The Last Flow of Water to, and Through, the Baths of Caracalla Age, Temperature and Chemistry

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aut enim limo concrescente qui interdum in cruxam indurescit, iter aquae coartatur
for the deposit hardens, and sometimes forms a layer of tartar, restricting the flow of water
(Frontinus, De Aquae ductu, 122)

Preliminary note (E. Hostetter)

Over ten years ago, an art history colleague told me that he had heard of a geology professor who could "date stone buildings". For an archaeologist, this remarkable statement bore investigating. I met with the geologist (B. Fouke, co-author of this article) who, it transpired, could not date stone buildings, but was working on close dating of the formation of calcium carbonate at hot springs in Yellowstone Park. I then proposed that the dating methods might be applied to Roman aqueducts, notorious collectors of calcareous deposits. Samples were taken from the Baths of Caracalla, and after seven years of research and laboratory experimentation, we presented the results of our collaborative project at a conference at the Austrian Institute in Rome in 2007. In the same year this article was submitted to the Austrian Institute to be published in a volume based on the conference papers. Sadly, this author learned in July of 2012 that the volume would not be published and I am grateful to the Journal of Ancient Topography for accepting this contribution on such short notice.

The present study is, to my knowledge, a pioneering investigation in the application of certain scientific methods of analysis to calcium carbonate deposits in Roman aqueducts. However, in light of ever-shifting 'accepted' scientific protocols and the inevitable turnover of equipment and personnel in multi-project laboratories, the reliability of these results, and of future research using the same methods, ought to be confirmed by replicating the work on identical samples in a second, independent laboratory. As I have observed over seven years, the results of laboratory analyses can be as problematic as results reached in research in the social sciences, and when historical context is critical, cautious optimism rather than inordinate faith in any given set of unverified metrics may be advisable.
Introduction

The date of the last flow of water to, and through, the Baths of Caracalla (Fig. 1), built between AD 212-216, from the *Aqua Nova Antoniniana*, usually held to be a branch line of the *Aqua Marcia*, is not known. This study investigates this and related questions by comparing the textual and archaeological records with the results of new analyses of calcareous deposits (travertine or CaCO$_3$ deposits) from the baths.

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Figure 1 - Plan of the Baths of Caracalla. Arrows indicate position of the Caracalla cistern and service gallery travertine sampling sites (after Piranomonte 1998).

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1 The authors wish to thank prof. Adriano La Regina and dott.ssa Irene Iacopi of the Soprintendenza Archeologica di Roma for permission to collect samples from the Baths of Caracalla and other Roman buildings, prof. Pietro Giovanni Guzzo, for permission to sample the travertine deposits in the *Castellum Aquae* at Porta Vesuvii at Pompeii, and dott.ssa Cinzia Conti for facilitating the sampling. Professors Hostetter and Fouke are especially grateful to dott.ssa Marina Piranomonte, Director of the Baths of Caracalla, who, in all stages of this project, offered ready and gracious assistance and gave generously of her time and her considerable expertise. This work was supported by research awards from the Research Board of the University of Illinois Urbana-Champaign and the NSF Biocomplexity in the Environment Program (EAR 0221743). Lastly, we thank Dr. Gunild Jenewein of the Istituto Storico Austriaco for organizing the conference on the Baths of Caracalla in March of 2007.

accumulations which represent a preserved crystalline record of the water from which the minerals were originally precipitated. The samples were collected from the corner wall surface of the eighth cistern from the northwest in the line of eighteen along the southwest side of the complex (Figs. 2-3), and from the spreading mass accumulated around the descending terracotta discharge pipes (robbed) and on the floor of, the service gallery of the *nymphaeum* overlooking the 'half-stadium' to the northeast (Figs. 4-5).4

Figure 2 - Site of cistern travertine sample.
Figure 3 - Detail site of cistern travertine sample.

Figure 4 - Site of service gallery travertine sample.
Figure 5 - Detail site of service gallery travertine sample with traces of terracotta pipes.

4 On the cisterns and the hydrological distribution system of the baths, see: Lombardi 2002, 52-53; Lombardi and Corazza 1995, 63-71 and, on this gallery, 67, fig. 48; Conforto and Iacopi 1992.
The scientific estimates of the date and character of the last significant flow of water from the *Aqua Antoniniana* presented here represent a broadly integrated petrographic and geochemical study of the precipitated travertine within the baths and apply well-established techniques in stratigraphy, cathodoluminescence (CL) petrography, and isotope geochemistry. In an unsuccessful attempt at proof of method, the same methods were applied to samples collected from one of the outflow channels of the *Castellum Aquae* at *Porta Vesuvii* in Pompeii (Figs. 6-8). Results have been synthesized to: (1) reconstruct the timing of the last flow of water in these hydrologic structures; (2) estimate possible rates of travertine precipitation; (3) determine temporal trends and changes in the temperature of the water as it flowed into the baths; and (4) interpret the chemistry and source of the aqueduct water that last flowed through these structures.

![Figure 6 - View Castellum Aquae at Porta Vesuvii.](image1)

![Figure 7 - Schematic plan Castellum Aquae at Porta Vesuvii (after Ohlig 2001).](image2)

![Figure 8 - Detail travertine sample within Castellum Aquae at Porta Vesuvii.](image3)
The article is divided into three parts: first, a brief summary of the archaeological and textual context for the last history of the baths and of issues associated with travertine precipitation and the *Aqua Antoniniana*; second, an integrated petrographic and geochemical study of the calcium carbonate mineral deposits precipitated within the baths; and third, a discussion of the historical implications of the results of these analyses for the Baths of Caracalla.

**PART I. ARCHAEOLOGICAL AND TEXTUAL CONTEXT OF THE BATHS OF CARACALLA**

The later history of the baths, the context for the last flow of water to the complex, remains vague, but the latest known restorations, based on brickstamps, were by Theodoric and indicate continued use through the 5th century AD. When the besieging Goths breached the aqueducts in AD 537 (Procopius, *Gothic War* 1.19.3), the *Aqua Antoniniana*, or at least the aqueduct from which it branched, may well have suffered, but the notion that the water supply to Rome suffered a single fatal blow is not supported by either the archaeological or the textual evidence. If significant damage was inflicted to Rome’s water supply, repairs followed quickly, as is attested by the *Pragmatic Section* of AD 554 recording the state fund for the preservation of public buildings, including aqueducts, and by a letter of Gregory the Great of AD 602 (*Letters* 12.6) lamenting the state of Rome’s aqueducts. While grand public baths such as those of Caracalla may no longer have remained in service following the Gothic siege (Procopius 1.20.5), their abandonment was more likely owed to the inability of the central authority to maintain the full complement of aqueducts in a city in which building despoliation, reuse and abandonment had been ongoing since the late 4th century AD and whose population had plummeted. By the 6th or 7th century, tombs possibly associated with the diaconate of SS Nereus and Achilleus (*Lib. Pont*. 42.68), are inserted in the baths.  

The vexed question of identifying the *Aqua Antoniniana* by its medieval toponyms remains unresolved, largely because, as Coates-Stephens has ably observed, the same or similar names may have been given to more than one Roman aqueduct (*Aqua Antoniniana* and *Alexandrina*). Among these are the *forma Iobia* repaired by Hadrian I (AD 776-777: *LP* 97c.61), the *Iovia* by Sergius II (AD 844-845: *LP* 104c.21) and the *Iocia* by Nicholas I (AD 858-867: *LP* 107c.16), the *forma Iobia* of the *Ensiedeln Itineraries* (CChr 175, 333, line 43), referring to the *Aqua Antoniniana*, and the *forma Jovia* of the *Registrum of Subiaco* (12, 14 and 105), used for the *Alexandrina*. Variants may also have been used for the *Julia/Tepula* system (*Iobia* and/or *Iulia=Julia*?). Whatever the correct identities of these toponyms, they might suggest that repairs on the *Aqua Antoniniana* may have been, or were, carried out in the 8th and perhaps the 9th century AD, and that water, if not for the purposes originally intended, continued to flow to and past the Baths of Caracalla for an indeterminate period thereafter.

Fieldwork by Coates-Stephens identifying later passages of *opus vittatum*, *opus latericium*, tufa *opus quadratum* and reused brickwork in aqueducts both within and

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9 For a detailed discussion, see Coates-Stephens 2003a, 169, 172 and 2003c, 137-138.
without of the city has also shed valuable light on their maintenance in the late antique and medieval periods. Aqueducts displaying repair or reworking of the late 3rd through the 6th century include the Claudia-Anio Novus, the Marcia-Tepula-Julia and the Alexandrina, but only the Claudia and Alexandrina reveal repairs of the 8th and 9th centuries.

Precipitated Travertine and the *Aqua Antoniniana*

Unfortunately, Frontinus (*De aquaeductu urbis Romae*) is silent on methods of travertine removal in aqueducts, perhaps because it was to him self-evident that this work was, at least in areas of relatively easy access, done by *aquarii* hacking and scraping their way along the lines.

Modern studies of travertine deposits in various aqueducts have attempted to determine geochemical composition, source, age and rate of travertine precipitation. Numerous factors have been considered, among them: the CO$_2$ content in the air and water; mixing of waters; water velocity, turbulence, pressure and depth; temperature of water, air, earth and conduit; ventilation; the number and the nature of travertine layers and their perceived correspondences to events or time spans in the historical record; archaeological stratigraphy; possible relationships between travertine layers and seasonal or climatological changes and solar cycles; and the nature of the surrounding building materials with which water interacted. To our knowledge, absolute $^{239}$TH/U dating has been used only at the water-tunnels at Troy (Ilios).

In their study of the *Aqua Antoniniana*, G. Garbrecht and H. Manderscheid posit that the layering of the precipitated travertine from the flow of water — estimated at a maximum of 49,400 m$^3$ per day, perhaps reduced to ca. 19,100 m$^3$ towards the end of the aqueduct's life — may reflect yearly seasonal temperature changes, velocity, turbulence, mixing of waters, and periods of disuse. In the section of the *species* of the *Aqua Antoniniana* at the 'Arch of Drusus' (Porta S. Sebastianio), they distinguish two

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10 On both fieldwork and the textual evidence for later aqueduct maintenance, Coates-Stephens 2003a, fig 4, 2003b, fig 1, and 2003c.
13 Other methods, such as the use of solvents such as heated wine vinegar have also been proposed, but the expense and the quantities required provoke skepticism. Fahlbusch (1991, 9-13) speculates that at Laodiikeia nearly 200,000 liters of heated 8.5 % concentration vinegar would have been required yearly to remove precipitated travertine from a twin pipe-line ca. 1,500 m long. Frontinus (2,122) does speak of aqueduct masonry requiring reinforcement owing to the increasing weight of the precipitated travertine in the *species*.
16 Frank, Mangini and Korfmann 2002, with a margin of error of +/- 570, too great for Roman aqueducts, but which indicated successfully that parts of the tunnels were first built over 4000 years ago and remained in use in the period 1700-1150 BC (Troy VI-VII). We are grateful to B. Rose for calling our attention to this study.
distinct sequences of travertine layers covering both the walls and bottom of the channel, followed by a third deeper (8-15 cm thick) and more compositionally mixed (brick and opus caementicium inclusions) accumulation of irregularly shaped deposits on the bottom (Fig. 9). The same three sequences are said to be discernable in the small tank above the cisterns in the baths, and the two perceived periods of disruption seen in the layers are attributed to lengthy repairs.

For comparative purposes, Garbrecht and Manderscheid then collated data from the aqueducts of Nîmes and Cologne (Eifel), noting that the rate of precipitation slowed as the distance from source increased (Table 1). Based on their figures, the presumed precipitation rate range at Nîmes runs from a maximum of 1.54 mm to a low of 0.86 per annum, and at Cologne from 1.58 mm to 0.37 mm.

19 Garbrecht and Manderscheid 1992, 224-226, notes 3, 52, fig. 28.
20 Garbrecht and Manderscheid 1992, 216-217, figs. 17, 19. On the aqueduct of Cologne (Eifel), presumably in use from AD 85 to 275, Schulz (1986, 266) and Brinker (1986, 235-247) also counted perceived 'annual' precipitated travertine layers and calculated accumulation rates of a 3 cm sample to be 1.20 mm per annum over 25 years, and a 10 cm sample to be 1.25 mm per annum over 80 years. See also Grewe 1986, passim.
Table 1: Estimated Annual Precipitation Rates for Aqueducts of Nîmes and Cologne (Eifel) (after Garbrecht and Manderscheid 1992, 216-217).

<table>
<thead>
<tr>
<th>NÎMES</th>
<th>Distance from Source km</th>
<th>Average Thickness Layers mm</th>
<th>Annual mm (over 400 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1.54</td>
<td></td>
<td>1.03</td>
</tr>
<tr>
<td>16</td>
<td>1.29</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>19</td>
<td>1.27</td>
<td></td>
<td>1.12</td>
</tr>
<tr>
<td>26</td>
<td>0.93</td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>29</td>
<td>0.86</td>
<td></td>
<td>0.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COLOGNE (EIFEL)</th>
<th>Distance from Source km</th>
<th>Thickness Wall Layers mm</th>
<th>Annual mm (over 190 years) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>150</td>
<td></td>
<td>0.79</td>
</tr>
<tr>
<td>35</td>
<td>300</td>
<td></td>
<td>1.58</td>
</tr>
<tr>
<td>61</td>
<td>100</td>
<td></td>
<td>0.52</td>
</tr>
<tr>
<td>75</td>
<td>70</td>
<td></td>
<td>0.37</td>
</tr>
</tbody>
</table>

Adopting the lowest (i.e., farthest from source) values for travertine accumulation rate from Nîmes and Cologne (Table 2, below), and applying them to the ca. 90 km length of the *Aqua Marcia* (the assumed source) and *Antoniniana* combined, Garbrecht and Manderscheid posit possible annual increases of precipitated travertine for the 180 mm thick deposits at the ‘Arch of Drusus’ to be between 0.40 and 0.80 mm per year.21

Table 2: Estimated Annual Travertine Precipitation Rates of *Aqua Antoniniana & Marcia* (after Garbrecht and Manderscheid 1992).

*Aqua Antoniniana and Marcia*

<table>
<thead>
<tr>
<th>180 mm total</th>
<th>Distance from Source km</th>
<th>Annual mm</th>
<th>Years in Use (hypothetical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85-90</td>
<td>0.40</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>85-90</td>
<td>0.60</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>85-90</td>
<td>0.80</td>
<td>225</td>
<td></td>
</tr>
</tbody>
</table>

The three spans, ranging from 225 to 450 years, easily encompass the conventional projection of 320 years for the functioning of the *Aqua Antoniniana*, from construction in AD 217 to disruption in AD 537, as well as a number-of-years beyond.22

Lastly, as others before, Garbrecht and Manderscheid link the *Aqua Antoniniana* to the *Marcia*, an association questioned by Coates-Stephens who suggests that the Tiburtina inscription — *aquam Marciam variskasibus impediatam, purgato fonte, excises et perforates montibus, restitutiforma, adquisito etiam fonte novo Antoniniano* (*CIL* VI. 1.245) — refers to a new source for the *Marcia* rather than to a new branch from it, and argues on both archaeological and textual grounds that the *Alexandrina* and the *Antoniniana* were one and the same.23 However, following strontium isotope

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analyses of the precipitated travertine in the cisterns and service gallery of the Baths of Caracalla and in several other aqueducts by Lombardi, Coates-Stephens and Barbieri,\textsuperscript{24} this position was abandoned in favor of the theory that the water reaching the Baths when they were in service arrived not from the \textit{Marcia}, but from the \textit{Julia}, and that a later ‘post-bath’ phase flow arrived from the Tepula, both aqueducts whose sources lay in the far closer Alban Hills.\textsuperscript{25}

\textbf{THE CARACALLA SAMPLES}

The two Caracalla travertine samples analyzed in this study represent demonstrate distinct phenomena. The 13.3 cm thick cistern travertine, taken ca. 1 m. above the floor in the northeast corner, suggests the continued use of the cistern as a reservoir, as originally intended (Fig. 2-3, 10).\textsuperscript{26} It is assumed that the innermost and outermost layers represent two ‘\textit{known}’ moments: first, the approximate time when travertine was last scraped from the walls of the cistern (last maintenance), and second, the time of the last flow of water from the \textit{Aqua Antoniniana} at that location.\textsuperscript{27}

The 5.4 cm thick service gallery travertine, on the other hand, represents a departure from design function, an uncontrolled flow of water running down and around the exteriors of two (now robbed) ca. 15+ cm diameter pipes, probably of terracotta and medieval in date, documented by the lengthy impressions in the travertine which grew around and outward from them and over the descending floor (Figs. 4-5, 13).\textsuperscript{28} In time, this crystalline growth covered both the floor and the lower walls of the service gallery. Thus, this sample has a ‘\textit{known}’ starting point but no ‘\textit{known}’ end: the earliest layer, collected from the surface of the impression of the robbed northernmost pipe, represents the point at which travertine first began to grow on the exterior of the pipe, while the outermost, or latest, layer, represents only the limit reached by that sample, not when water last flowed down the pipe nor when these accretions rose to meet those rising upward from the floor.

The comparative control sample from Pompeii, collected from the interior wall of the one of the discharge channels of the \textit{Castellum Aquae}\textsuperscript{29} near \textit{Porta Vesuvii} at ca. 10 cm above the floor of the channel (Figs. 6-8) reached a maximum of ca. 1 cm in thickness (Fig. 8).\textsuperscript{30}

\textsuperscript{24} Lombardi, Coates-Stephens and Barbieri 2005, 211-216. The study is the conceptual heir of the pioneering attempt by C. Puliti, A. Borgiolo and C. Terzano (1998, 195-198), perhaps the first in Rome to employ the comparative analyses of precipitated travertine, which included the \textit{Marcia} and \textit{Tepula} but not the \textit{Antoniniana}. Puliti, Borgiolo and Terzano wisely concluded that, for a range of reasons, there was great variability in the presence of certain metals (especially Sr and Mn) in different aqueducts and (as with the \textit{Marcia}) within a single aqueduct.

\textsuperscript{25} Lombardi, Coates-Stephens and Barbieri 2005, 214-215. The \textit{Tepula} collected water in the Marciana Valley (18 km) and the \textit{Julia} from the Squarciarelli springs just southeast of Grottaferrata (22 km).

\textsuperscript{26} This does not mean, however, that the cistern travertine was precipitated when the baths were in service.

\textsuperscript{27} It is also assumed that no partial maintenance was carried out between the deposition of layers in the sample.

\textsuperscript{28} We know that the travertine grew outward from the pipes because of the direction of the crystal growth; hence, the pipes were not inserted into the travertine mass. \textit{Pace}, Coates-Stephens 1998, 175, note 25 and Lombardi, Coates-Stephens and Barbieri 2005, 213.

\textsuperscript{29} Ohlig 2001.

\textsuperscript{30} But for the more continuous flow, the situation at Pompeii may be considered somewhat analogous to that of the Caracalla cistern sample: the innermost layer on the mortared surface of the channel represents the time of last maintenance and the outermost layer the time of the last flow.
Terminology

The term *travertine*, in its broadest sense, refers to all non-marine CaCO₃ mineral precipitates formed in or near terrestrial springs, rivers, lakes, and caves and is used to describe CaCO₃ mineral deposits that precipitate in terrestrial environmental settings from water that has a neutral pH and contains high concentrations of Ca, Mg, HCO₃⁻ and SO₄²⁻. In this study, we will use the term *travertine* to describe the CaCO₃ deposits that precipitated within the hydrologic systems of ancient Rome. However, the data collected in the present study indicate that the water, from which the CaCO₃ minerals were deposited, ranged from as low as 4 °C to as high as 48 °C. Therefore, in a technical sense, both *travertine* and *tufa* could be applicable to describing and classifying these sedimentary deposits. In order to conform with previous studies in the geological and archeological literature, we have chosen to use the term 'travertine'.

Methods

The approach utilized in this study has been to conduct high-resolution integrated petrographic and stratigraphic analyses of the crystalline layering and isotope geochemistry of travertine encrusting Roman brickwork and pipes. Careful screening for post-depositional (*diagenetic*) physical and chemical alteration of the travertine (described below) was first completed to ensure that the travertine has not been altered since its original deposition. This ensures that the original 'last flow' aqueduct waters can be accurately reconstructed from the travertine deposits. The crystalline stratigraphic layering of the travertine has been used to create a relative time framework for microdrilled analyses of ⁸⁷Sr/⁸⁶Sr, d¹³C, d¹⁸O, and U-series isotopes. The stratigraphic distribution of these isotopic analyses have been used to reconstruct the age and aqueous conditions associated with specific mineralization events that took place within the hydrologic system.

Both of the Caracalla travertine samples were collected using a hammer and chisel. The cistern yielded a travertine and brick sample 25 cm in thickness (13.3 cm of travertine adhering to 9.0 cm of brick), while the service gallery sample yielded a 5.4 cm cm-thick piece of travertine. The Pompeii channel travertine was collected with a small 1 cm x 3 cm water-cooled Starlight diamond drill core attached to a portable electric hand drill. Once returned to the laboratory, each travertine sample was cut with diamond-coated saw blades and vacuum impregnated at 40°C with low-viscosity Petroxy cathodoluminescence resistant epoxy. Each impregnated travertine sample was then cut into 3 cm³ chips and prepared as 30 mm-thick uncovered thin sections on standard petrographic glass slides. Each thin section, polished using a 4 mm-diameter diamond impregnated resin lapidary wheel cover, was examined on a CITL 1200 Cold Cathodoluminoscope operating at 11 KV and 550 mA mounted to a...
Nikon Photophot petrographic microscope equipped with an Optronics DEI-750 three-chip HCCD thermoelectronically-cooled camera. Sample powders for isotopic analysis were collected from non-impregnated travertine rock chips with a hand-held electric Oshima dental drill mounted with a 0.25 mm-diameter diamond coated Braessler drill burr. Prior to drilling, rock chips were scrubbed with soap and water, ultrasonically cleaned in 0.1% HCl, rinsed in deionized water, and dried in a dust-free low-temperature oven. Each sample powder was then analyzed for its \( ^{87}\text{Sr}/^{86}\text{Sr} \), \( ^{13}\text{C} \), \( ^{18}\text{O} \), and U-Th-Pa isotopic composition.

Carbon- and oxygen-isotope analyses were measured on the CO\(_2\) released during digestion of 20 to 50 mg of the sample powder in 100% phosphoric acid at 50°C on a Finnigan-Mat mass spectrometer. Data are reported as \( ^{13}\text{C} \) and \( ^{18}\text{O} \) values for CO\(_2\) gas relative to VPDB using the standard delta notation. Analytical precision was 0.1 per mil for oxygen and 0.2 per mil for carbon. Strontium separation was done by standard chemical methods. This included dissolving 1 mg of sample powder in 3N HCl at 110°C for 10 hours, centrifuging to remove organics, drying at 110°C, acidification in 1.5N HCl, transport through cation exchange columns loaded with Aminex Q15S, and loading onto outgassed zone-refined Re filaments.

Travertine \( ^{87}\text{Sr}/^{86}\text{Sr} \) were conducted on sample powders dissolved in nitric acid and measured on a Nu ICP-mass spectrometer. Normalization was made to a \( ^{88}\text{Sr}/^{86}\text{Sr} \) ratio of 8.37521 \( (^{88}\text{Sr}/^{86}\text{Sr} = 0.1194) \). Sr isotope ratios from 10 replicate analyses of NBS SRM 987 yielded a mean value of 0.710251 (1 sigma \( \pm 0.000016 \)). Average in-run precision was \( \pm 0.000015 \) for the standard and \( \pm 0.000014 \) for each sample. Travertine powders were also analyzed for their U-series isotopic composition on the same ICP MS instrument. Travertine sample powders were dissolved in concentrated HNO\(_3\) and simultaneously spiked with \( ^{239}\text{Th}, ^{236}\text{U} \) and a few samples with \( ^{235}\text{Pa} \). Chemical separations of U-series nuclides followed previously published procedures.

The Caracalla and Pompeii travertine data have been modeled using single-stage iterative water/rock interaction and mixing equations described in Langmuir et al. (1975), Faure (1986), and Banner and Hanson (1990). The simulations were run with Visual Basic macro programs embedded within Microsoft Excel. The cumulative water/rock molar ratio (N) at any given stage during the interaction process, as well as the percent mixing, are shown at strategic positions along each curve.

**Results**

Travertine stratigraphy, petrography and geochemistry are presented in this section. These analyses indicate that the Caracalla and Pompeii travertine samples were created by \textit{in situ} mineral growth, rather than the deposition of sedimentary grains and particles that were transported by the flow of aqueduct water. Cathodoluminescence (CL) petrography resulting from electron bombardment has been used to characterize and fingerprint the individual events of CaCO\(_3\) mineral

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34 Described in Fouke and Rakovan 2001.
35 Housed in the Illinois State Geological Survey at the University of Illinois.
36 Swart et al. 1991.
37 Housed in the Department of Geology at the University of Illinois.
38 Edwards et al. 1987; Lundstrom et al. 1998.
39 A detailed description, presentation and application of the computer code are presented in Fouke 1993, 1994, 1996 et al., 2000 et al., 2005 et al.
40 The single element distribution coefficient value for Sr in calcite (\( K_d ^{\text{Sr-Ca}} \)) of 0.05 reported in Kinsman (1969) and Veizer (1983) was applied in these models.
growth. These mineralization events have been systematically mapped based on their CL emissions within the layered stratigraphy of each travertine deposit to determine the relative timing of crystallization and to facilitate the correlation of travertine precipitation between sample sites.

**STRATIGRAPHY AND PETROGRAPHY**

Two categories of crystalline calcite stratigraphy are observed in the Caracalla cistern travertine sample (Fig. 10). Each 'layer' is defined by a sequence of porous encrusting crystal growth capped by a light colored dense layer of crystal growth; this approach groups higher frequency, thinner layering, often of various distinct colors, into distinct 'packages' based on this observable crystal sequence.

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*Figure 10 - Cistern sample showing brick and mortar and 11 travertine layer sequences. Box A, B and C, D refer to thin section microphotographs (see Fig. 11).*

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41 E.g. Meyers and Lohman 1985; Tucker and Wright 1996; Fouke et al. 2005, among many others.
Table 3: Layer Thicknesses in Cistern Sample

<table>
<thead>
<tr>
<th>LAYER</th>
<th>THICKNESS (13.3 cm. total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~0.1—0.2 cm  Category 1</td>
</tr>
<tr>
<td>2</td>
<td>~0.2—0.3 cm  &quot;</td>
</tr>
<tr>
<td>3</td>
<td>~1.0—1.2 cm  Category 2</td>
</tr>
<tr>
<td>4</td>
<td>~0.3—0.4 cm  &quot;</td>
</tr>
<tr>
<td>5</td>
<td>~1.5—1.8 cm  &quot;</td>
</tr>
<tr>
<td>6</td>
<td>~0.7—1.2 cm  &quot;</td>
</tr>
<tr>
<td>7</td>
<td>~0.6—2.1 cm  &quot;</td>
</tr>
<tr>
<td>8</td>
<td>~1.0—2.1 cm  &quot;</td>
</tr>
<tr>
<td>9</td>
<td>~1.1—1.8 cm  &quot;</td>
</tr>
<tr>
<td>10</td>
<td>~2.2—3.0 cm  &quot;</td>
</tr>
<tr>
<td>11</td>
<td>~1.8—2.8 cm  &quot;</td>
</tr>
</tbody>
</table>

In the first category are two thin (0.1—0.2 and 0.2—0.3 mm-thick) horizons (layers 1-2) of densely inter-grown columnar calcite crystals that vary from 100 to 300 mm in length (Figs. 11a and 12a, b). The crystals directly encrust the outer surface of the Roman plasterwork and mortar that sealed the interior wall of the cistern (Fig. 10). The columnar crystals in this layer are inclusion-rich and exhibit a dark non-CL core, followed by a thin bright red-orange CL concentric crystal growth zonation at the outmost margin of each crystal (Fig. 12a, b). The thickness of this late bright CL zonation progressively decreases from ~50 mm at the base of the layer to just a few microns in thickness at the top (Fig. 12a, b).

Figure 11 - Thin section photomicrographs of the Caracalla and Pompeii travertine samples. A. Caracalla cistern travertine (sample position within the hand sample is shown in Fig. 6). B. Pompeii channel travertine (sample position within the core is shown in Fig. 11). C. Caracalla cistern travertine (sample position within the hand sample is shown in Fig. 6). D. Caracalla pipe travertine (sample position within the hand sample is shown in Fig. 9).
Figure 12 - Paired plane-light (left) and cathodoluminescence (right) photomicrographs of the Caracalla cistern travertine. Sample position shown in Fig. 6. A and B. Uppermost layers of the encrusting travertine. C and D. Lowermost travertine in contact with Roman plaster work.

The second category of crystalline calcite stratigraphy in the cistern travertine is a sequence (layers 3-11) that is repeated at multiple length scales throughout the remaining ~ 12.9 cm of the sample (Fig. 10). A total of nine have been observed (Fig. 10), including:

Each sequence is composed of a high-porosity layer of large columnar calcites capped by a dense low-porosity layer of smaller columnar calcite crystals. The stratigraphic layering observed in hand sample (Figs. 10 and 11c) is created by the contact between a completed lower sequence and the initiation of the next overlying crystallization sequence (Fig. 12b). In rare occasions, the layers are formed by ~ 10 to 100 mm thick layers of micrite (i.e. defined as calcite crystals ≤ 1 mm in diameter).  

The top of each of these crystalline sequences have an undulately irregular bulbous surface morphology as it grew from the cistern wall (Fig. 10 and 11a). Each crystalline sequence is initiated with the precipitation of large columnar calcite crystals that reach more than 1 mm in length (Figs. 11c and 12a, b). Because the crystals are not densely inter-grown, these layers of columnar calcite have high porosity and contain large holes (Fig. 11c). Each columnar calcite crystal is inclusion-rich and has a non-CL core,

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42 Bathurst 1975.
followed by the precipitation of a thin mauve CL concentric zoning on the outermost crystal margins (Fig. 12a, b). The columnar crystals are then capped with the precipitation of a layer of different type of calcite (Figs. 11c and 12c). These clear relatively inclusion-free CaCO₂ crystals are 100 to 500 mm long and exhibit moderate to bright red-orange CL as concentric hairline crystal zonations (Fig. 12c, d).

The 5.4 cm thick service gallery travertine exhibits repeated fine-scale stratigraphic layering that varies from ~ 0.5 to 4 mm in thickness (Figs. 13 and 14a). Because the porous to dense “packaging” of crystal growth, observed in this deposit occurs on a very fine scale (~ 1 – 2 mm) in this deposit, any attempt at defining discrete layers would be problematic. Mineralization in contact with the outer surface of the pipes was a deposit of rounded botryoidal arrays of columnar calcite ~ 300 to 500 mm in thickness (Fig. 14a, b). The crystals are inclusion-rich and exhibit a moderately bright mauve CL with bright red-orange CL concentric hairline crystal zonations (Fig. 14a, b). The entirety of the remaining travertine is composed of large columnar ~ 0.5 to 4 mm-long calcite crystals that form botryoid-like arrays of radiating crystals (Fig 14a, b). Individual crystals throughout the deposit exhibit mauve to red-orange, moderate to bright CL, with high-frequency concentric hairline crystal zonations (Fig. 14). The stratigraphic layering observed in hand sample (Fig. 14) is created by extremely fine ~ 10 mm-thick layers of micrite. These micrite layers are then encrusted by columnar calcites that syntaxially grew atop the underlying columnar crystals, creating a dusted micrite layer within columnar crystals that are in optical continuity (Fig. 14). The top of each array created an undulatory surface due to the hemispherical shape of terminations of each bundle of columnar calcites (Figs. 12c, d and 14c, d).

The Pompeii channel travertine exhibits repeated high-frequency crystalline stratigraphic layering on the scale of ~ 50 to 100 mm (Fig. 15). These layers are undulatory as a result of the hemispherical growth form of columnar calcite terminations (Fig. 16a, b). The first layer of mineralization in direct contact with the
Figure 14 - Paired plane-light and cathodoluminescence photomicrographs of the Caracalla service gallery travertine. Sample position shown in Fig. 3. A and B. Upper layers of the encrusting travertine. C and D.

Figure 15 - Pompeian Castellum Aquae channel travertine core samples. Sample location is shown in Figures 1 and 2. The positions microdrilled for geochemical analyses are shown (analyses presented in Tables 1 and 2). The photograph has been rotated 90°, with the "up" direction to the left. Roman plasterwork is at the base of the sample.

Roman plasterwork was a dense deposit of small columnar calcite crystals (Figs. 11b and 16a, b). These crystals have a relatively low concentration of inclusions and exhibit a dark non-CL (Fig. 16a, b). This was followed by precipitation of a dense layer of small inclusion-rich columnar calcite crystals that have an undulatory upper surface (Figs. 11b and 16a and b). The crystals are ~100 mm-long and have a bright red-orange
The Last Flow of Water to, and Through, the Baths of Caracalla

CL concentric crystal zonation at the outer margin of the crystals (Fig. 16a, b). This was in turn followed by the precipitation of larger ~ 100 to 300 mm-long columnar calcite crystals that exhibit mauve CL concentric zonations terminated by a bright red-orange CL zonation at the outmost margin (Fig. 16a, b). The remaining ~ 0.5 cm-thick Pompeii channel travertine deposit is composed of variable inter-layering of the dense inclusion-rich columnar calcites and the larger columnar calcites with fewer inclusions. As in the Caracalla service gallery travertine, the stratigraphic layering observed in hand sample (Fig. 15) is formed by fine ~ 10 mm-thick layers of micrite on which syntaxial overgrowth of the next layers of columnar calcite crystals grew.

**GEOCHEMISTRY**

The $d^{18}O$, $d^{13}C$, $^{87}Sr/^{86}Sr$, and U-series geochemical analyses of the Caracalla and Pompeii travertine deposits are summarized in Tables 4 and 5 and Figures 17 and 18. Detailed evaluation and comparison of these geochemical analyses, both within and between each travertine deposit, is presented in the following sections.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Sample</th>
<th>Collection Sample</th>
<th>Elevation above</th>
<th>Elevation above</th>
<th>Position of</th>
<th>CLS (cm)</th>
<th>CES (cm)</th>
<th>U-Th/U</th>
<th>U-Th/U (cm)</th>
<th>$^{87}Sr/^{86}Sr$</th>
<th>$^{87}Sr/^{86}Sr$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caracalla Service Gallery Travertine</td>
<td>1</td>
<td>71902-1-2</td>
<td>6.35</td>
<td>2.59</td>
<td>72.86</td>
<td>0.71034</td>
<td>0.71034</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>71902-1-1</td>
<td>1.80</td>
<td>3.65</td>
<td>28.13</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>71902-1-4</td>
<td>1.80</td>
<td>2.33</td>
<td>28.56</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>4</td>
<td>71902-1-5</td>
<td>1.45</td>
<td>2.06</td>
<td>78.73</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>5</td>
<td>71902-1-6</td>
<td>3.30</td>
<td>2.20</td>
<td>28.60</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>6</td>
<td>71902-1-7</td>
<td>3.70</td>
<td>2.24</td>
<td>28.55</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
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<tr>
<td></td>
<td>7</td>
<td>71902-1-8</td>
<td>3.20</td>
<td>1.74</td>
<td>29.06</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>71902-1-9</td>
<td>1.79</td>
<td>20.01</td>
<td>0.6999</td>
<td>0.6999</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 4 - Geochemical analyses of Caracalla and Pompeii travertine samples.
Table 5 - U-series results from dating Caracalla and Pompeii samples.

<table>
<thead>
<tr>
<th>Sample No. in Figure</th>
<th>Sample</th>
<th>U ppm</th>
<th>Th ppm</th>
<th>Th/U</th>
<th>(337T) (238U)</th>
<th>error</th>
<th>(337T) (238U)</th>
<th>error</th>
<th>Age before present (kyr)</th>
<th>Age uncertainty (1σ-kyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pompeii cistern travertine</td>
<td>1 72V02-1 WR</td>
<td>2.676</td>
<td>5.657</td>
<td>2.114</td>
<td>0.897</td>
<td>0.007</td>
<td>0.889</td>
<td>0.007</td>
<td>1.104</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>2 72V02-1-4 WR</td>
<td>3.982</td>
<td>11.034</td>
<td>2.017</td>
<td>0.977</td>
<td>0.007</td>
<td>0.968</td>
<td>0.007</td>
<td>1.309</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>2 72V02-1 Ca</td>
<td>1.238</td>
<td>1.035</td>
<td>0.786</td>
<td>0.378</td>
<td>0.002</td>
<td>0.385</td>
<td>0.002</td>
<td>1.017</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td>2 72V02-1 Si</td>
<td>6.708</td>
<td>40.160</td>
<td>2.055</td>
<td>2.055</td>
<td>0.000</td>
<td>0.989</td>
<td>0.019</td>
<td>2.798</td>
<td>0.134</td>
</tr>
<tr>
<td>Caracalla cistern travertine</td>
<td>1 71V02-1-B WR</td>
<td>2.785</td>
<td>0.566</td>
<td>0.520</td>
<td>0.046</td>
<td>0.004</td>
<td>0.057</td>
<td>0.003</td>
<td>1.648</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>2 71V02-1-4 WR</td>
<td>2.696</td>
<td>0.318</td>
<td>0.385</td>
<td>0.004</td>
<td>0.004</td>
<td>0.069</td>
<td>0.001</td>
<td>1.367</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>3 71V02-1-Ca II'R</td>
<td>2.335</td>
<td>0.715</td>
<td>0.315</td>
<td>0.104</td>
<td>0.001</td>
<td>0.080</td>
<td>0.001</td>
<td>1.601</td>
<td>0.016</td>
</tr>
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<td></td>
<td>12 71V02-1 Ca</td>
<td>1.666</td>
<td>0.311</td>
<td>0.171</td>
<td>0.046</td>
<td>0.000</td>
<td>0.043</td>
<td>0.000</td>
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<tr>
<td></td>
<td>12 71V02-1 Si</td>
<td>1.100</td>
<td>4.093</td>
<td>4.196</td>
<td>4.196</td>
<td>0.000</td>
<td>0.828</td>
<td>0.001</td>
<td>1.383</td>
<td>0.014</td>
</tr>
<tr>
<td>Caracalla service gallery travertine</td>
<td>3 71V02-1a-WR</td>
<td>7.844</td>
<td>5.616</td>
<td>0.797</td>
<td>0.263</td>
<td>0.003</td>
<td>0.012</td>
<td>0.002</td>
<td>1.577</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>8 71V02-1-B WR</td>
<td>2.131</td>
<td>1.793</td>
<td>0.845</td>
<td>0.279</td>
<td>0.003</td>
<td>0.176</td>
<td>0.002</td>
<td>1.553</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>8 71V02-1-Ca</td>
<td>1.661</td>
<td>0.597</td>
<td>0.179</td>
<td>0.059</td>
<td>0.006</td>
<td>0.053</td>
<td>0.000</td>
<td>1.321</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>8 71V02-1 Si</td>
<td>2.664</td>
<td>7.610</td>
<td>2.817</td>
<td>2.817</td>
<td>0.010</td>
<td>0.334</td>
<td>0.003</td>
<td>1.173</td>
<td>0.014</td>
</tr>
</tbody>
</table>

**WRT** refers to initial digestion of sample

**Ca** refers to position of sample dissolvable in acetic acid and exclusive of EDTA leach of residual grains (interpreted to be dominantly carbonates)

**Si** refers to sample not dissolved in acetic acid which has also been leached of surface adherents using EDTA

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**Figure 17 - Isotope chemostratigraphic of the Caracalla and Pompeii travertine deposits.**
INTERPRETATION

The Caracalla and Pompeii travertine samples were screened using integrated optical and chemical techniques for evidence of physical (i.e., abrasion, fracturing), chemical (i.e., water-rock chemical exchange, dissolution) and biological (i.e. borings) post-depositional alteration that may have taken place after the original precipitation of the travertine (herein referred to as diagenesis). This critical initial step of evaluating diagenetic alteration is required in order to validate use of the travertine isotopic composition to reconstruct the date, timing and chemical composition of the water from which the travertine was originally precipitated. Results strongly suggest that the Caracalla and Pompeii travertine deposits have not been significantly diagenetically altered since their original precipitation within the Roman hydrologic structures.

Without exception, the columnar calcite crystals comprising the Caracalla cistern travertine, Caracalla service gallery travertine, and Pompeii channel travertine
deposits exhibit well-preserved concentrically zoned CL (Fig. 12, 14, 16). No crystal fabrics such as etching, truncation, or etch pits were observed under plane-light analysis (Figs. 12, 14, 16). Furthermore, no smeared out or diffuse CL patterns were observed within the travertine crystals (Figs. 12, 14, 16), with the intensity and color of the CL emitted from each crystal reflecting the Mn/Fe chemistry of the calcite.\textsuperscript{44} These combined PL and CL observations strongly suggest that no significant post-depositional diagenetic alteration has taken place since the original precipitation of the travertine.\textsuperscript{45}

A minimal extent of diagenetic alteration is further supported by analysis of covariations in the d\textsuperscript{18}O and d\textsuperscript{13}C composition of the Caracalla cistern and service gallery travertine samples (Fig. 14). The geoarcheological setting suggests that the most probable diagenetic water at the Baths of Caracalla (and at Pompeii) was dilute fresh meteoric water derived from rainfall. Covariations in the isotopes produce data arrays that are not coincident with predicted fresh water-travertine reaction curves.\textsuperscript{46} During freshwater reaction with travertine, the d\textsuperscript{18}O would be completely re-equilibrated first, followed by re-equilibration of the Sr\textsuperscript{87}/Sr\textsuperscript{86} and then the d\textsuperscript{13}C.\textsuperscript{47} This sequence of chemical re-equilibration reflects the relative concentrations and isotopic ratios of O, C and Sr in the fresh water with respect to the solid phase travertine.\textsuperscript{48} The result would be a L-shaped reaction trajectory, which is not observed in the Caracalla travertine data.\textsuperscript{49} Therefore, this geochemical evidence combined with the petrographic evidence indicates that the travertine has not been altered via single-stage reaction with fresh water, and thus is consistent with the combined PL and CL petrographic screening in suggesting that the travertine has not been significantly diagenetically altered.

AGE OF THE LAST FLOW OF WATER

The U-series geochemical data and calculated ages for the Caracalla and Pompeii travertine deposits are summarized in Table 5. \textsuperscript{230}Th ages for each sample were calculated using an iterative algorithm for \textsuperscript{238}U-\textsuperscript{234}U-\textsuperscript{230}Th\textsuperscript{50} with the resulting initial (\textsuperscript{234}U)/(\textsuperscript{238}U) shown in Table 5. Detrital Th corrections on ages for the Caracalla cistern and service gallery travertine samples are negligible because the (\textsuperscript{230}Th)/(\textsuperscript{232}Th) ratios were greater than 50.\textsuperscript{51} Conversely, the small yet significant amount of insoluble residue detritus observed from the Pompeii travertine suggests that the detrital Th correction significantly impacted the calculated age for the Pompeii channel travertine sample. In all travertine samples, \textsuperscript{238}U-\textsuperscript{234}U-\textsuperscript{230}Th ages are concordant or nearly concordant with \textsuperscript{230}U-\textsuperscript{234}Pa age, suggesting closed system behavior, again consistent with no diagenetic alteration.

A precipitation age of AD 776 ± 3 (the ± 3 year 2-sigma uncertainty of the U-series age dating technique), or AD 773-779, was calculated from both the top and the bottom samples of the Caracalla cistern travertine (Table 5). This result indicates that the entire ca. 13.3 cm-thick Caracalla cistern travertine deposit was precipitated over a time interval that could have been as short as 1 year (or less) but not more than 6 years. For the 5.4 cm thick service gallery sample, a date of AD 936 ± 16 (AD 920-952) was

\textsuperscript{44} Barker and Kopf, 1991.
\textsuperscript{45} E.g., Ward and Reeder 1993.
\textsuperscript{46} Fouke et al. 2000.
\textsuperscript{47} Meyers and Lohman 1985.
\textsuperscript{48} Banner and Hanson 1990.
\textsuperscript{49} Fouke et al. 2000.
\textsuperscript{50} Cheng et al. 2000.
\textsuperscript{51} Kaufman et al. 1998.
determined for both the top and the bottom layer (Table 5). Thus, the entire 5.4 cm sample was precipitated over a time interval that could have been as short as 1 year (or less) and not more than 32 years — though it must again be noted that the bottom layer represents only the layer reached in collecting the sample, not the complete depth, so the rate of precipitation could, conceivably, have been and likely was more rapid.

For the Pompeii channel travertine sample (Table 5) analyzed as a test of methodology given the known moment of the city's destruction, yielded an impossible precipitation date of 674 +/- 134 BC, most likely as the result of high detrital Th (Table 5) that prevented correct age concordance. A high concentration of Th is consistent with water-rock interactions of the source aqueduct water with the volcanic terrain of Mount Vesuvius that surrounds Pompeii.

**Rate of Precipitation**

The age of AD 776 ± 3 AD for the 13.3 cm-thick Caracalla cistern travertine deposit yields a variety of possible precipitation rates ranging from: a minimum rate, using the maximum possible duration of 6 years, of ca. 22.17 mm per year (or 0.061 mm per day); a maximum rate, using an estimated minimum duration of 1 year, of ca. 133.00 mm per year (or 0.364 mm per day); and a mean precipitation rate, based on a 3 year duration, of 44.30 mm per year (or 0.121 mm per day). The age of 936 ± 16 AD for the 5.4 cm-thick Caracalla service gallery travertine yields the following range of precipitation rates: a minimum rate, using the maximum possible duration 32 years, of 1.69 mm per year (or 0.005 mm per day); a maximum rate, using an estimated minimum duration of 1 year, of 54.0 mm per year (or 0.148 mm per day); and a mean precipitation rate, based on a 16 year duration, of 3.38 mm per year (or 0.009 mm per day).

Although fast for most natural geological environments, these calculated rates for the Caracalla cistern and service gallery travertine are several orders of magnitude slower than the in situ natural travertine precipitation rates of 37 to 1865 mm/yr (0.1 – 5 mm/day) at Mammoth Hot Springs in Yellowstone National Park (the only active modern site of travertine precipitation in which travertine precipitation has been quantified using 765 precipitation substrates measured in triplicate. Extensive CO$_2$ out-gassing is the primary mechanism driving these exceedingly high rates of carbonate mineral precipitation, the effects of which systematically increase with progression along the spring drainage outflow system. The spring water emerging at Mammoth Hot Springs is similar in chemical composition to the Apennine hot spring water that fed the Roman aqueducts.

However, the potential for travertine precipitation at the Baths of Caracalla was significantly reduced because the spring water was transported through the aqueduct system from source to the Caracalla cisterns. This would have been due to; (1) the coupled vigorous effects CO$_2$ degassing, dropping temperature, and mixing and

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52 Turi 1986.
53 Fouke et al. 2000; Veysey 2006; and Schickel 2006. There are several other spring localities around the world in which single measurements of travertine precipitation rate have been made. However, these analyses are without specific description of sample location within each spring drainage systems and they are not easily verified because they were not done in triplicate measurements.
54 Schickel 2006.
55 Veysey 2006.
holding with other waters\(^5\); (2) differences in physical and chemical constraints imposed by the aqueduct (i.e. variable water flow rate, depth, and length minimal surface area to atmosphere contact, increased humidity in the covered or subterranean aqueduct air headspace); (3) regional groundwater composition (i.e. water temperature, pH dissolved CO\(_2\) chemistry, and subsurface water-rock interaction history; (4) estimates of mass of travertine precipitated in the aqueducts using equilibrium and kinetic equations for carbonate crystallization dynamics.\(^5\) These characteristics would largely explain the expectedly lower, but scientifically plausible, precipitation rates for the Caracalla cistern and service gallery travertine with respect to modern Mammoth Hot Spring travertine.

No previous analyses of natural travertine layering, found in various springs around the world, have previously observed cm-scale layering of travertine that has been consistently correlated with annual, seasonal, or solar cycles. Thus, equating travertine layering with annual cycles in the manner done for tree-ring ‘dendrochronology’ cannot be substantiated by published evidence to date. In natural settings, changes in travertine precipitation rate of as much as an order of magnitude (e.g. 10\(^x\)) are commonly observed at successive positions along the central axis of the primary flow path (thalweg) of any single spring drainage system.\(^5\) This results in the precipitation of multiple layers of travertine of dramatically different thicknesses at any one site.

**HYDROLOGY**

Because the physical, chemical, and biological controls on calcite crystal growth are highly complex and often do not follow predicted crystallization mechanisms (as described above), it is not possible to quantitatively reconstruct changes in ancient water flow conditions directly from the crystalline morphology, stratigraphy, and chemistry of the travertine deposits. In addition, the deposition of each new successive travertine layer does not necessarily indicate a break or cessation in flow. However, a series of multiple working hypotheses regarding possible relative trends and changes in flow during the course of travertine precipitation can be postulated.

The travertine precipitation in the Caracalla cistern appears relatively straightforward, for the most part being the result of 11 successive layers of lateral growth. Two initial thin layers (\(\leq 4\) mm thick) of travertine crystal precipitation (Layers 1 and 2) encrusted the cistern mortar substrate (Figs. 10, 13, 15). This is consistent with nucleation control by the initial substrate during the earliest phases of precipitation.\(^5\) The crystal morphology and chemistry of the travertine in these first layers would be expected to differ between sites, depending on the mineralogy and chemistry of the surface being encrusted by the travertine. However, once the surfaces were fully encrusted (or armored) with calcite, some level of steady state crystallization would have been initiated and ensuing precipitation would no longer be influenced by the substrate.

Following this are 9 distinct layers (sequences) of porous to dense columnar calcite cement observed in the cistern travertine (Fig. 10) imply that water flow and/or chemistry in the cistern changed during the course of travertine precipitation. In theory, the large porous network of columnar calcite (the lower portion of each

\(^{56}\) Veysey 2006.
\(^{57}\) E.g., Banner and Hanson 1990; Fouke 1994.
\(^{58}\) Veysey et al. 2006.
\(^{59}\) Fouke et al. 2006.
crystalline sequence) would be consistent with higher travertine precipitation rates that may have resulted from higher water flow and/or calcite mineral saturation state. Conversely, the smaller and more densely inter-grown columnar calcites, which contain fewer inclusions and cap each sequence (Fig. 10), imply lower crystal growth rates due to lower water flow and/or chemical saturation levels. If correct, each crystalline sequence represents a period of decreasing calcite precipitation rate resulting from decreases in water flow and/or calcite saturation.

By contrast, the travertine growth in the service gallery — where water might have flowed downward over a longer period of time and in a more turbulent manner, thus creating a greater accumulation of travertine, albeit at a slower rate — is more complex. Here, the travertine grew both outward from and around the descending pipes and upward, across the floor. As we did not sample the lowermost floor sample, it is not possible to say at what date the precipitation began there.

**Chemistry and Temperature**

The cistern and service gallery travertine deposits exhibit very similar isotopic compositions, which range from -1.19 to -3.29 in d18O, -5.27 to -6.52 in d13C, and 0.710119 to 0.710254 in 87Sr/86Sr. This therefore suggests that the two travertine deposits were precipitated from similar or at least closely related spring water transported through the aqueduct system.

There are four distinct chemostratigraphic trends in d18O observed within the cistern travertine, herein labeled Intervals I - IV (Fig. 17): (1) Interval I (0 - 6 cm) shows little variation in d18O (-1.19 to -2.02 ‰), suggesting the water was at a relatively consistent temperature for the duration of precipitation; (2) Interval II (6 - 10 cm) exhibits a consistent increase in d18O from -1.19 to -2.87 ‰, indicating that the water consistently warmed during the precipitation of this interval; (3) Interval III (10 - 12 cm) travertine has d18O from -2.87 to -2.24 ‰, suggesting a relative cooling of water temperature during this interval; and (4) Interval IV (12 - 13 cm) exhibits an increase in d18O from -2.24 to -3.29 ‰, indicating another relative increase in water temperature during this interval of travertine precipitation. The service gallery travertine exhibits only a single upward increasing trend in d18O from -2.91 to -1.79 ‰, indicating a relative decrease in water temperature during the period of travertine precipitation represented by the sample.

Reconstruction of the temperature of the water from which the cistern and service gallery travertine precipitated has been calculated using the carbonate mineral d18O equilibria equations presented in Kim and O'Neal (1997). These temperature reconstructions are predicated on accurate estimation of the oxygen-isotopic composition of the original water from which the minerals precipitated. To do this, analogy has been made with present-day ground water and spring water in central Italy, which exhibit broad compositional ranges of -3 to +3 ‰, d18O SMOW. Furthermore, significant variations are frequently observed both within and between nearby springs. Therefore, the aqueduct water may also have had a similarly broad and variable range in isotopic composition. If this assumption is accurate, the total variability in reconstructed water temperature ranges from 4 – 48 °C, with an

60 Ward and Reeder 1993.
61 Quattroocchi et al. 2000.
uncertainty of +/- 2°C for each calculation (Fig. 19). The Caracalla cistern travertine exhibits a range in δ18O travertine of -1.19 to -3.29‰, yielding a temperature range of approximately 8 to 28°C (Fig. 19). The Caracalla service gallery travertine exhibits a more narrow range of -1.74 to -2.91‰ d18O, suggesting a temperature range of approximately 6 to 31°C (Fig. 19).

Sr-isotope Analyses

To identify possible sources for the Caracalla water, we have measured the strontium isotope ratio (87Sr/86Sr) of the Sr ions that were derived from the aqueduct water and precipitated within the crystal lattice of the CaCO3 travertine mineral deposits.

Prior to being channeled from each hot spring source into an aqueduct intake, the subsurface ground water feeding the hot springs flowed through porous and fractured bedrock in a variety of geological terrains surrounding Rome. Along the course of its subsurface flow path, the ground water continually experienced water-rock geochemical interactions, during which time the rock-forming minerals in the host bedrock were dissolved and/or precipitated. This resulted in the exchange of Sr ions from the surrounding bedrock into the ground water, imparting the distinct 87Sr/86Sr signature of the regional bedrock to the ground water. In turn, as each ground water erupted in the source hot springs and was funneled into and transported through the aqueducts, the 87Sr/86Sr of the aqueduct water was recorded by the Sr ions precipitated in the aqueduct travertine. As a result, the 87Sr/86Sr of diagenetically unaltered aqueduct travertine has been used to reconstruct the regional bedrock through which the hot spring source of aqueduct water was originally transported (e.g. the source of aqueduct water).

In the region surrounding Rome, the bedrock includes a combination of Cenozoic volcanic rocks and Mesozoic marine limestones, each of which exhibit overlapping
ranges with respect to their strontium isotope ratios (Fig. 20, see below). The volcanic bedrock exhibit a wide range in $^{87}\text{Sr}/^{86}\text{Sr}$, which reflects their variable ages and chemical compositions (0.70600 to 0.71500). The thick sequence of marine limestone region contains variable $^{87}\text{Sr}/^{86}\text{Sr}$ signatures due to changes over geological time in the mixing of different Sr sources to the world's oceans (0.70690 to 0.70805). Our results (Table 4) indicate that the Caracalla cistern travertine ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710201 - 0.710254$) and the service gallery travertine ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710119 - 0.710222$) exhibit relatively high Sr-isotope ratios, which are most consistent with the upper range of volcanics observed in the region south-southeast of Rome that includes the Alban Hills (Fig. 21). Conversely, the Pompeii channel travertine contains a lower $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.707638 to 0.707675, which is consistent with precipitation from groundwater that reacted with Cenozoic volcanics associated with Vesuvius (Fig. 20).
PART III. ARCHAEOLOGICAL IMPLICATIONS

CHRONOLOGY OF THE LAST FLOW

The five dates obtained for the Caracalla cistern sample (all of AD 776 ± 3; range AD 773-779) and the four dates for the service gallery sample (all of AD 936 ± 16: range AD 920-952), indicate that water ceased to flow through the cistern around AD 776 and that water last flowed through the service gallery (at least at the location sampled) around the second quarter of the 10th century AD. Because the inner and outermost cores in both samples are identical in date, neither provides an absolute time scale for formation. None of these dates bear on when (much earlier), precisely, the baths ceased to function as baths.

These dates present no evidence for any interruption of water flow caused by Witigis. The presence of water in the cistern around AD 776 (+3 years) does, however, accord well with the time of the repairs on the Iobia aqueduct by Hadrian I recorded in the Liber Pontificalis in the same year. Perhaps the rapid armoring of the cistern with 13.3 cm of travertine in less than six years, only to be discontinued (even though the aqueduct feeding the baths continued to flow), is simply due to the repeated and turbulent charging and recharging of the cistern by crews working in Hadrian’s construction campaigns to repair the aqueduct. The task completed on this segment of the aqueduct and a steady flow of water assured, perhaps repeated refilling of the cistern was no longer required and thus discontinued. Or, less convincing, perhaps in the years immediately following the repairs of Hadrian water was stored regularly in the cistern, and so encrusted the reservoir, but that as a steady flow of water was secured, the practice was discontinued. And there are doubtless other possible explanations.

The date of the last flow in the service gallery (AD 936 ± 16) suggests that water last flowed at this location around the second quarter of the 10th century. This date is
later than, hence concordant with, the recorded aqueduct repairs of both Sergius II (Iovia, AD 844-845) and Nicholas I (Iocia, AD 858-867). Regardless of which of the variant medieval toponyms — Iovia, Iobia, Iovia, Iopia or Iocia — refer to the Antoniniana (or to the Alexandria or Julia), the dates obtained from this sample suggest that water continued to flow for roughly three quarters of a century, and perhaps somewhat longer, after the latest of these rebuilding campaigns. Further, the date of AD 936 ± 16 and the fact that water was now flowing in an uncontrolled manner outside of the pipes in the service gallery suggests that by this time the aqueduct system was, once again, in a state of disrepair. This late, near-terminal timing of AD 936 ± 16 may accord with the possible timing of last use of aqueduct water use at other, ‘down-stream’ sites. After reaching the Baths of Caracalla, the Einstedeln Itineraries record that the Iobia / Antoniniana coursed to the Tiber (...currit usque ad ripam). A water-mill constructed in a chamber of the east hemicycle of the Circus Maximus within a channel believed to be a branch of the forma Iobia coming from the Baths of Caracalla and perhaps associated with the diaconia of Saint Lucy in Septem Vias, is thought to have remained in use between the 6th and the 10th century AD, and a baptistery, seemingly utilizing water from the same channel behind Santa Maria in Cosmedin, has also been dated down to the 10th century.

Water may also have been needed within and in the immediate vicinity of the Baths of Caracalla in the 9th and 10th centuries. Within the baths, the 6th and 7th century AD burials were probably associated with Saints Nereus and Achilles (LP xlii, 68), located immediately to the north, a church whose titulus probably became a diaconia after ca. AD 600 but before AD 776-777. The latter date is the time of the repairs undertaken by Hadrian I on the forma Iobia and the two events, elevation of church status and the upgrading of the water supply, may conceivably have been in some way linked. Speculating, this diaconia, rebuilt by Leo III (AD 795-816), may have boasted its own balneum and an associated xenodochium (in viae Nova?), but it could also be that the water supply to the church was never problematic. The Liber Pontificalis (2.33) records the construction of the new church (...a fundamentis in loco superiore...) owing to the presence of excessive ground water, and a renaissance (?) well-head in the north exedra seems to have exploited a continuous flow in the Roman drains.

The amount of water that could be drawn from however many of the Caracalla cisterns may have remained in use in the medieval period cannot be known, but conceivably, several cisterns, probably those closest to the aqueduct discharge, may well have remained in use for whatever purpose. Lombardi and Corazza have estimated the capacity of the main eighteenth cisterns (8.5 m width x 13 m length x ca. 5 m height) to be somewhere between ca. 9,000 and 10,000 m³ (or somewhere between 500-552.5 m³ per cistern), with a 5 m water height within the cistern determined by the level of the top of the precipitated travertine on its sides. If the upper- and outermost

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65 Coates-Stephens 2003c, 138 and Belardini 2003, 211-212 On whether the Agua Antoniniana was constructed solely for the Baths of Caracalla, and not to supply other sites, see Garbrecht and Manderscheid 1992, 229-230, note 58 and Belardini and DeLogu 2003, 211.
66 Brandizzi Vitucci 1991; Bellardini and DeLogu 2003, 210-212; Coates-Stephens 2003a, 175, fig. 7, no. 24 and 2003c, 138.
67 De Spirito 1996; Pavolini 1999, 437, note 85, with earlier bibliography; and DeLaine 1997, 40-41.
69 Lombardi and Corazza 1995, 101, fig. 86.
70 Lombardi and Corazza 1995, 65 (10,000 m³); and Lombardi 2002, 52 (9000 m³).
level of the precipitated travertine is taken to represent the date of last flow, and the
date of the travertine at 5 m above the floor corresponds to the date of our cistern
sample, AD 776 ± 16, then the capacity of the cisterns in the 8th century AD may still
have been significant, even if only a few, partially filled cisterns remained in service for
however short a time.

RATES OF PRECIPITATION

The maximum, mean and minimum possible yearly and daily rates of travertine
precipitation for the 13.3 cm cistern and the 5.4 cm service gallery samples, lying at an
unknown distance (ca. 20 or 90 km?) from their water source(s), are:

TABLE 6: MAXIMUM, MEAN AND MINIMUM POSSIBLE YEARLY / DAILY RATES OF TRAVERTINE
PRECIPITATION CISTERN AND SERVICE GALLERY SAMPLES.

<table>
<thead>
<tr>
<th>CISTERN (AD 776 ± 3) over 13.3 cm</th>
<th>Annual mm</th>
<th>Daily mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum duration (6 years)</td>
<td>22.17</td>
<td>0.061</td>
</tr>
<tr>
<td>Mean duration (3 years)</td>
<td>44.30</td>
<td>0.121</td>
</tr>
<tr>
<td>Minimum duration (1 year)*</td>
<td>133.00</td>
<td>0.364</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SERVICE GALLERY of (AD 936 ± 16)* over 5.4 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum duration (32 years)</td>
</tr>
<tr>
<td>Mean duration (16 years)</td>
</tr>
<tr>
<td>Minimum duration (1 year)*</td>
</tr>
</tbody>
</table>

* '1 year' is a figure of convenience for purposes of calculation.
* * Precipitation rates for the service gallery are minimum possible accurate rates, because the sample
gives us a starting point (surface of the pipe) but no known ending point.

These absolute, U-series-based rates of precipitation (see above, part II) range
from somewhat faster to extremely faster than those rates previously estimated, using
different methods, by various authors for the Nimes, Cologne and Aqua Antoniniana
aqueducts (Tables 1-2). The 22.17 mm minimum yearly rate of precipitation for the
cistern sample is roughly fourteen times faster than the highest yearly rate (1.58 mm)
proposed for the aqueduct at Cologne and nearly twenty times faster than the highest
yearly rate for the aqueduct of Nimes, while the minimum rate for the service gallery
sample, at 1.69 mm, is only slight faster the maximum 1.58 yearly rate of Cologne
(Table 1) and over twice as fast as the maximum yearly rate of 0.80 mm proposed for
the Aqua Antoniniana at the 'Arch of Drusus', though, with only a known start point,
it may have precipitated yet faster (Table 2).71 Were we to compare the maximum
rates of the two Caracalla samples with those from Cologne, Nimes or the Aqua
Antoniniana, those from the baths would be significantly faster.

In fact, even the slowest yearly precipitation rates for either Caracalla samples of
22.17 mm and 1.69 mm are, respectively many orders of magnitude, or somewhat,
slower than those posited for any Roman aqueduct. However, as noted above and as
shown by Garbrecht and Manderscheid, these rates would have tended to slow as

71 Perhaps the proposed rates are not so surprising if, as posited by Garbrecht and Manderscheid (1992, 231) water may, after thick
deposits of travertine had constricted the specus, still have flowed at a respectable, if reduced rate, of
up to 19,100 m³ per day. L. Quilici (1989, 60) has
calculated that the Aqua Marcia alone transported
ca. 47 metric tons of lime per day.
distance to source (ca. 18 km from the Alban Hills and ca. 95 km from the Aniene Valley) increased. On the other hand, there is no evidence that the rates of precipitation could not have been somewhat faster as the flow may, occasionally, have stopped for repair or other reasons for shorter or longer periods.

If these precipitation rates for the Baths of Caracalla appear high compared to past estimates of travertine in aqueducts made by other methods, they are nevertheless orders of magnitude slower than those that can be observed at natural sites such as Mammoth Hot Springs in Yellowstone National Park, where rates ranging from 37 (0.1 mm/day) to 1865 mm per year (5 mm/day) have been observed. The results of the present study, therefore, strongly suggest that related applications of travertine stratigraphy, petrography, geochemistry, modeling, and U-series isotopic dating to other aqueducts might also yield significantly faster rates of precipitation and that precipitation rates of many aqueducts have been significantly underestimated. If this is the case, then numerous issues of aqueduct design, maintenance and duration may well need to be revisited for both the Roman and medieval periods.

**Temperature**

Data from this study indicate that the water from which the CaCO$_3$ minerals were deposited ranged from ~ 8-28° C for the cistern sample and ~ 7-31° C for the service gallery sample. Both of these rather broad ranges fall within those commonly cited for water from those aqueducts sometimes cited as sources for the water that flowed to the Baths of Caracalla: the Marcia (ca. 9° C), the Tépula (ca. 17-18° C) and the Julia (ca. 11-12° C). The ranges disallow distinguishing between a colder aqueduct source such as the Marcia from a warmer source such as the Tépula. Further, even if the estimated temperatures were much narrower, the admixture of other waters into both the Julia and Tépula described by Frontinus — if he can in any way be considered reliable so many centuries later — suggests that the chances of identifying the diluted waters of any single aqueduct course on the basis of temperatures are small.

The cistern travertine sample displays only four alternating trends in water temperature (Fig. 19): from no change, to warming, to cooling, then to a final warming over six years or less. So few and such gradual changes are difficult to attribute to shifts in seasonal or climatological changes, and more likely relate to changes in water pressure, mixing and sources, and to other, probably unknowable reasons. By contrast, the 5.4 cm sample from the service gallery, with many fine layers demonstrates a consistent cooling trend over a period of 32 years or less.

**Sources of Water**

Identifying the source(s) of the water, and hence the likely aqueduct(s) that supplied the Baths of Caracalla both during the centuries when the complex was in service for bathing or in the centuries thereafter on the basis of our results is complex. The literature indicates that volcanics in the region of Rome containing 87Sr/86Sr are generally higher than, or can slightly overlap with, regional bedrock limestone Sr-isotopes (Fig. 20). The Alban Hills volcanic terrain exhibits a range in 87Sr/86Sr of ~

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72 Fouke et al. 2000; Veysey et al. 2006; and Schickel 2006.
0.70920 to 0.71090 (Fig. 20),\(^23\) while the Apenninic limestone terrain exhibits a range in \(^{87}\text{Sr}/^{86}\text{Sr}\) of \(~0.7680\) to \(0.7080\).\(^{24}\)

As demonstrated above (Table 4), because the strontium-isotopic ratios obtained from the analyses taken from our two samples all fall within a range of 0.710119 to 0.710254, the water could not have originated from limestone sources alone. It could, however, have originated from either a mixture of volcanic and limestone sources, or from a single volcanic source(s). Thus, the traditional favorite, the \textit{Marcia}, can be eliminated, at least as the sole source of the water for the \textit{Antoniniana} which fed the Baths of Caracalla during this period. More likely sources for the water flowing into the \textit{Antoniniana} are the \textit{Julia}, \textit{Tepula} or \textit{Alexandrina}\(^25\) aqueducts, all of which originate in volcanic terrain, possibly mixed with water from the \textit{Marcia}.

In 1998 Coates-Stephens suggested that the \textit{Antoniniana} might be an extension of the \textit{Alexandrina},\(^26\) but later abandoned this position in a 2005 study,\(^27\) coauthored by L. Lombardi and M. Barbieri, which employed strontium-isotopic analyses of precipitated aqueduct travertine (Table 7, below) to reconstruct the hydrologic connectivity between individual lines of the aqueduct system. Assumptions, stated or implied, in that 2005 study appear to be:

1) The waters that precipitated the travertine in the cisterns and in the service gallery were single-sourced, not an admixture from various sources.
2) Travertine in the Caracalla cisterns and in the semi-circular tank which fed the cisterns precipitated from water that flowed when the baths were in still use, while the travertine in the lower service gallery was from a later, ‘post-bath’ flow.
3) There were two major flows resulting in travertine precipitation, and these correspond to those observed by Garbrecht and Manderscheid at the ‘Arch of Drusus’ (two major flows followed by third, heavy in detritus, each separated by lengthy periods of cessation).
4) Modern water samples drawn from the likely sources of the \textit{Tepula} (Preziosa) and \textit{Julia} (Grottaferrata) aqueducts may substitute for precipitated travertine samples from the aqueducts themselves.

On the basis of \textit{specus} elevations, they argue, surely correctly, that the \textit{Appia}, \textit{Vergine} and \textit{Augusta} aqueducts were too low to have fed the Baths of Caracalla and, on the basis of comparison of strontium-isotopic ratios of precipitated travertine from the Baths of Caracalla with samples from the \textit{Marcia} and \textit{Alexandrina} aqueducts and from modern water collected from the likely sources of the \textit{Tepula} and \textit{Julia} aqueducts, that the \textit{Julia} was the source for water during the period of the Baths’ operation (the \textit{novio fonte antoniniano}) and the \textit{Tepula} during an undefined but later, ‘post-bath’ flow.\(^28\)

\(^{23}\) Turi 1986.
\(^{24}\) McArthur et al. 2001.
\(^{25}\) The latter named after Alexander Severus (\textit{Registrum of Subiaco} 12, 14 and 105 – \textit{Forma Jovia}). Also called the \textit{Alexandrina}.
\(^{26}\) Coates-Stephens 1998, 176.
\(^{27}\) Lombardi, Coates-Stephens and Barbieri 2005.
\(^{28}\) Coates-Stephens 2003c, 137-138 and Lombardi, Coates-Stephens and Barbieri 2005. This scenario would make the \textit{Forma Iobia} of the \textit{Einseleiten Itinerary} a derivation of the \textit{Tepula-Julia} (Iobia = Julia) system rather than of the \textit{Marcia} or of the \textit{Alexandrina}. 
Table 7: Strontium-Isotopes Ratios: Lombardi et al. (2005) and Hostetter/Fouke

<table>
<thead>
<tr>
<th>Travertine - Caracalla:</th>
<th>Lombardi et al. 2005</th>
<th>Hostetter &amp; Fouke</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 samples cisterns/channel</td>
<td>0.71015</td>
<td>0.710201—0.710254</td>
</tr>
<tr>
<td></td>
<td>0.71015</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.71018</td>
<td></td>
</tr>
<tr>
<td>Service gallery samples “average”:</td>
<td>0.71043</td>
<td>4 samples 0.710119—0.710222</td>
</tr>
<tr>
<td>Travertine - Marcia and Alexandrina:</td>
<td>0.70886</td>
<td></td>
</tr>
<tr>
<td>Aqua Marcia “vari campionii”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parco degli aquedotti (average values – or values of each sample identical?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AQUA Alexandrina, TOR TRE TESTE</td>
<td>0.71023</td>
<td></td>
</tr>
<tr>
<td>2 samples of “identico valore”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER - Grottaferrata &amp; Preziosa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Squarciarelli (Grottaferrata)</td>
<td>0.71016</td>
<td></td>
</tr>
<tr>
<td>drinking fountain (“Aqua Julia”)</td>
<td>0.71015</td>
<td></td>
</tr>
<tr>
<td>Preziosa spring, well over source (“Aqua Tepula”)</td>
<td>0.71038</td>
<td></td>
</tr>
</tbody>
</table>

The model suggested by the data of the present study differs in the following ways:

1) First, all the dates for the cistern sample, a very tight AD 776 +/- 3 years in both the earliest and the latest layer, indicate that the travertine was precipitated in less than 6 years, with no major hiatuses, from a ‘post-bath’ flow occurring long after the baths were last in service and, again, possibly associated with the repairs of Hadrian I. By contrast, the date of the lower service gallery sample (936 +/- 16 AD), again, for both the earliest and the latest layer, suggests water flow at a time when the medieval system had, once again, fallen into disrepair.

2) The geochemical similarity of the cistern and service gallery samples strongly suggest that the same water — from however many sources — flowed through both the cistern and service gallery, despite the ca. 160 years bracketed by the two samples.

3) The calcite crystal growth structure in the cistern samples indicate at least eleven flow or crystal growth sequences within 6 years or less79 hence, at least at that precise location within the cistern, there is no evidence for two or three major flows or for significant hiatus between flows. The crystal growth structure of the smaller service gallery sample indicates only multiple, small-flow crystal growth sequences over less than 32 years.

4) The temperature range of ca. 8–28° degrees C for the cistern travertine and ca. 6–31° degrees C for the service gallery travertine present plausible ranges but ranges too broad to distinguish between a colder aqueduct source such as the Marcia (ca. 8–9° C), from a warmer source such as the Julia (ca. 10–12° C) or the Tepula (ca. 17-18° C).

79 ‘Dirty’ layers between travertine layers interpreted as major hiatus in water flow (as seen in the ‘Arch of Drusus’ specus (Fig. 9), may represent either a long hiatus in flow or as little as a few days of flowing contaminants.
Even if the resulting ranges were much narrower, the mixing of the waters of the *Julia* and *Tepula* (and with others as well) as described by Frontinus — if he can in any way be relied upon so many centuries later — suggests that our ability to identify the water of any single aqueduct course on the basis of temperatures are quite small.

(5) Lastly, the 0.710119 to 0.710254 strontium isotopic ratios for the cistern and service gallery travertine samples suggest either a solely Alban Hills volcanic source or a mixed volcanic and limestone source. Thus, while it is possible that the last or later flow of water to the baths arrived from the *Tepula* or the *Julia*, it could equally have come from the *Alexandrina*, whose water also derived from volcanic terrain, or yet from any of the three with an admixture from another source such as the *Marcia*.

Perhaps, the *Alexandrina* may once again be the most likely candidate for the water source(s) for the *Antoniniana*. As Coates-Stephens argued in 1998, the trace of the *Alexandrina* roughly aligns with that of the *Antoniniana*, and its elevation of ca. 46 m at the last documentable site would have descended gently to the *Antoniniana* at ca. 42 m asl, whereas the elevations of the *Julia* or *Tepula* (or *Marcia* for that matter) were significantly higher. Moreover, the *Alexandrina* (along with the *Claudia*) is reported to display 8th and 9th century repairs and, too, it may not be coincidental that property documents of the 10th and 11th centuries refer to branch supplies off the main channels of the *Alexandrina*.

In sum, the unresolved nature of the textual and archaeological evidence and the inconclusive nature of the strontium-isotopic ratios obtained by the present study disallow the secure identification of the aqueduct(s) which fed water into the *Antoniniana* and the Baths of Caracalla. The *Julia* and *Tepula*, individually or in combination with the *Marcia*, and, once again, the *Alexandrina*, all remain viable candidates.

Were a comprehensive, integrated isotopic and petrographic analyses study conducted with several hundred of *87Sr/86Sr* analyses on many scores of samples from numerous locations along the same aqueduct lines, and the results coupled with analyses of key elemental concentrations, firmer answers might emerge. Such a suite of analyses would also lend itself to quantitative interpretation of the mixing of aqueduct waters which, in turn, might eliminate a number of aqueducts as possible sources for the Baths of Caracalla and so, conceivably, permit identification of the source of the *Agua Antoniniana*.

CONCLUSIONS

For the Baths of Caracalla, we may now posit that, from the time when the encrusting travertine was last scraped off the walls of the cistern, water flowed for six or fewer years, sometime around AD 776, and that it flowed through the service gallery for less than 32 years, until late in the first half of the 10th century. The last years in which the cistern remained in use may have been around the time of the repairs to the aqueduct by Hadrian 1. By contrast, water flowed, not necessarily

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80 Agrippa mixed the warmer and distasteful waters of the *Tepula* with those of the clearer, colder and more palatable *Julia* in order to improve the former and to allow for the diversion of waters of distinct character and quality to the most suitable venues. On all three aqueducts, see Evans 83-103.


82 Coates-Stephens 2003a, 169, 172, fig. 2.
uninterruptedly, in an uncontrolled manner down the outside of the pipes and across the inclined floor of the service gallery as late as in the second quarter of the 10th century, and conceivably later, probably in the service of several 'downstream' diaconiae. The data therefore suggests, in accordance with the archeological and textual evidence of the medieval period, a more prolonged, if not continuous, use of the Aqua Antoniniana/Jovia than previously thought, a flow probably connected to other 'downstream' sites such as SS Nereus and Achilleus, S Lucy in Septem Vias and S Mary in Cosmedin.

Rates of travertine precipitation may have been significantly faster than earlier believed and past methods of age estimations based on the counting of supposed annual layers and the correlation of layers to known historical events or to seasonal and solar cycles may now be abandoned.\(^{83}\) Four alternating warming and cooling trends are discernable in the travertine precipitated by the water flowing through the cistern and a more consistent and longer cooling trend is discernable in the flow of the service gallery. Neither can be associated with climatalogical changes. The similar water chemistry of the travertine from both the cistern and service gallery samples suggest a single, still unknown volcanic or, possibly, a combined volcanic/limestone source, despite their age difference of ca. 160 years. This would exclude the Aqua Marcia, originating in Apenninic limestone terrain, as the sole source, but could include the Julia, Tepula and, especially, the Alexandrina, all originating in the volcanic regions of the Alban Hills.

**Bibliography**

Adolphe 1973

Banner and Hanson 1990

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Bathurst 1975

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\(^{80}\) Blanc (2000, 249-261) also noted that the attractive notion of annual cycles was not supported by the scientific evidence.
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Cattalini 1986a
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Conforto and Iacopi 1992
De Laine 1997
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Edwards et al. 1987
Espérandieu 1926
Evans 1994
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Fiches and Paillet 2000
Ford and Pedley 1996
Fouke 1993
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Fouke et al. 1996
Fouke et al. 2000
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Frank, Mangini and Korfmann 2002
Garbrecht and Manderscheid 1992
Geertman 2003
Gilly 1971-1972
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Grewe 1986
Grewe and Blackman 2001
Guendon and Vaudour 1986
Guendon and Vaudour 2000
Hauck and Novak 1987
Hodge 1991
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Iacopi 1985
Joseph, Gilly and Rodie 2000
Kaufman et al. 1998
Kim and O’Neil 1997
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Langmuir et al. 1978
Leveau 1991
Lombardi 2002
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Lombardi and Corazza 1995
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Magnusson and Squatriti

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