 7 to 10 corresponds to a similar pattern at the top of the deposits in the samples from the drainage area (R8, R9; Fig. 4*A*). Since these later carbonate deposits postdate the deposits of Phase 1 in the well, they must be linked to Phase 2 of the well and the newly installed water-lifting machinery (Fig. 3*C*). Therefore, the patterns in the carbonate deposits correspond with the chronological development of the building.

Since deposits of Phases 1 and 2 in the pool (R7 and R6) are about 11 and 4 mm thick, respectively, and deposits of Phase 1 are 7 mm thick in the well, 2 to 3 mm of carbonate should have been present there from Phase 2 assuming similar deposition rates. The absence of deposits of Phase 2 must therefore represent a more efficient water lifting machine than in Phase 1, with less leakage.

Although the $\delta^{13}C$ cycles in carbonate crusts from the well and the bath can be correlated, the absolute isotope values vary significantly. $\delta^{13}C$ values decrease from the well to the pools and the drainage system, and the amplitude of the cyclicity increases in this order (Fig. 4*A*). This can probably be attributed to the addition of organic matter as discussed above.

Other Structures. In the Stabian Baths, sample S1 represents splash water spilling from the uplifted buckets and moving wheels in the well, while S6 represents "deep water" running in from the gutter that was situated below the buckets (Fig. 3*A*). S1 and S6 show similar cyclic pattern in $\delta^{13}C$, despite differences in depositional setting (Fig. 4*B*). The $\delta^{13}C$ profile displays periodic variations like those observed in the Republican Baths, which terminate with an increasing trend. The reception basins of the wells of the Forum Baths (F1) and the CRI (E3) also show cycles in $\delta^{13}C$ (Fig. 5*C* and *SI Appendix*, Fig. S3). The pattern of the periodicity differs for all four wells investigated here, probably because they represent different times of deposition, different operation of water lifting machines and different ambient conditions. Covariation exists in R7 between $\delta^{13}C$ and Mg ($R = 0.44$), which is expected during enhanced heating, while a weak anticorrelation exists between $\delta^{13}C$ and Sr ($R = -0.29$) and $\delta^{13}C$ and P ($R = -0.38$) in the drainage sample R9 (Fig. 5 *B* and *C*).

Almost all investigated samples show cyclicity in both stable isotopes, with $\delta^{13}C$ showing a larger amplitude (Fig. 5*C*). As seen in the Republican Baths, this isotopic cyclicity holds significant potential for archaeological applications, particularly when cycle patterns are sufficiently distinct. The recurring $\delta^{13}C$ and $\delta^{18}O$ signatures observed in carbonate incrustations from different parts of the same structure enable the correlation of chronologically equivalent profiles—from wells to pools to drainage systems—even when the connecting structures between these components are unexposed or no longer preserved.

Origin of the δ^{13}C Cyclicity. A periodic cyclicity of δ^{13}C, often accompanied by antithetic δ^{18}O cycles, has been observed in many aqueduct carbonate deposits and typically interpreted as seasonal signals driven by seasonal fluctuations in air and soil temperature (δ^{18}O) or in precipitation and degassing rate (δ^{13}C), affecting buried water channels (11). If the δ^{13}C cycles in Pompeii's carbonates were likewise seasonal, the total time span recorded by these deposits would be relatively short—no more than ten years. For the Republican Baths, Phase 1 would only represent six years, and Phase 2, which included the installation of a new water-lifting machine and restoration work, 4 y of use. However, archaeological evidence suggests that the wells of the Stabian, Republican, and Forum Baths were in use for c. 100 to 120 y (6, 12–13, 15) (Fig. 1*C*). This discrepancy implies that the cyclicity may not reflect seasonal changes. Instead, the periodic δ^{13}C variations may result from longer-term shifts in groundwater composition. For example, decadal changes in soil productivity in the catchment area, or multiannual fluctuations in volcanic CO_2 input into the aquifer (27, 36–38), relative to atmospheric and soil-derived CO_2, could account for the observed δ^{13}C patterns.

The Wells and the Aqueduct. The public baths of Pompeii were originally served by man-powered water lifting machines in the well shafts, which provided between 0.9 (Republican Baths) and 5 m^3/h (Stabian Baths), enough to fill the pools of the baths once, and in some cases twice a day (6). However, this type of water provision for the baths had several disadvantages compared to an aqueduct: first, to supply water using wells is labor-intensive and costly. Given the depth of the Pompeian groundwater table, an expensive water-lifting device/machine is needed which demands regular maintenance and human power. By switching the supply to a public water pipe system fed by an aqueduct, the bath administration could outsource most efforts and tasks related to the provision of water. Second, the aqueduct delivered water with more reliability and in higher quantities of initially 167 m^3/h (29). The increased volume of accessible water of an aqueduct allowed the implementation of cool water pools supplied permanently and a more frequent renewal of the content in the warm water pool, thus elaborating the bathing culture. In addition, the aqueduct could deliver water at 3 to 7°C lower temperature (Table 1) than the wells, increasing the contrast between the cold and hot baths, which must have been an improvement, providing the desired Roman bathing experience. Finally, the aqueduct delivered potable water: the groundwater of Pompeii was not up to drinking water standards and drinking water was mostly supplied by rainwater cisterns before introduction of the aqueduct (1–6). Considering that the well supply and the cisterns could never reach the standards of an aqueduct which could provide clean water on a permanent basis with a greater discharge, the switch from the wells to the aqueduct was a logical and ultimate decision.

The changes in the water supply system of Pompeii revealed by carbonate deposits show an evolution from well-based to aqueduct-based supply with an increase in available water volume and in the scale of the bathing facilities, and likely an increase in hygiene. Carbonate deposits in water supply systems of Pompeii can therefore provide a significant contribution to our understanding of the ancient water culture in Pompeii and of Roman culture as a common heritage of mankind.

Conclusions

- δ^{13}C, δ^{18}O, and trace elements such as Mg, P, and Sr in carbonate deposits reveal insights into the history of water management in the public baths of Pompeii, their use and development.
- Differences in stable isotope composition, especially δ^{13}C, and of some trace elements such as Sr can be used to identify the provenance of water for the baths, either from wells or from the aqueduct of Pompeii.
- Variations of Pb, Zn, and Cu in the carbonate deposits reveal the use and replacement of boilers for heating water and renewal of water pipes in the water supply structures of Pompeii. This particularly applies during the modifications made in the Republican Baths which received additional metal devices in the second phase of use, leading to an increase in Zn concentration.
- Lead (Pb) contamination was present in Pompeii, especially in the water system supplied by the aqueduct, but was reduced by carbonate deposition in the lead pipes.
- δ^{13}C profiles of carbonate in different parts of the Republican Baths can be cross-correlated and used to reconstruct the relative timing of modifications made to connected elements of the baths and identify simultaneously deposited carbonate in well, pools, and drainage.
- A dramatic drop in δ^{13}C values from wells to pools to the drainage system in the Republican Baths indicates high contamination by human waste in the pools of the baths and possibly poor hygienic conditions for the Pompeiian bathers before the arrival of the aqueduct.
- The study of carbonate deposits provides a valuable tool for investigating maintenance practices, structural modifications, and technological improvement in ancient water systems, such as the transition from well-based water sources to aqueduct systems.

Materials and Methods

During site investigations in 2016 and 2017, we sampled carbonate encrustations from the structures described above (Fig. 1*B* and *SI Appendix*, Fig. S2 and Tables S3 and S4) and groundwater from a Roman well in Pompeii (Table 1). Carbonate sampling sites were selected to represent different depositional settings and carbonate deposition from two distinct water sources and hence different elements of the water structures in Pompeii, although sampling was restricted by permit regulations. Samples were selected to represent different ambiance conditions (e.g., temperature, humidity) and water composition of the aqueduct and baths. 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 to 5 mm wide and parallel to the lamination (*SI Appendix*, Fig. S2). The sample powders were analyzed using a semiautomated device (Gasbench II) linked to a ThermoFisher Delta V isotope ratio mass spectrometer. Isotope values are reported relative to VPDB. Long-term precision is better than 0.1‰ for both δ^{13}C and δ^{18}O (39). Some samples were very small and are represented by single measurements only. Trace element analyses were performed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) using an ArF Excimer laser system (ESI NWR193, TwoVol^2 ablation cell) with an output wavelength of 193 nm coupled to an Agilent 7500ce ICP-MS at the Institute for Geosciences, JGU, Mainz. Analyses were carried out on polished slabs creating lines of spots with a spot size of 100 μm and a spacing of 300 μm, either inside, or parallel to and less than 1 mm adjacent to the micromilling track of the stable isotope analysis. Samples S1, F2, and R7 were chosen for U-series dating and were cut using a diamond wire saw (sample sizes between 150 and 250 mg) and treated with weak HNO_3 to remove potential surface contamination. Subsequently, the samples were dissolved in 7 N HNO_3, and a ^{229}Th-^{233}U-^{236}U spike was added. Chemical purification of U and Th was performed following (40). Finally, mass spectrometric analyses were conducted using a Neptune Plus MC-ICP-MS with a Cetac Aridus II introduction system following (40) at the Institute for Geosciences, University of Mainz. The results are shown in *SI Appendix*, Table S2. For SEM analysis, the surface of samples was embedded in epoxy resin where necessary, polished down to 1 μm and coated with 2 nm platinum. SEM (scanning electron microscopy) analyses were carried out on a Tescan "Clara" field emission gun SEM at JGU Mainz, equipped with an Oxford "Ultim Max 100" EDS (energy dispersive spectrometer) detector. EDS measurements (*SI Appendix*, Table S1) were carried out at a working distance of 10 mm, 3 nA, and 15 kV acceleration voltage. Semiquantitative, normalized spot analysis was carried out and processed with the Oxford software "Aztec."

Data, Materials, and Software Availability. Study data are included in the article and/or *SI Appendix*.

ACKNOWLEDGMENTS. Carbonate analysis was carried out under the direction of G.S. Funding by the European Union scheme of Marie Curie Individual Fellowship 890454 (G.S.) at the University of Oxford and Deutsche Forschungsgemeinschaft projects SU864/2-1 (G.S.) and PA578/17 (C.P.) at Johannes Gutenberg University of Mainz, is gratefully acknowledged. We thank Regina Mertz-Kraus for Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry analyses, Hubert Vonhof for stable isotope analysis of spring water, and Jon Baker for principal component analysis of stable isotope and trace element values. The carbonate investigations were carried out in the framework of the archaeological project "Pompeii: Bathing Culture and the Development of Urban Space," under the direction of M.T. and funded by the Excellence Cluster Topoi, the Freie Universität Berlin, and the University of Oxford. We would like to thank all institutions and people who made the research possible, especially the Parco Archeologico di Pompei with its directors Massimo Osanna and Gabriel Zuchtriegel and their colleagues, as well as the Ministero dei beni e delle attività culturali e del turismo.

Author affiliations: [a]School of Archaeology, University of Oxford, Oxford OX1 3TG, United Kingdom; [b]Institute for Geosciences, University of Mainz, Mainz 55128, Germany; [c]Institut für Klassische Archäologie, Freie Universität Berlin, Berlin 14195, Germany; and [d]Institute of Geology, University of Innsbruck, Innsbruck 6020, Austria

Author contributions: G.S. designed research; G.S., C.P., M.T., T.H., C.S., and D.S. performed research; C.S., D.S., and F.H. contributed new reagents/analytic tools; G.S., D.S., M.W., and F.H. analyzed data; and G.S. and C.P. wrote the paper.

1. A. Maiuri, Pozzi e condotture d'acqua nell'antica città. Scoperta di un antico pozzo presso "Porta Vesuvio". *Not. Scavi* **1931**, 546–557 (1931).
2. H. Eschebach, Die Gebrauchswasserversorgung des antiken Pompejis. *Antike Welt* **10**, 3–24 (1979).
3. G. C. M. Jansen, *Water in de Romeinse stad: Pompeji–Herculaneum–Ostia* (2002).
4. R. Olsson, The water-supply system in Roman Pompeii. Master thesis, Lund University, Sweden (2015). https://lucris.lub.lu.se/ws/files/6332923/8163872.pdf. Accessed 20 January 2025.
5. T. Heide, Der brunnen der republikanischen thermen in Pompeji. Architektonische analyse und rekonstruktion des antiken wasserhebemechanismus. *Röm. Mitt.* **127**, 221–253 (2021).
6. T. Heide, *Wasserbewirtschaftung Öffentlicher Badeanlagen in Den Vesuvstädten. Bauhistorische Und Hydrotechnische Untersuchungen An Den Republikanischen Thermen, Den Stabianer Thermen Sowie Den Forumsthermen Von Pompeji Und Herculaneum* (Freie Universität, Berlin, Germany, 2023).
7. A. Marturano, Sources of ground movement at Vesuvius before the AD 79 eruption: Evidence from contemporary accounts and archaeological studies. *J. Volcanol. Geotherm. Res.* **177**, 959–970 (2008).
8. F. Filocamo, J. Carlut, H. Dessales, P. Burckel, S. Borensztajn, Roman builders facing the risk of disaster: Coupling archaeological and geochemical analyses on a section of the 'aqua augusta' (the roman Serino aqueduct, southern Italy). *Archaeometry* **60**, 915–932 (2018).
9. S. C. Nappo, "L'impianto idrico a Pompei. Documentazione e nuovi dati" in *Atti del Convegno Internazionale Di Studi Su Metodologie Per Lo Studio Della Scienza Idraulica Antica. Ravenna, 13–15 Maggio 1999*, D. Giorgetti, I. Riera, Eds. (Agorà Edizioni, 2005), pp. 91–108.
10. N. de Haan, K. Wallat, "Die Zentralthermen (Terme Centrali)" in *Pompeji. Archäologie eines Bauprojektes* (Papers of the Royal Netherlands Institute in Rome, 2023), p. 71.
11. G. Sürmelihindi, C. W. Passchier, Writ in water–Unwritten histories obtained from carbonate deposits in ancient water systems. *Geoarchaeology* **38**, 63–88 (2023).
12. M. Trümper *et al.*, Stabian baths in Pompeii: New research on the development of ancient bathing culture. *Röm. Mitt.* **125**, 103–159 (2019).
13. M. Trümper, "The Stabian baths in Pompeii and Agency" in *Roman Baths and Agency. BABESCH suppl.*, K. Beaufay, S. Maréchal, Eds. (Leuven, 2025).
14. W. Lorenz, G. Libertini, B. Miccio, N. Leone, G. de Feo, Prominent features of the Augustan aqueduct in the Naples Bay area. *Water Sci. Technol. Water Supply* **18**, 1968–1975 (2018).
15. M. Trümper *et al.*, Republican baths at Pompeii. New research on the development and function. *Arch. Anz.* **2024**, 34–100 (2025).
16. T. Heide, ""Water management in the Forum Baths of Pompei. Bathing culture and technological innovation" in Bathing Culture in Budapest" in *Proceedings of International Conference of the Frontinus Society on the History of Water Management and Hydraulic Engineering, Budapest 08.09.–15.09.2022G. Wiplinger* (Peeters, Leuven, 2023).
17. D. Keenan-Jones, Somma-vesuvian ground movements and the water supply of Pompeii and the Bay of Naples. *Am. J. Archaeol.* **119**, 191–215 (2015).
18. P. Kessener, "Roman water taps and (two) paradigms" in *Wasserwesen zur Zeit des Frontinus. BABesch Supplements*, G. Wiplinger, Ed. (Peeters Publishers, Leuven, 2017), vol. 32, pp. 371–379.
19. S. Aquino, V. Alocca, L. Esposito, P. Celico, *Risorse Idriche Della Provincia di Avellino* (Appennino Meridionale, Italia, 2006). https://www.researchgate.net/publication/360454077_Le_Risorse_Idriche_della_Provincia_di_Avellino. Accessed 20 January 2025.
20. WHO, *Guidelines for Drinking-Water Quality* (WHO, Geneva, Switzerland, ed. 4, 2011), p. 246. https://www.who.int/publications/i/item/9789241549950. Accessed 31 May 2025.
21. V. Amato, M. Covolan, H. Dessales, A. Santoriello, Seismic microzonation of the Pompeii Archaeological Park (Southern Italy): Local seismic amplification factors. *Geosciences* **12**, 275 (2022).
22. D. Sparice *et al.*, Unveiling the volcanic history of ancient Pompeii (Italy): New insights from the Late Pleistocene to Holocene (pre-79 CE) stratigraphy. *Quaternary 2025* **8**, 4 (2025)
23. G. Della Porta, "Carbonate build-ups in lacustrine, hydrothermal and fluvial settings: comparing depositional geometry, fabric types and geochemical signature" in *Microbial Carbonates in Space and Time: Implications for Global Exploration and Production. Geological Society London, Special Publications*, D. W. J. Bosence *et al.*, Eds. (Geological Society London, 2015), vol. 418, pp. 17–68.
24. D. Keenan-Jones, J. Hellstrom, R. Drysdale, "Lead contamination in the drinking water of Pompeii" in *Pompeii. Art, Industry and Infrastructure*, E. Poehler, M. Flohr, K. R. Cole, Eds. (Oxbow Books, Oxford, 2011), pp. 131–148.
25. S. Wenz *et al.*, ^{230}Th/U-dating of carbonate deposits from ancient aqueducts. *Q. Geochronol.* **32**, 40–52 (2016).
26. C. Federico *et al.*, Magma-derived gas influx and water-rock interactions in the volcanic aquifer of Mt. Vesuvius, Italy. *Geochim. Cosmochim. Acta* **66**, 963–981 (2002).
27. C. Federico, A. Aiuppa, R. Favara, S. Gurrieri, M. Valenza, Geochemical monitoring of groundwaters (1998–2001) at Vesuvius volcano (Italy). *J. Volcanol. Geotherm. Res.* **133**, 81–104 (2004).
28. F. Giustini, M. Brilli, A. Patera, Mapping oxygen stable isotopes of precipitation in Italy. *J. Hydrol. Reg. Stud.* **8**, 162–181 (2016).
29. C. Ohlig, C. De Aquis Pompeiorum, *Das Castellum Aquae in Pompeji* (Zuleitung und Verteilung des Wassers, Norderstedt, Germany, 2001).
30. J. Curie, Geoarchaeology of "anthropogenic" travertine: A story of water and life etched in stone. *Eur. Geol.* **38**, 20–23 (2015).
31. J. Smitt *et al.*, Carbon isotope constraints on the deglacial CO$_2$ rise from ice cores. *Science* **336**, 711–714 (2012).
32. S. A. Welch *et al.*, Impact of anthropogenic disturbance on the chemistry of a small urban pond. *Appl. Geochem.* **83**, 158–170 (2017).
33. G. G. C. Kuhnle, A. M. C. P. Joosen, C. J. Kneale, T. C. O'Connell, Carbon and nitrogen isotopic ratios of urine and faeces as novel nutritional biomarkers of meat and fish intake. *Eur. J. Nutr.* **52**, 389–395 (2013).
34. M. G. A. Keuten *et al.*, Quantification of continual anthropogenic pollutants released in swimming pools. *Water Res.* **53**, 259–270 (2014).
35. W. Ahmad *et al.*, Toxic and heavy metals contamination assessment in soil and water to evaluate human health risk. *Sci. Rep.* **11**, 17006 (2021).
36. C. Federico, P. Madonia, P. Cusano, S. Petrosino, Groundwater geochemistry of the Mt. Vesuvius area: Implications for volcano surveillance and relationship with hydrological and seismic signals. *Ann. Geophys.* **56**, S0447 (2013).
37. G. Iacono-Marziano, F. Gaillard, B. Scaillet, M. Pichavant, G. Chiodini, Role of non-mantle CO$_2$ in the dynamics of volcano degassing: The Mount Vesuvius example. *Geology* **37**, 319–322 (2009).
38. C. Ricco, S. Petrosino, I. Aquino, P. Cusano, P. Madonia, Tracking the recent dynamics of Mt. Vesuvius from joint investigations of ground deformation, seismicity and geofluid circulation. *Sci. Rep.* **11**, 965 (2021).
39. C. Spötl, T. W. Vennemann, Continuous-flow isotope ratio mass spectrometric analysis of carbonate minerals. *Rapid Commun. Mass Spectrom.* **17**, 1004–1006 (2003).
40. J. Klose, M. Weber, D. Scholz, Central European warm phases recorded by episodic speleothem growth during MIS 3. *Commun. Earth Environ.* **5**, 719 (2024).