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Lead Contamination in the Drinking Water of Pompeii

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Was poisoning from lead pipes a risk for the people of ancient Pompeii? The question of lead poisoning in Roman water systems has been a matter of debate for some time (Kobert 1909; Gilfillan 1965; Waldron 1973, 392–393; Hodge 1981; Scarborough 1984, 475). The current consensus holds that a layer of calcium carbonate called sinter developed on the inside of lead pipes, protecting the drinking water from lead contamination. A study of ninety-two skeletons from Herculaneum, however, shows exceptionally high levels of lead concentrations in a contemporary and nearby population believed to have been supplied by the same aqueduct. These concentrations are higher even than modern workers who endured long-term exposure to lead (appendix 1). There were, however, several possible sources of lead poisoning in ancient Pompeii other than the lead pipe water supply. Our research has shown that very high levels of lead are found within the sinter deposits themselves at varying locations along the water distribution system within Pompeii. These facts bring into question the commonly held belief that sinter build up prevented lead contamination in Roman drinking water.

Therefore, the present study examines the issue of lead contamination in Pompeii's water supply by attempting answer to two related questions. First, was sinter build up an effective protection against the absorption of lead in the water supply? Second, what was the source of the lead found in sinter deposits in Pompeii? To answer each of these questions, the potential sources of lead contamination must be isolated. The paper therefore begins with a discussion of the aqueduct systems that might have served Pompeii and their sources (parent water), as well as consideration of environmental contaminants and the city's water distribution system itself. The second half of the paper details the results of our study of eighteen samples of sinter using a method called laser ablation inductively coupled plasma mass spectrometry in order to determine whether lead concentrations changed as the sinter deposits grew over time. To our knowledge, this is the first time such a method has been employed. Detailed discussion of the sampling strategy (appendix 2) and methodology (appendix 3) are found at the end of the paper.

Background

The piped water supply of ancient Pompeii

Pompeii's aqueduct and piped water distribution system are fairly well understood (Fig. 9.1) Water was conveyed by gravity from one of the highest points in the town, the *castellum aquae* near the Porta del Vesuvio, through lead pipes (Fig. 9.1, dotted lines) to public fountains, baths and private dwellings. Water towers (Fig. 9.1, circles) topped by open lead basins were placed periodically

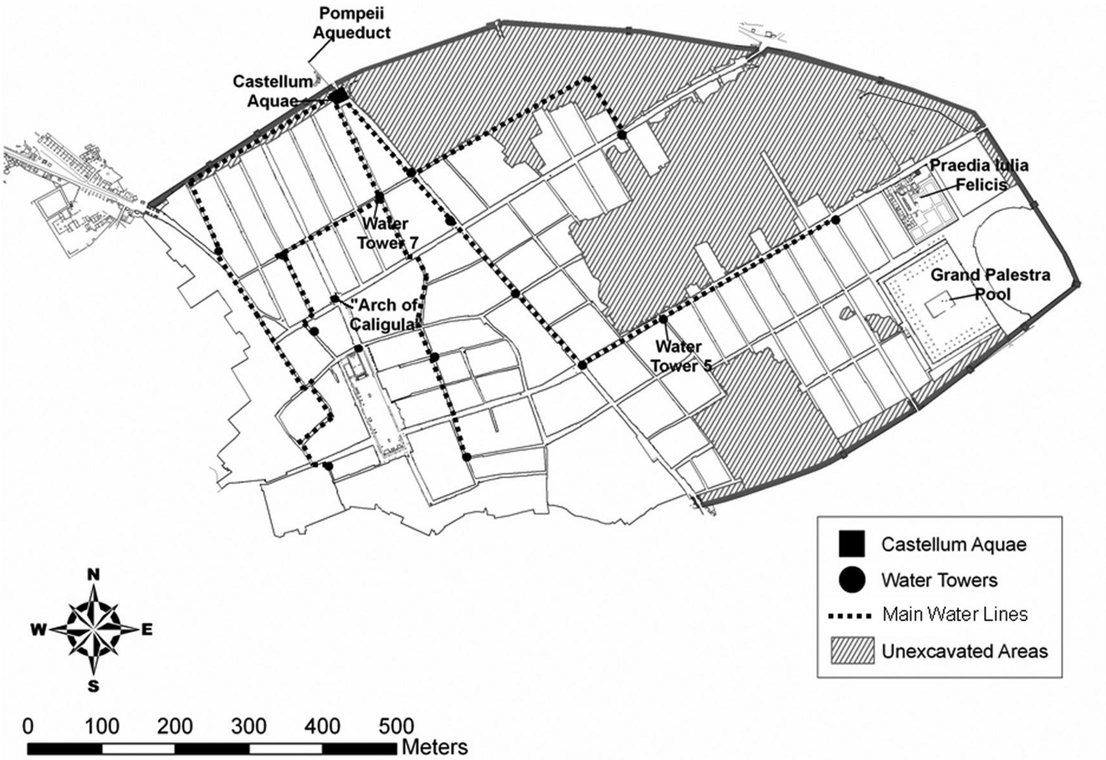

Fig. 9.1 – The water system of Pompeii. The location of samples considered in the work are labelled.

throughout the system to control the pressure and probably to provide junction points (Dybkjaer Larsen 1982; Wiggers 1996). Pompeii's *castellum aquae* was supplied by an aqueduct, which can be followed underground for approximately 110m before it is blocked. Only one other known piece of this aqueduct has been uncovered, some 20m further away from the city (Ohlig 2001, 85). As a result the source of the water is not known.

Even before the "rediscovery" of the Pompeii in the 1590s, it had been thought that a branch of the Roman aqueduct known as the *Aqua Augusta* or the *Fontis Augustei Aquaeductus* supplied the ancient town. In 1560, Pietrantonio Lettieri described a branch of the *Augusta* heading towards "the location of the city of Pompeii in ancient times, which was on the heights in front of Torre Annunziata" (Lettieri 1560, 406). Clearly, Lettieri knew the approximate location of Pompeii before the site was happened upon during the excavation of the Sarno Canal between 1594 and 1600 (Foss 2007, 29). By the middle of the 19th Century, this branch to Pompeii was no longer extant, unless one channel of the short duplicated section of the *Augusta* cut by the railway line at Ponte Tirone, near Palma, was part of it (Abate 1864, 26). Sampaolo (1987, 122) believed the branch leading to Pompeii to be the north channel at Ponte Tirone, which contains no sinter, suggesting only a short period of use, if any. Such an absence is in stark contrast to the thick deposits on the southern channel, which testify to a much longer period of water flow. The short period of use of the north channel would correlate well with the observed dysfunction in the water supply of Pompeii, probably due to seismic disturbances, in the decades leading up to the AD 79 eruption (De Haan 2001, 46; Marturano *et al.* 2006, 95ff). Any branch to Pompeii, however, would have

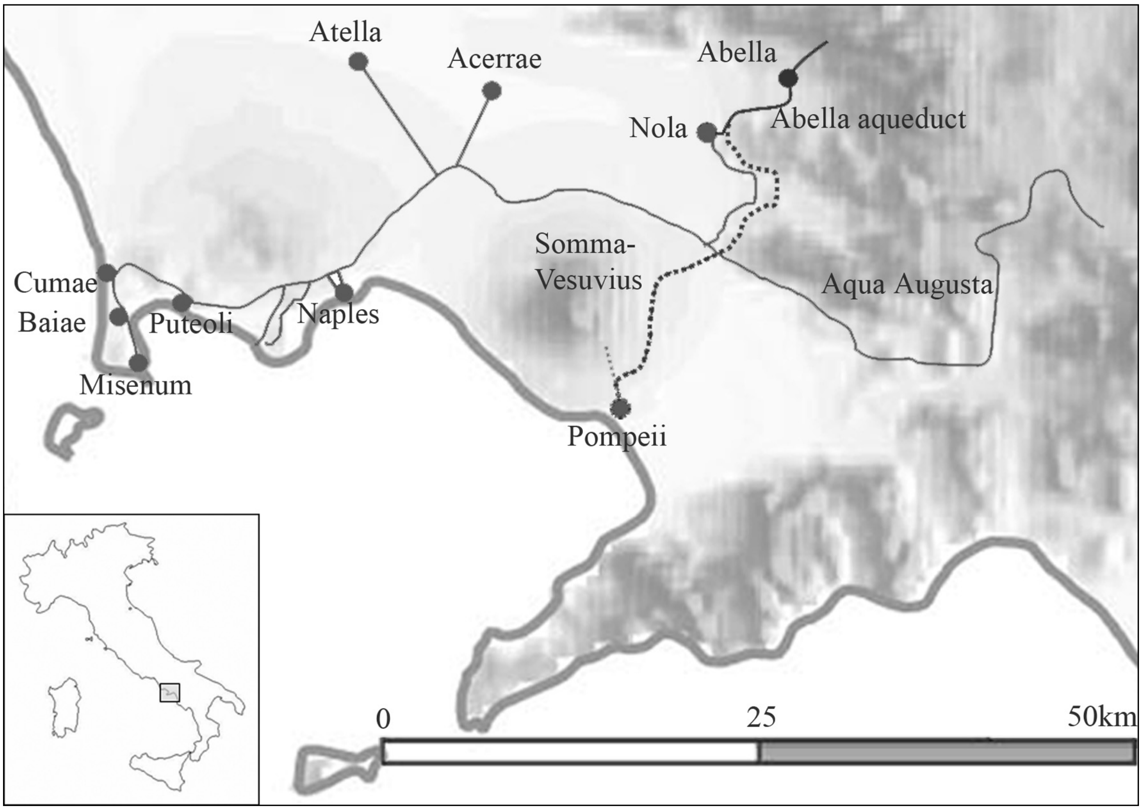

Fig. 9.2 – Aqua Augusta and Abella aqueduct routes. Solid lines represent aqueduct routes; dotted lines represent hypothesized aqueducts or aqueduct sections; round dots represent towns supplied by aqueducts.

run to the south of the main line. A more likely explanation is that the north channel, built in *opus reticulatum*, was the original channel of the *Augusta*, but after a short period it was bypassed by a new brick channel just to the south. Similar bypasses are found in other sections of the *Augusta* (Abate 1864, 21; Elia 1938). Although it is the most likely source for the city's water supply, no physical evidence of a branch channel from the *Augusta* to Pompeii has been discovered.

The *Aqua Augusta* was built, as its name suggests, in the late first century BC or the early first century AD. The route of the aqueduct (Fig. 9.2) is well known via the writings of two Italian engineers, Pietrantonio Lettieri in the 16th century, and Felice Abate in the 19th century, who were contracted to assess the feasibility of repairing the *Augusta* so it could serve as the water supply of Naples. An inscription confirms that in AD 324 the *Aqua Augusta* supplied the towns of Puteoli, Neapolis, Nola, Atella, Cumae, Acerrae, Baiae, and Misenum (AE 1939, 151; *NSc* 1938, 75–97). The *Augusta*'s sources were the Acquaro and Pelosi springs in the Apennine Mountains, which are fed by the Terminio-Tuoro aquifer. This aquifer is composed of calcareous (calcium carbonate-rich) and calcareous-dolomite (calcium magnesium carbonate-rich) rock layers, overlain by more recent deposits (Fiorillo and Esposito 2006, 2). This calcium carbonate-rich source could definitely have deposited the sinter found in the water system of Pompeii, an interpretation supported by Lettieri's identification.

Another aqueduct that may have supplied Pompeii is known from a poem composed in January, AD 407 by Paulinus of Nola (Poem 21, 704–753). The poem mentions the repair of an old aqueduct that carried water from the calcareous mountains near the town of Abella, approximately 10 km northeast of Nola (Fig. 9.2). It supplied Abella and Nola, and many country estates, including, eventually, Paulinus' own monastic community of Cimitile. Scattered remains of several aqueducts are found in this area, one of which probably corresponds to that mentioned by Paulinus (Pietro *et al.* 1981). Ohlig (2001, 52–57) has recently adapted the theory of the 19th century engineer Murano (1894) that this aqueduct continued south and supplied Pompeii, hypothesizing that this occurred prior to the town's connection to the *Aqua Augusta*. In addition, he has suggested that the *Aqua Augusta* was connected to the Abella aqueduct between the Apennines and Vesuvius (Fig. 9.2), and their waters combined (Ohlig 2001, 58–75).

There are also a number of springs on the slopes of Somma-Vesuvius today (Pagano 1996, 103; Federico *et al.* 2002, 965) that potentially could have been the source of Pompeii's aqueduct. These include the Olivella springs at 382m above sea level and the Chianatelle spring at 734m above sea level, both on the north flank of the volcano. In modern Ercolano itself there is a spring known as San Ciro (Camardo 2007, 173). Procopius (*Goth.* 8.35.7), writing in the sixth century AD, mentioned potable springs near the base of Vesuvius whose waters flowed very near to Pompeii's neighbor, Nuceria. It is possible that such a spring could have supplied Pompeii. At least one aqueduct on Vesuvius is known: a smaller aqueduct in the vicinity of Herculaneum that presumably served a nearby villa (Pagano 1996). The Somma-Vesuvius volcanic aquifer is contained in fractured lava and coarse-grained pyroclastic deposits from eruptions of the Somma-Vesuvius and Campi Flegrei volcanoes (Federico *et al.* 2002, 964). Modern studies of wells and springs in the area have shown that this aquifer also receives inflows of water from an underlying carbonate aquifer and could have deposited the sinter found in the water system of Pompeii (Caliro *et al.* 1998, 21; Federico *et al.* 2002, 976).

Sources of lead contamination in ancient Campanian water supply

It is possible that the source water not only carried calcium carbonate to deposit sinter, but also carried dissolved lead into Pompeii's drinking water. The lead levels in spring, ground and river water are affected by the geology of the area. Rain and snow also pick up atmospheric lead pollution, which then become part of surface and ground waters. Palaeoatmospheric indicators such as Greenland ice have revealed that during the Roman period, northern hemisphere lead aerosol pollution levels were the highest in pre-industrial times (Hong *et al.* 1994; Rosman *et al.* 1997). The isotopic ratio "fingerprint" of this lead suggests most of it came from Spanish ores, which were being smelted and used in large quantities all over the Roman world. More locally, lead smelting did occur in Campania at Puteoli (Plin. *HN* 33.106) and possibly on the island of Ischia (Boni *et al.* 2000, 201) during the Roman period. Coring of the Volturno flood plain just to the north-west of Pompeii has also revealed evidence of anthropogenic lead pollution in river water during the Roman period (De Vivo *et al.* 2001, 110).

On the other hand, no lead deposits of any note occur in Campania, and while smelting occurred, there is no history of lead mining (Boni *et al.* 2000, 201; Albanese *et al.* 2007, 25). Lead does occur in smaller amounts in other geological formations. Recent and extensive sampling of stream sediments in Campania has determined a baseline for geogenic lead levels by removing the modern anthropogenic contribution to lead concentrations (Albanese *et al.* 2007). This baseline can be safely applied to the Roman period as the only major geological events since that period have been the eruptions of Somma-Vesuvius, and there is little difference in the lead content of Somma-Vesuvius eruption products before and after AD 79 (Ayuso *et al.* 1998, 56, table 1). Albanese and his team (2007, 31) found that the highest levels of baseline lead concentration (29–51 ppm) were in stream sediments derived from Campanian volcanic deposits. Testing of Vesuvian eruption material, the most relevant volcanic deposit for our purposes, shows an average lead concentration of 42.5 ppm, which is in accord with the stream sediment results. Baseline concentrations of 5–21 ppm were found in stream sediments from Campanian siliciclastic and alluvial deposits. Both of these are higher than the average worldwide distribution in the continental crust (17ppm) and in limestone (8ppm).

The Campanian alkalic volcanic rocks and pyroclastics, represented by Mount Vesuvius, had the greatest positive effect on stream sediment lead levels, followed by modern anthropogenic factors, whereas other geological formations within the study area, such as the Sarno Basin/Vesuvian plain and limestone, or carbonate, outcrops had no significant effect on these levels (Albanese *et al.* 2007, 32–33). Thus, significant geological lead contamination of waters in ancient Campania can be assumed to have come from volcanic deposits, such as Somma-Vesuvius, and *not* from carbonate outcrops such as those found in the Apennines. The importance of these results for this study is that both the source of the *Aqua Augusta* and the Abella aqueduct should contain practically no geological lead, but noticeable amounts of geological lead might be found in the waters of the Somma-Vesuvius aquifer. Still, we must consider sources of the lead contamination in Pompeii's water supply beyond the parent water. The next source of lead for the water to come into contact is the pipes of the water supply system itself.

Lead contamination in Roman water systems

Written sources reveal that some Romans were aware of the possibility of lead contamination of drinking water from pipes. Vitruvius (*De Arch.* 8.6, 10) states his preference for terracotta pipes over lead ones for this reason. His advice was largely disregarded, at least in the Roman west, probably due to the ease of working and maintenance of lead and lead products. However, a number of factors may have reduced the potential for lead contamination in Roman water systems (Hodge 1981, 489–491).

One factor was that Roman systems were largely free-flowing when compared to modern ones. Pompeii is a good example. The *castellum aquae* functioned only to clean and distribute the water (Ohlig 2001, 216; 234–235). There was no facility to shut off supply to the city entirely. Shutting off the flow to parts of the piped system would have been possible at other parts of the system downstream of the *castellum* as the water towers provided means to vent the surplus water into the streets. The 112 taps found within Pompeii seem to have been located at the upstream end of the pipe, just after a junction point (Fig. 9.3), rather than the downstream end (Jansen 2001, 29; Dessales 2006, 366). Rather than serving to prevent water leaving the downstream end of the pipe, they instead functioned to control the flow of water entering the pipes. The overflow from the fountains at the end of domestic pipes went either to an underground cistern or to the street via a drain (Jansen 2001, 29). The public fountains also seem to have flowed continuously, judging from the lack of taps and the ever-present grooves in the rims of the basins for conveying overflow into the adjacent street (Poehler, this volume). There is also a lack of storage within the distribution system that could have taken advantage of water saved through closure of taps. The only surviving possible sign of such storage is a large reservoir across the Vicolo delle Terme from the Forum Baths (insula VII 6) that could have taken overflow from the baths and the adjacent water tower. The result of this continuous flow was that the water spent less time in contact with lead before its end use, and hence there was less time for water to dissolve lead from the pipe. In modern studies of lead piping systems this factor has been shown to be significant (Crawford and Morris 1967; Moore 1973, 223; Pocock 1980, 47; Sharrett *et al.* 1982, 459).

A further factor is the hardness of the water, that is, the amount of dissolved calcium and magnesium compounds. Research on modern drinking water systems containing lead piping has shown that hard water generally correlates with lower lead levels in drinking water (Moore 1973, 223; Pocock 1980, 47). The lead solvency of water, however, varies greatly in different systems and at different times within the same system (Troesken 2006, 128–135) and some hard waters have been shown to contain significant amounts of lead dissolved from pipes. Hard waters tend to be alkaline and it may be the associated alkalinity, rather than the hardness itself, that is the major factor in the low lead

Fig. 9.3 – Lead junctions, with associated taps, from the water system of Pompeii. Tape measure shows 10cm.

concentrations. Moreover, alkaline waters are less corrosive to lead pipes than acidic waters. Testing of the aquifers feeding the Abella and *Augusta* aqueducts shows them to contain alkaline hard waters (Sacco 1943; Lambertini and Mondelle 1959; Celico *et al.* 1980).

Another consideration related to water hardness is the formation of a coating of sinter on the inner surface of the lead pipe, limiting contact between the pipe and the water. Reported rates of sinter build up in ancient systems include 0.0123mm/year in an underground water channel at Troy (Frank *et al.* 2002, 311), 0.6–1mm/year in the aqueduct at Nimes (Fabre *et al.* 2000, 27) and 1.67mm/year in the aqueduct supplying Frejus (Dubar 2006, 166). Under some conditions, only a small amount of deposit is required to prevent contact between the pipe and water: an investigation of the use of sinter as a corrosion preventative coating in iron pipes found significant reductions in corrosion and water discoloration for deposits thicker than 0.4mm (Hasson and Karmon 1984, 16).

Recent investigations of the sinter deposits of the Nymphaeum of Trajan at Ephesus suggest that significant lead contamination from metal components did occur in at least some Roman water systems containing sinter (Prochaska and Quatember 2006). The researchers found widely varying lead levels in the sinter deposits and surmised that elevated lead levels in some deposits resulted from their proximity to metal objects in the Nymphaeum.

Sinter deposits are found throughout the system at Pompeii: in the *castellum aquae*, on the water towers, in pools, and in tanks. Pressurized pipe flow is generally very turbulent, which favours the fast deposition of sinter (Buhmann and Dreybrodt 1985, 210). Despite this, visual inspection of several surviving lead pipes in Pompeii has revealed very little or no sinter, which may be due to the repairs

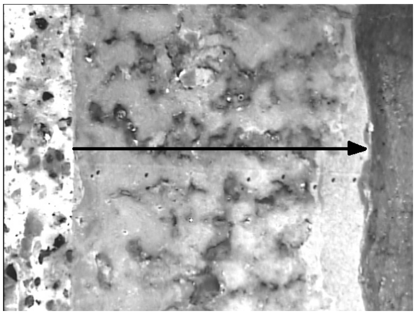

Fig. 9.4 – Enlarged photograph of Pompeii aqueduct lower wall sample. The sinter is 4.9mm thick. Black arrow indicates the growth axis.

after seismic activity preceding the AD 79 eruption. These new pipes are the best candidates to be the source of lead contamination in Pompeii's water supply.

Using the method developed for our research, it is possible to test if the pipes were the source of the contamination by analyzing the sinter deposits. The concentration of lead in the sinter is related to the concentration of lead in the parent water that formed it, as well as other factors, such as temperature, pressure, the amounts of other dissolved chemical compounds, biological activity and rate of sinter build up (Tucker and Wright 1990, 299; Gabitov 2005, 1). We cannot calculate the exact value of the original water lead concentration because of the uncertainty in some of these other factors and the current poor understanding of the behavior of lead in the sinter formation process (Wang and Xu 2001, 1530). We can, however, use the sinter lead concentration as an indicator, or proxy, of the original water lead concentration, as long as the other factors do not have an overwhelming effect. That is, the sinter samples with higher lead concentrations were probably deposited by water with higher lead concentrations than the water that deposited the samples with lower concentrations.

The coating effect of the sinter should result in a decrease in lead concentration in the water over time as the sinter deposits build up. There should be a corresponding decrease in the lead concentration in the sinter with time. Since the direction in which a sinter deposit has grown (called the "growth axis"; Fig. 9.4) can generally be determined, analysis of the lead concentration along the growth axis can verify the occurrence of this sinter coating effect. To our knowledge, this is the first time such an approach has been employed.

Research

To test if lead pipes were the source of contamination and if sinter build up was effective in reducing lead pipe contamination, seven sinter samples from within Pompeii's water distribution system (intramural samples) and eleven samples from outside of Pompeii (extramural samples) were chosen for analysis (Fig. 9.5; appendix 2). The method of analysis (appendix 3) used was laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). In this process, a laser vaporizes a specific point on the sample in order to analyze the resulting vapor in a mass spectrometer. The pulsing laser then moves along the growth axis of the sample at a constant rate so that changes in elemental concentrations over time can be detected and interpreted.

Results

In the graphical presentation of the results, the samples have been grouped according to the part of the ancient Campanian water system from which they were recovered. The Pompeii aqueduct lower wall sample, has been split into two sections, A and B, as the two sections have clearly different morphologies (Fig. 9.4) and different concentrations of many elements other than lead. This suggests that they were formed by different water sources.

The median lead concentration for each sample is plotted in Fig. 9.6. The median concentration is the middle value when all the lead concentrations along the growth axis of a particular sample are arranged in order from lowest to highest concentration. The two columns for each sample represent the total lead concentration as estimated from the measured concentrations of two different lead isotopes, ^{206}Pb and ^{207}Pb. Within the intramural and *Augusta* sample groups, samples have been arranged from left to right in

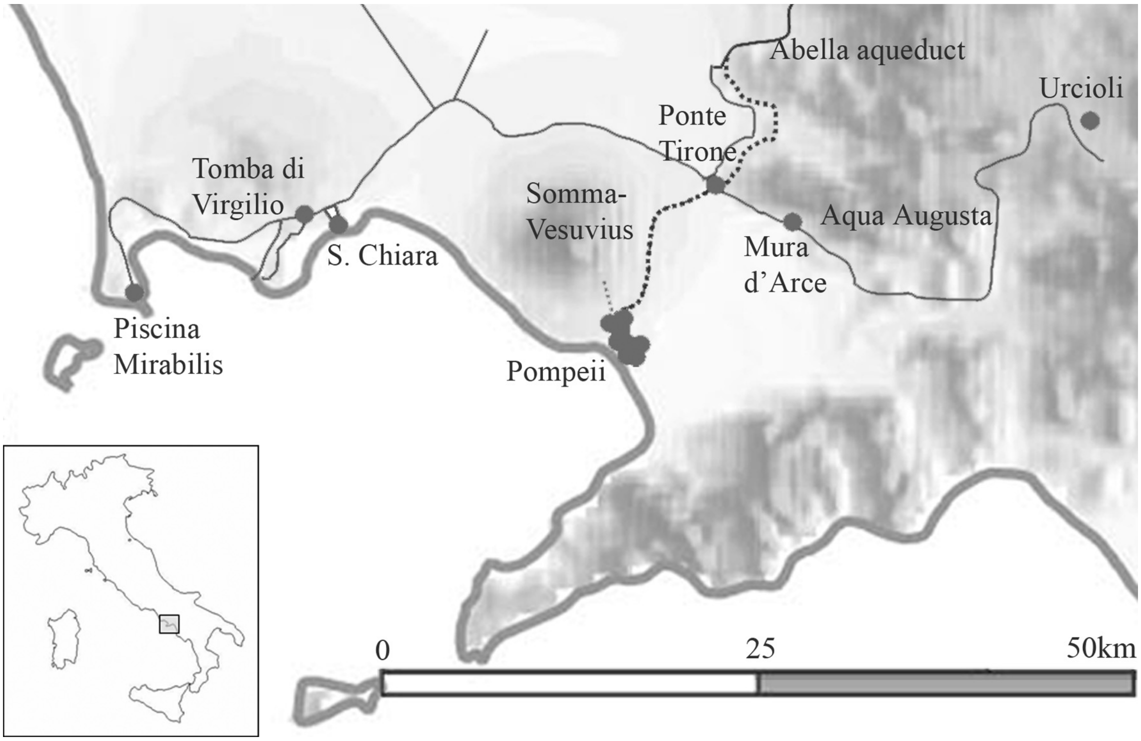

Fig. 9.5 – Aqua Augusta and Abella aqueduct routes: sample locations. Solid lines represent aqueduct routes; dotted lines represent hypothesized aqueducts or aqueduct sections; round dots represent sample locations.

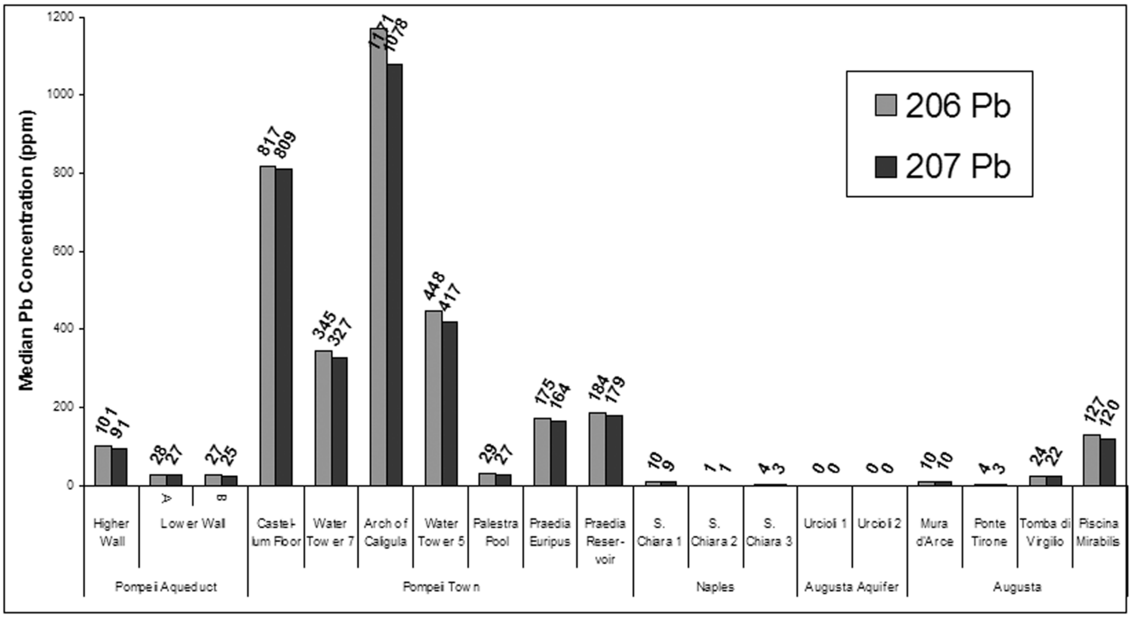

Fig. 9.6 – Median lead concentrations.

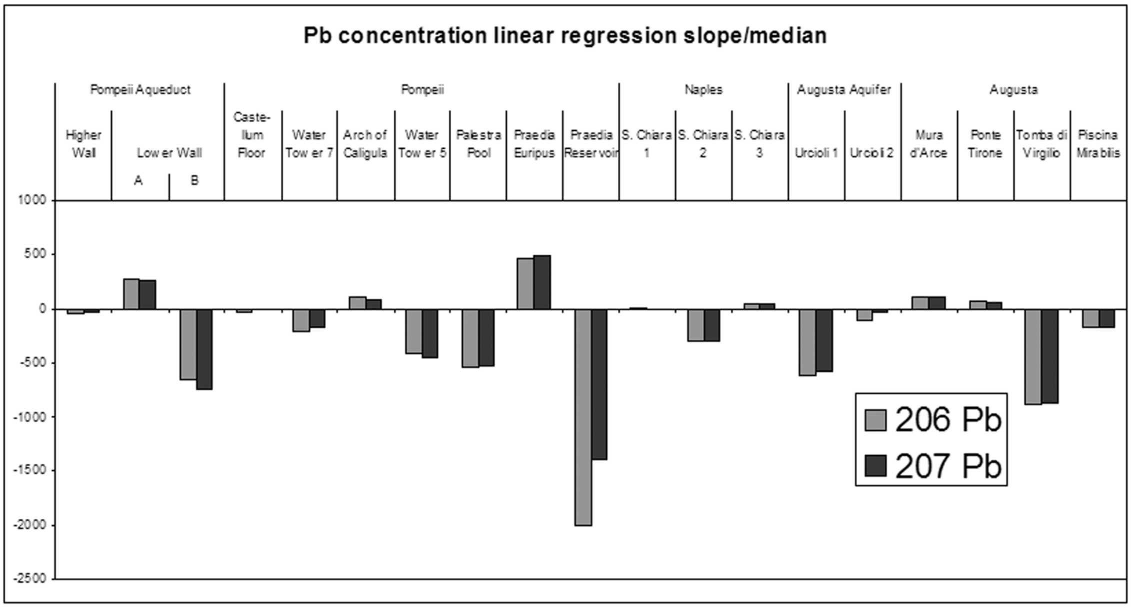

Fig. 9.7 – Lead concentration regression slopes divided by median lead concentration.

order of increasing distance along the flow path(s) to see if lead concentration changes with flow path distance. For the same reason, the Pompeii aqueduct and the *Augusta* aquifer sample groups have been placed to the left of the intramural and *Augusta* sample groups, respectively. If the source of the Santa Chiara samples was the *Augusta*, then these samples would be located between the Ponte Tirone and Tomba di Virgilio samples according to distance along the flow path (Fig. 9.5). There does not seem to be any clear relationship between lead concentration and flow path distance for the intramural and *Augusta* sample groups, given that the high lead concentration of the Piscina Mirabilis sample was probably due to lead pipes or fittings.

The slopes returned by linear regression of the lead concentration data are shown in Fig. 9.7. For purposes of comparison between samples, the slopes have been normalized by dividing each slope by the median lead concentration for that particular sample. Thus the bars shown in the graph represent the change in lead concentration relative to the median concentration. Negative slopes indicate a decrease in the total concentration of lead over the life of the sample. Any decrease may have been caused by the formation of sinter over lead surfaces.

Discussion

Lead levels and sources in ancient Campanian waters

In general, the intramural samples show far higher lead concentrations than any of the extramural samples, including the Pompeii aqueduct samples. The two exceptions, the Palestra Grande pool sample and the Piscina Mirabilis sample, will be discussed below. The water that the inhabitants of Pompeii were drinking contained lead in far higher levels than water from the carbonate aquifer of the *Augusta*, water from the channels of the *Aqua Augusta* and the Pompeii aqueduct, and water in the Santa Chiara baths. Such a clear result shows that lead concentration in the water was the dominant factor controlling the lead levels in this set of sinter samples, rather than the other possible factors such as temperature, pressure, and formation rate mentioned above. Moreover, the much higher lead concentrations in the intramural samples compared with those in the Pompeii aqueduct samples show that the water from the aqueduct, whichever spring it came from, was not the main source of lead in the drinking water of Pompeii. These results strongly indicate that the lead pipes and fittings within the system were the major source of lead contamination, despite the possible mitigating factors mentioned above. We hope to confirm the city's lead pipe system as the source of lead in the Pompeii sinter deposits in a forthcoming analysis of the lead isotopes.

The exception among the intramural samples is the sample from the Palestra Grande pool (II, 7), which has lead concentrations in line with the extramural samples, suggesting it was not supplied by the piped system. The presence of the thin sinter deposit extending from the bottom to the top of side of the pool confirms that it had been filled by water from a spring via the aqueduct and/or local groundwater at least once. While excavating the pool, Maiuri (*NSc* 1939, 189–190) found stone housings for a piped supply system, but not the pipes themselves. A pipe trench and pieces of lead pipe were also found running from the nearest water tower on the Via dell'Abbondanza to the north-west corner of the Palestra (*NSc* 1939, 200–202; 208). Hence it seems very likely that at one time the pool was supplied by the lead pipe distribution system, although probably not at the time of the eruption. Indeed, it is difficult to see how else it could have been supplied. There is no sign of a direct connection to the pool from the closest well, located just north of the Palestra (*NSc* 1939, 214). Such a connection would have required a water lifting device, evidence for which is similarly lacking. The pool also does not seem to have been connected to the rainwater collection system of the portico, which fed underground cisterns (*NSc* 1939, 182–183). It would have required almost 140,000 10 liter bucket loads of water just to fill the pool once by hand. This equates to a bucket added every single minute for almost 100 days, not counting evaporation over this period, so this possibility can also be excluded. Assuming that the pool was supplied by the piped system, shown in Figure 9.1, the water supplied to this pool would almost certainly have passed through the *castellum aquae* and probably also water tower five (Wiggers 1996, 29), which both show elevated lead concentrations. Both samples, especially water tower five (see below), show signs of sinter coating, as they have lead concentrations that decrease with time. But the effect of the coating was not sufficient in any of the intramural samples to reduce the lead concentrations to that found in the Palestra Grande pool sample. The results from this sample are an anomaly for which it is difficult to account.

In contrast, the Piscina Mirabilis sample, taken from the large reservoir near the end of the *Augusta*, shows exceptionally high lead concentrations for an *Augusta* sample, and has the highest concentration of any sample outside of Pompeii. The high lead concentration of this sample and the strong signs of sinter coating it displays suggest the presence of lead pipes or fittings within or just upstream of the reservoir. The water inlet to the reservoir is lost, but was probably in the north-west corner near the stairs, and this inlet may have contained lead fittings. There also may have been lead fittings within the reservoir. There must have been a device to close the opening in the bottom of the reservoir (Tsuk 1996, 119), which would probably have been made of metal.

The Pompeii aqueduct higher wall sample has a lead concentration that is lower than the samples associated with lead pipes and fittings (*i.e.*, the intramural samples), with the exception of the Palestra pool sample, and lower than that of the Piscina Mirabilis. Its concentration is higher than the rest of the samples, including both sections of the Pompeii aqueduct lower wall sample. The two Pompeii aqueduct wall samples are thought by Ohlig (2001, 113–114) to have been deposited at different times by water from different sources. He considers the higher wall deposit to be the older deposit, whose water supplied, intermittently, a greater volume than the later water that created the lower deposit. This greater volume necessarily extended higher up the aqueduct wall, thus the higher deposit also extended further up the aqueduct wall than the lower deposit. The higher deposit is very thin, raising the possibility that it may have been formed by ground water that had dissolved calcium carbonate from the more permeable cement of the aqueduct roof and upper wall. Its lead concentration may be related to the many inclusions that it contains. This sample is currently the focus of further study, which will hopefully clarify the reason for its anomalous lead concentration.

The rest of the samples contain distinctly lower levels of lead. In future sinter research, median lead concentrations less than 30ppm can be taken as evidence of the absence of lead pipes and fittings upstream of the sample. The very low lead concentrations in the S. Chiara samples suggest that the water flowing into these baths had not passed through lead pipes and fittings. The minimal lead content of the samples from the vicinity of the Urcioli springs, and the slightly higher, but still very low, content of the samples from the early part of the *Aqua Augusta* are consistent with the modern results of Albanese and his team (2007) discussed above.

Sinter Coating

Sinter coating should result in a reduction of lead content in the water over time, shown as a negative slope in Figure 9.7. Five of the seven samples (71%) whose high lead concentrations confirm their association with lead pipes and fittings (the intramural samples, excluding the Palestra Grande pool sample, plus the Piscina Mirabilis sample) show negative slopes. The eleven other samples (counting parts A and B of the Pompeii aqueduct lower wall sample separately and not including the anomalous Palestra pool sample) have little or no association with lead pipes and fittings and thus can be considered a control group. Of these eleven, six (55%) have negative slopes. Thus, there is a slight indication that sinter coating has reduced the absorption of lead into the water. The still high levels of lead in the intramural samples suggest that while sinter coating had an effect, it was not sufficient to prevent lead contamination of the water. The replacement of old pipes and fittings and installation of new ones would have increased the amount of uncoated lead surfaces in contact with the water in the system. Some of this lead would have been dissolved by the water and then precipitated out into the sinter. The seismic activity leading up to the AD 79 eruption necessitated many repairs to the water system of Pompeii (Nappo 2002a, 106–107). These repairs appear to be reflected in the positive slopes, which indicate an increase in lead concentration with time, displayed in the samples from the so-called "Arch of Caligula" and the *euripus* of the Praedia Iuliae Felicis. The lead concentration of the water that formed these deposits seems to have increased over time, most likely because there was an increase in the amount of uncoated, or new, lead upstream. There would also be factors other than the exposed lead surface, such as water pH and flow rate, affecting the lead concentration in the water (Troesken 2006, 128–135). These factors would be very difficult to account for, especially considering we do not know the period of time represented by these samples (see below) and hence cannot account for the large seasonal variations that occur in a Mediterranean climate (Baker *et al.* 1998, 393).

The lead concentration results for the water tower five sample are the most consistent of all of the Pompeii samples with the process of coating. The total lead concentration as calculated from the ^{206}Pb concentration at each point along the growth axis of this sample is shown in Figure 9.8. Each point represents the measurement of lead concentration at one particular moment during the scan. Lead concentration (in ppm) is plotted on the y axis, and the distance along the growth axis (in mm) on the x-axis. 0mm is the stone surface of the tower, where the oldest part of the sample formed, and 4.9mm (the total thickness of the sinter sample) is the youngest part of the sample surviving in 2006. Allowing for some experimental scatter of the points, the lead concentration decreases steadily with age (*i.e.*, moving left to right) until the midpoint of the sample, after which it remains fairly constant, with some oscillation about a central value, with a slight increase at the very end (right).

The best explanation of these results is that the beginning of this sample represents a period when there were many uncoated lead surfaces upstream of water tower five, which would be just after the initial construction to the piped system or just after a major cleaning or replacement of lead parts. The system then operated for a period of time without major cleaning or replacement of lead parts upstream of water tower five. During this time sinter

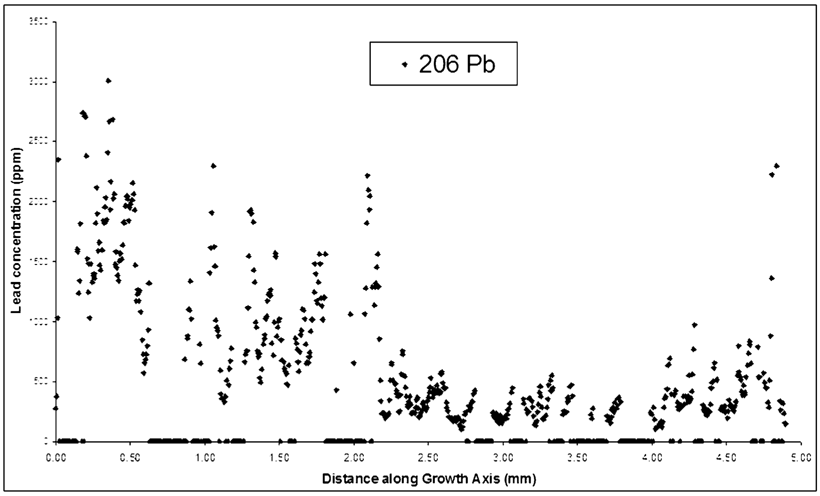

Fig. 9.8 – Pompeii water tower 5 sample lead concentration (determined from ^{206}Pb concentration) along the growth axis.

built up on those lead surfaces, causing a decrease in the lead concentration of the water until a sinter thickness threshold had been reached. After this threshold had been reached, a period without major cleaning or replacement of lead – represented by the basically constant lead concentration – continued until the end of the period represented by this sample, possibly with a small amount of cleaning or replacement at the very end. The median value of this constant second half is 299ppm, still well above any of the extramural samples. The few high lead concentrations at the very end of the growth axis, that is, on the outer surface of the sample, may be due to modern lead aerosol pollution.

It is difficult to date the period of time represented by this sample, and thus difficult to assign these two halves to periods in the history of Pompeii. It seems unlikely that the sinter deposits would have been cleaned from the surface of the water tower as they did not impede its functioning. Where sinter covered a pipe that was to be repaired or removed, the sinter would have been removed, but probably not from the stone surface of the tower, from where this sample came. So the oldest part of the sample almost certainly dates to the first time the overflow from the lead basin on top of this water tower flowed down this particular part of the tower's surface. This was probably shortly after the tower was constructed, assuming there was not a significant delay before the water supply was connected.

Heres (1992, 50) dates water tower five to after AD 62 on the basis of the mortar and by comparison with the adjacent wall. Larsen (1982, 63), relying on Carrington's dating of Pompeian construction materials, cautiously dated all the water towers built of tuff blocks to after AD 50, and probably after 62, whereas Adam (2007, 107–108) seems to date them to before AD 62. In any case, dates from construction material or method should not be viewed with the same reliability as those derived from stratigraphy (Jones and Robinson 2004, 107). Further uncertainty derives from the realization that earthquake damage or reconstruction in the last decades of Pompeii should not necessarily be associated with AD 62 (Allison 1995).

The youngest part, or outer surface, of this sample is also difficult to date. There is considerable uncertainty regarding the extent to which the piped water system was functioning at the time of the eruption, if it was functioning at all (Koloski-Ostrow 1996, 83; Nappo 2002a; Marturano *et al.* 2006, 95–107). Thus the last overflow of water from the lead basin surmounting the tower that flowed down this part of this particular water tower may have been significantly before AD 79. Furthermore, it is by no means certain that most recent sinter

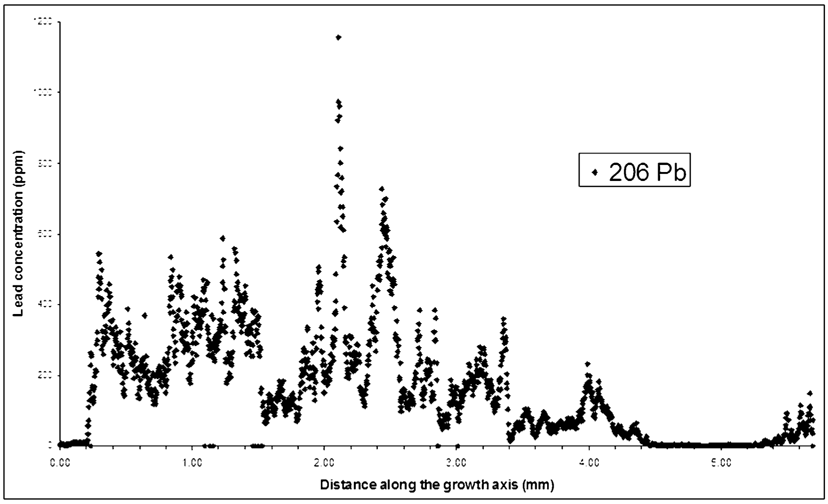

Fig. 9.9 – Piscina Mirabilis sample lead concentration (^{206}Pb) along the growth axis.

deposited in the exact location sampled on the water tower had survived until 2006. A relatively protected area, the interior corner of the indentation on the north-east side of the water tower, was chosen for sampling, nevertheless, damage to the deposit at any point from after its formation until the present day could have been considerable. Passing traffic (ancient or modern), the excavation of the tower and acid rain could all have removed outer layers of sinter.

The lead concentration distribution along the growth axis from the sample from the Piscina Mirabilis (Fig. 9.9) is similar to that from Pompeii water tower five. It shows a gradual decline in lead concentration consistent with sinter coating. Unlike water tower five, the first (oldest) 2mm along the growth axis contains negligible lead. The section may represent a period before the installation of lead in the Piscina, or before a major replacement or cleaning of lead in the Piscina. This change in lead concentration correlates with changes in other elements, such as strontium, and requires further investigation. Also unlike water tower five, the lead concentration reaches a sustained zero value between 4.5mm and 5.3mm (15% of the total length of the growth axis). Sinter coating seems to have been more effective at the Piscina Mirabilis than within Pompeii's piped distribution system. These results support the idea that the water distribution system at Pompeii was the source of lead contamination. The more complex system of lead piping and lead boxes at Pompeii required more frequent replacement of lead surfaces, with consequent removal of sinter deposits on those objects, especially in the seismically active period in the few decades before the AD 79 eruption. The Piscina represents a simpler system, where lead was probably confined to the Piscina itself and its immediate upstream area, and required less maintenance. The Piscina sample also probably dates from a later period than AD 79, since the *Augusta* was still supplying Misenum as late as AD 324.

Conclusion

The results of this research demonstrate that the water supply at Pompeii was contaminated with lead. Lead is a dangerous, cumulative poison that builds up in the body (World Health Organization 2006, 393). Thus repeated exposure to even small amounts of lead can have negative impacts on health. Samples analyzed from within the aqueduct channel(s) and distribution points along its course (Fig. 9.5) reveal very low levels of lead (Fig. 9.6), suggesting the water contained very little lead when it exited the spring and subsequently encountered very little lead inside the aqueduct. From these results, future sinter research can consider median lead concentrations less than 30ppm as evidence of the absence of lead pipes and fittings upstream of the sample.

With both the origin of the water and its means of conveyance to Pompeii ruled out as the source of lead contamination, only the network of lead pipes within the city remains to be considered. The problem with this conclusion, however, is that it seems to contradict the long-standing consensus that the building up of sinter within Roman water systems prevented the absorption of lead. Such a contradiction is actually a false one, derived from looking at the question in theory rather than in practice. In theory, the deposition of sinter does prevent water from absorbing lead out of the pipe it is passing through. The simple system of a single reservoir (the Piscina Mirabilis) approximates this theoretical situation and over time this sinter coating mechanism reduced lead concentrations to zero. In practice, however, a city wide distribution system is more complex. While sinter can protect its own pipe, the inevitable changes and maintenance required elsewhere in the system continually exposed fresh section of lead to the water. In case of large-scale changes, such as the original introduction of the system or the likely effects of seismic activity in the two decades before AD 79, significant percentages of the system would have to be replaced, causing lead levels to spike. Although we do not yet have dating information, these are the kinds of events that were observed by our method of taking measurements along the growth axis of sinter, especially in the sample taken at water tower five (Fig. 9.8). Finally, our sinter testing within Pompeii allows us to identify median lead concentrations of greater than 160ppm as evidence of substantial use of lead piping or other lead fittings upstream of the sample, which will be an important threshold for use in future research where similar methods are employed.

Appendix 1: Lead levels in Herculaneum and their consequences

A study of the tibia bones of 92 skeletons preserved on the beach at Herculaneum found a mean lead concentration of 82.7 parts per million (where 1 ppm = 0.0001% by weight), a concentration that is much higher than the mean (3.3ppm) from five pre-metal Neolithic skeletons from the Greek Argolid (Bisel and Bisel 2002, 459–460). To compare these levels to modern studies of live subjects, the Herculaneum mean must be divided by 1.2 to account for the organic material lost from the bones during post mortem decomposition (Waldron *et al.* 1976, 226). After correction, the Herculaneum mean (68.9ppm) is still much higher than the mean from all modern studies of tibial bone lead found, including long-term lead factory workers (Table. 9.1). Even by modern standards the inhabitants of Herculaneum were being exposed to very high levels of lead.

The Herculanuem mean, however, was less than that from ten individuals from Hellenistic Athens (125ppm; Bisel and Bisel 2002, 459–460). Hellenistic Athens had only a small number of lead water pipes (Camp II 1977, 172–173; 1991, 109–110), but did have a long history of extensive silver/lead mining and smelting at nearby locations Laurion, Almiropotamos and Kallianou (Stos-Gale and Gale 1982, 468; 485), which may account for the higher values. A higher concentration of lead in the 49 males (93.8ppm) than the 43 females (70.1ppm) in Herculaneum may be due to a significant, but not dominant, contribution from male occupations that involved exposure to lead, such as *artifices plumbarii* (Vitr. *De Arch.* 8.6, 10–11). Occupations involving lead production and use show higher levels in modern studies (Fig. 9.10). There were several major sources of anthropogenic lead exposure for both sexes, other than lead piping: lead cooking implements and containers (*vasa plumbea*; Plin. *HN.* 14.136, Col. 12.19.1), many of which are to be found in the storerooms of Pompeii; cosmetics (Ov. *Medic.* 70; Pl., *Mos.* 1.3, 258–259; Plin. *HN* 34.176); and medicine (Plin. *HN* 34.166–170; 174; Cels., 3.10, 2; 3.19, 2; 4.31, 7; 5.1; 5.15; 5.19, 1–2; 5.19, 23–28; 5.22, 2; 5.27, 13B; 5.28, 15E; 6.8, 1A). This included exposure to *cerussa* (white lead, lead carbonate), *plumbum combustum* (lead sulphide), *plumbi recrementum* (lead slag) and *spuma argenti* (litharge, lead oxide).

Study Subjects			Lead Conc. (ppm)	Reference
No.	**Description**	**Location**		
63	Young adults	Boston	1.3	(Kim*, et al.* 1996)
146	Adolescents	Pennsylvania	1.5	(Needleman*, et al.* 2002)
23	Young adults	Boston	3	(Hoppin*, et al.* 1995)
26	Adults	Urban Finland	3.5	(Erkkila*, et al.* 1992)
168	Adolescents	Boston	4	(Hoppin*, et al.* 1997)
100	Adolescents	Mexico City	4.8	(Farias*, et al.* 1998, 733, 736)
38	Lead factory office workers	Finland	7.7	(Erkkila*, et al.* 1992)
127	Construction carpenters	USA	9.8	(Watanabe*, et al.* 1994)
194	Adolescent convicted delinquents	Pennsylvania	11	(Needleman*, et al.* 2002)
98	Recent mothers	Mexico City	12.5	(Hernandez-Avila*, et al.* 1996)
20	Adults	Birmingham, UK	16.7	(Somervaille*, et al.* 1988)
719	Middle-aged to elderly men	Boston	20.8	(Hu*, et al.* 1996)
91	Current lead workers (mean 12 years exposure)	Finland	21.1	(Erkkila*, et al.* 1992)
87	Lead glass factory workers	UK	31	(Somervaille*, et al.* 1988)
88	Lead acid battery plant workers	UK	32.3	(Somervaille*, et al.* 1988)
16	Former lead workers (mean 15 years exposure)	Finland	32.4	(Erkkila*, et al.* 1992)
15	Precious metal smelter workers	UK	54.8	(Somervaille*, et al.* 1988)
92	**Eruption victims (corrected)**	**Herculaneum**	**68.9**	**(Bisel and Bisel 2002)**

Table 9.1 – Mean tibia bone lead concentrations from modern studies compared to those from the decomposition corrected Herculaneum study. Concentrations are in parts Pb per million parts live mineral bone by weight.

Ingestion of large amounts of lead (leading to a blood lead concentration of over 140 micrograms per tenth of a litre) can lead to acute lead poisoning and death. Long-term exposure to lower levels of lead causes a number of health and social problems, such as mild mental retardation, increased blood pressure, anaemia, gastrointestinal complaints, hearing loss, reproductive problems, reduced growth, lethargy and increased delinquency and violence (Prüss-Üstün *et al.* 2004, 1495–1497; 1505–1506). Bone lead concentrations are a better measure of long term exposure than blood, as lead is retained in the bones for longer (half-life in adults of 17–27 years) than in blood (36–40 day half-life; Hu *et al.* 1998, 1–2; World Health Organization 2003, 3).

Several modern studies have correlated bone lead concentrations with some of the symptoms mentioned above. Needleman *et al.* (2002) found that convicted Pennsylvania delinquents were four times more likely to have tibia bone lead concentrations above 25ppm (a concentration well below the corrected Herculaneum mean) than a control group of their peers. González-Cossío *et* *al.* (1997) found that children born to mothers with tibia bone lead concentrations greater than 15.14ppm were on average 156 grams lighter than those born to mothers with lead concentrations less than 4.46ppm. Both groups of mothers had tibia bone lead concentrations far below the decomposition-corrected mean of the women of Herculaneum (58.4ppm). Birth weight has been found to be a good predictor of survival, growth, health and cognitive performance in modern subjects. Bisel and Bisel (2002, 452–454; 459) noticed an unusually high number of adults in the Herculaneum skeletons compared to other ancient populations. They interpreted this as the result of a low birth rate, which received confirmation when analysis of the skeletons of women over the age of 15 in the group led them to estimate they had borne an average of only 1.69 children each. In addition to low birth rate largely due to contraception use and possible lead-induced sterility, this age discrepancy could also have been due to high neo-natal and infant mortality resulting from lead-induced low birth weight.

With such high lead concentrations evidenced in their bones, the inhabitants of Herculaneum would have experienced significant health and social problems arising from lead exposure. Extrapolating from the Herculaneum skeletal lead data and historical sources, it is likely that the inhabitants of Pompeii were also being exposed to higher lead levels in their daily life than the majority of people today, with consequent health and social impacts.

Appendix 2: Sampling

With the kind permission of the Archaeological Superintendencies of Naples, Pompeii and Salerno, approximately 120 sinter samples from Campania were collected by Duncan Keenan-Jones in the period 2006–2007. Seven more samples were generously provided by Dr. Christoph Ohlig. Table 9.2 correlates the designations of these samples by Ohlig (2001, 67–72) with those in the present work. Two samples from a recent excavation by the Soprintendenza Archeologica of Naples were also provided, thanks to the generosity of Dott.ssa Maria Louisa Nava, Dott.ssa Daniela Giampaola and Dott.ssa Serenella de Natale. These last two samples have not been analysed in the research presented here.

Ohlig 2001	The Present Study
P-ZK-h	Pompeii aqueduct higher wall
P-ZK-n	Pompeii aqueduct lower wall
P-C	Intramural *castellum* floor
S-MdA	Mura d'Arce
S-PM1	Piscina Mirabilis
S-PM2	Not analysed
PT	Ponte Tirone

Table 9.2 – Sample designations in Ohlig 2001 and the present work.

Seven of the samples collected in 2006 from various locations in the water distribution system within Pompeii (intramural samples) were analysed. Samples from outside of Pompeii (extramural samples) were also analysed and were taken from i) the channel of the Pompeii aqueduct, ii), the Roman period baths under the monastery of Santa Chiara in Naples, iii) a Roman period aqueduct channel at the Urcioli spring, part of the same Terminio-Tuoro aquifer as the Aquaro and Pelosi springs which supplied the *Aqua Augusta* (Fiorillo and Esposito 2006, 1), and iv) the channel of the *Aqua Augusta*. The locations of these samples are shown by the round dots in Fig. 9.5. More detail on the locations of the Pompeii aqueduct and intramural samples is given in Fig. 9.1.

The intramural samples were taken from locations where the water is definitely known to have come into contact with lead before deposition. The *castellum aquae*, although upstream of the piped system, is known to have contained several metal fittings, including lead sheeting across its entire width (Ohlig 2001, 220–227). Thus the sample from the *castellum* was formed by water that had been in contact with lead. Lead pipes have been found at the Santa Chiara baths, but water seems to have entered the reservoir from where the samples were taken via a masonry channel, which shows no evidence of lead fittings. It would be unusual in

Roman water engineering for water to flow through lead pipes before entering a masonry channel. None of the samples used in this study grew on a lead surface, so there should not be any significant contamination from the substrate.

Appendix 3: Method of analysis

All samples were initially tested for the presence of carbonate using an acid test, in order to confirm that the sample was sinter. Hydrochloric acid was added to a sacrificial piece broken off the sample, with the bubbling of carbon dioxide confirming the presence of carbonate.

These samples were then prepared for analysis with the help of Dr. Zhiyu Jiang and others at the Environmental and Climate Change Centre, University of Newcastle, Australia. First, fresh faces parallel to the growth axis of the samples were exposed. They were then mounted in Daystar clear casting resin, using methylethyl ketone peroxide as a hardener and a polished surface was prepared.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was used to analyze forty-three elemental concentrations along the growth axis of nineteen samples in December 2006 at the University of Melbourne, under the supervision of Dr. John Hellstrom. The lead concentrations of eighteen of those samples are presented here. Laser ablation ICP-MS uses a laser to vaporize a spot on the sample and analyze the resulting vapor in a mass spectrometer. The pulsing laser was moved along the growth axis of the sample at a constant rate. The laser ablation scan for the Pompeii Wall 2 sample is visible as a faint horizontal line just below the arrow indicating the growth axis in Figure. 9.4. These scans along the growth axis allowed the high definition investigation of variation of concentrations over the period during which the sample was laid down. Analysis was made of the entire growth axis of all the samples presented here except for those from Mura d'Arce and Ponte Tirone, where only part of the growth axis was analyzed. When choosing the location for the laser ablation scans, obvious inclusions (non-sinter, such as dirt, sand, rock particles and water, trapped within the sinter as it formed) were avoided.

The methodology followed Desmarchelier and his team (2006) except as noted below. Pulsing was set at either 5 or 10 Hz. The NBS 612 glass standard was used. Unlike the data in Desmarchelier and his team (2006), long-term temporal trends have not been removed from the data presented in this work. Areas of abnormally low calcium concentration were excluded by setting a minimum level of calcium concentration after inspecting a graph of the calcium concentrations along the growth axis. These low calcium areas (presumed to represent voids or inclusions in the sample) were excluded as the type of calibration employed will produce errors when used on material not predominantly composed of calcium carbonate. Three of the samples (Pompeii aqueduct higher wall, Praedia Euripus and Praedia Reservoir) showed much greater variability in calcium concentrations, seemingly due to greater levels of impurities. This combined with their very short growth axes made it difficult to assign the minimum calcium threshold by visual inspection, so a value of 85% of the median was used as the threshold. 85% was chosen because this was the highest percentage of the median that any of the visually assigned thresholds constituted and thus would be the most conservative option.

The lead concentration data were gathered as the total lead concentration estimated from the concentrations of each of three lead isotopes, or forms of lead, and their naturally occurring abundances. These isotopes are designated by a number preceding the chemical symbol of lead, Pb representing the varying sums of the protons and neutrons in the lead atom's nucleus. Two lead isotopes, ^{206}Pb and ^{207}Pb, occur in much greater amounts in the samples, and the natural world at large, than the other, ^{204}Pb. ^{206}Pb and ^{207}Pb thus provide more accurate measurements of total lead concentration than ^{204}Pb and only the results from the first two isotopes have been presented. The spread of the data does not conform to the bell-shaped "normal" distribution, but rather has a small number of very high concentration values, or outliers. Therefore, the median, rather than the mean, of both of these lead concentrations along the growth axis has been calculated, as the median is less sensitive to such outliers, and used as a representation of the lead concentration in the sample.

As a rough method of detecting the presence of sinter coating (see above), linear regressions have been performed on the lead concentration data with respect to distance along the growth axis (*i.e.*, with respect to time), using the Microsoft Excel SLOPE function.