The Iron Streets of Pompeii

ERIC POEHLER, JULIANA VAN ROGGEN, AND
BENJAMIN CROWTHER

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In July 2014, we conducted a survey of Pompeii's street network to document traces of iron that were observed on the stone-paved streets, which resulted in the identification of 434 instances of solid iron and iron staining among the paving stones. This paper describes the iron deposits, categorizing them into six observable types, and argues that, in the final days and weeks before the eruption of Mount Vesuvius in 79 C.E., Pompeians were—in addition to using solid iron wedges—pouring molten iron and iron slag onto their streets as a method of emergency repair. Before discussing the evidence available for how the melting, transporting, and depositing of these ferric materials might have been accomplished, we address whether the Romans had the technical ability to achieve sufficiently high temperatures to melt iron, finding much evidence to affirm the claim that they did. Finally, we consider why Pompeians undertook such measures to repair their streets. Recent research on the costs of paving stone streets in terms of time, money, and opportunity provides the economic context for this novel repair process and shows the use of iron and iron slag to have been an expedient alternative.[1]

INTRODUCTION

By the late first century C.E., within only decades of the Roman conquest of Britain, the iron-rich region of the Weald was already producing more than 550 tons of wrought iron annually,[2] making it one of the largest iron production sites within the Roman empire.[3] Extracting the raw iron from the stone ore that encased it required reducing the ore to a slurry so that a viscous sponge-like bloom of iron collected within the furnace, while the remaining materials were liquefied and drawn off as slag. Later, the bloom was reheated and hammered to remove remaining impurities and give shape to the metal. The bloomery process, however, was surprisingly inefficient and a significant percentage of the iron, from 40% to 70%, remained in the slag,

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[2] Cleere 1976; Cleere and Crossley 1985; Rackham 2001, 40–1.

[3] See Pleiner (2000, 41–7) for an overview. Craddock (2008, 108) reports the annual iron output of the Roman Empire was 82,500 tons, but see Sim (2011, 22–3) for other estimates.

which the ironworkers subsequently deposited in enormous waste piles.[4] In some cases, this waste material was recycled or repurposed for building material; the largest example of reuse of slag was as paving for long stretches of the London-Lewes Way in Sussex. Averaging 4.5 m to 5.5 m wide and as much as 0.35 m deep, the slag covered more than 30 km of roadway, an amount that Straker and Margary calculate to be no less than 35,000 tons.[5] Over decades of exposure and use, one stretch of the roadway, near Holtye, became oxidized and fused into a single, seamless, ferrous mass (fig. 1). The deep ruts found worn into this surface were likely created by the iron rims of wagon wheels made of the very metal separated from the slag paving. This is England's great iron road, a curious artifact and testament to the scale of industry in the imperial age.

Only a few other routes paved with slag are known from antiquity. These include a second road in Britain (in the Forest of Dean), this one connecting a mine and production facilities.[6] Elsewhere, Roman cities such as Cardiff (Wales) and Rouen (France) paved some of their urban streets in slag. In fact, at Rouen the practice was widespread; multiple streets were covered with slag, including one street that Romans paved in this fashion multiple times.[7] While slag paving is rare, deep ruts are a famous aspect of Roman roads everywhere. Investigations at Pompeii have shown that particularly high volumes of traffic concentrated in narrow streets could wear down even a stone-paved surface in only a few decades. One option for repair, complete repaving in stone, was a difficult and expensive endeavor that might block important through routes in a city for months.[8] Research by the authors has revealed that the Pompeians devised another option that was ingenious and unconventional: after heating iron or iron-rich slag to a molten state, they poured out hundreds of individual repairs onto, into, and below the paving stones of the city's most important streets. This claim is controversial not only for the novelty of such a procedure but also because of the commonly held, but erroneous, belief that Romans could not achieve temperatures necessary to melt iron.[9] To explore the use of iron in Pompeian streets, we first describe our method of study and our classification of the more than 400 instances of iron used in solid and in liquid forms in Pompeii's streets. Next, we address the technical feasibility of such a process and attempt to reconstruct where and how it might have been accomplished. In the final section, we attempt to answer to why such an unusual procedure was undertaken.

FIG. 1. London-Lewes Way, a Roman road near Holtye, Sussex, paved in iron slag (Margary 1965, frontispiece).

The primary unit of our analysis is the individual deposit of iron or ferric material. We have divided these deposits into six types. The online supplementary table Description of Iron Deposits (at https://works.bepress.com/eric-poehler/107/) presents these data.[10]

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[4] Tylecote 1986, 175–76; Craddock 2003, 233; Saredo Parodi 2013, 18–22; Pérez Macias et al. 2014, 15–9.

[5] Straker and Margary 1938, 58. On calculating slag heaps more recently, see Humphris and Carey 2016.

[6] Pleiner 2000, 45, 267. Davies (1935, 90) notes slag-paved roads in Normandy near Mayenne and Tourouvre (Mézières).

[7] Deglatigny 1931, 177, 185, 187–90, 195, 208–9; Davies 1935, 90–1; Schubert and Ingen Housz 1957, 41 n. 2.

[8] Poehler and Crowther 2018, 599–601.

[9] Specialists in metallurgy have long been disabused of this belief (e.g., Read 1934, 545–46), but modern reference works continue to repeat the idea (e.g., Humphrey et al. 1998, 218). Even in 2012, the *Oxford Classical Dictionary* entry on metallurgy states that iron could not be melted until the 19th century (*OCD* 2012, 939).

[10] This article's online supplementary content is hosted by the University of Massachusetts Amherst's institutional repository.

References in figure captions and footnotes to specific iron deposits use the format "ID_[number]." Some deposits contain solid iron remnants. Others are represented only by a stain on the paving stones, and we cannot be certain if these deposits were formed from iron metal, highly ferric slag, or some combination of the two. We therefore refer to deposits generally as "iron/iron slag" or "ferric materials" to acknowledge that ambiguity. Throughout the discussion, we refer to the ancient streets by their modern names, and specific locations mentioned in the text are indicated by number on the map (fig. 2).

METHOD AND DATA

In July 2014, we conducted a survey over 5.5 km of Pompeii's excavated streets, representing 73.5% of the surfaces with visible stone paving.[11] In total, we examined approximately 17,500 m^2 of paved streets (see fig. 2). The method for this survey was to walk each street, documenting and describing on a tablet computer any visible traces of iron. Textual and visual descriptions were captured in a FileMaker database and a GPS point was taken using the Spyglass app.[12] Most instances of iron were obvious and did not require cleaning before they were documented. For less clear examples, we brushed away grit and debris and, in a few cases, poured water onto the street to bring out the iron's visual qualities of metallic sheen or the rich orange and ocher colors of oxidization. While extensive and representative, our examination was not exhaustive, and we expect that additional deposits could be found on streets with particularly dense iron repairs, such as Via Stabiana, and on those with reduced visibility, such as Via di Nola, as well as on the streets excluded from this survey. It should be noted that there was no correlation between the distribution of iron use and the dates when the streets were first excavated. Iron is found on streets excavated in the late 18th century (e.g., Via Consolare), the mid 19th century (e.g., Via Stabiana), and the early 20th century (e.g., Via dell'Abbondanza). This fact demonstrates that the use of iron and iron slag was an ancient phenomenon and not an early modern intervention. Moreover, the locations of these ferric deposits are too specific and too frequent to have been accidental.

In total, the survey documented 434 occurrences of ancient iron in the streets at Pompeii. We identified six types of deposits that fall across a spectrum including individual, solid iron objects apparently driven between paving stones, solidified slurries of composite materials filling deep ruts or holes, iron stains at the seams between paving stones, and droplets and splatters of iron on top of paving stones. Each instance offers evidence for the process of its deposition as well as for the effect Pompeians expected it to have on their street surfaces. In the following discussion, we describe each type in detail and then attempt some quantification of all six types and their distributions.

Type 1: Solid Without Staining

Within our surveyed streets, there are 132 instances of solid iron embedded among the paving stones. Although it can be difficult to distinguish between them, it is clear that workers introduced these pieces of iron into the street either (1) by pounding a solid iron piece between the paving stones (fig. 3), or (2) by pouring molten iron into a cavity, which left a visible, top surface of solid iron (fig. 4). These instances range in size from very small (ca. 1 cm in the largest dimension in cross section) to very large (ca. 5 cm x 3 cm in cross section) and vary in shape from roughly circular to elongated rectangles.[13] Unfortunately, it was never possible to examine the depth of these solid iron pieces. In many cases, when the iron itself was oxidized and deteriorating, it was impossible to determine its original shape and size. Conversely, the deteriorated condition and comparatively large size easily distinguished the ancient iron from modern nails that were also found in the streets but were not recorded.[14] A few pieces of solid iron were clearly driven down between two stones, likely to create compression, as documented

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[11] Several streets were inaccessible due to safety concerns or ongoing work by the Grande Progetto di Pompei.

[12] The Spyglass app was regularly accurate to within a meter, sufficient to place observations in the correct general location and in the order of our survey as we moved down each street. A few, however, deviated dramatically, and we relocated these by their sequence. Because of time limitations, we did not record the exact location of 222 points, 91% of which were on Via Stabiana. To preserve their general locations, we bracketed these points between known points, which again allowed us to place these iron deposits by their sequence.

[13] Particularly large examples include ID_078, ID_214, ID_259, ID_273, ID_374. Particularly small examples include ID_067, ID_084, ID_121, ID_185, ID_338.

[14] Through the 1990s, prior to the common use of reflectorless theodolites, nails were used in the streets (and elsewhere) as station points for surveying.

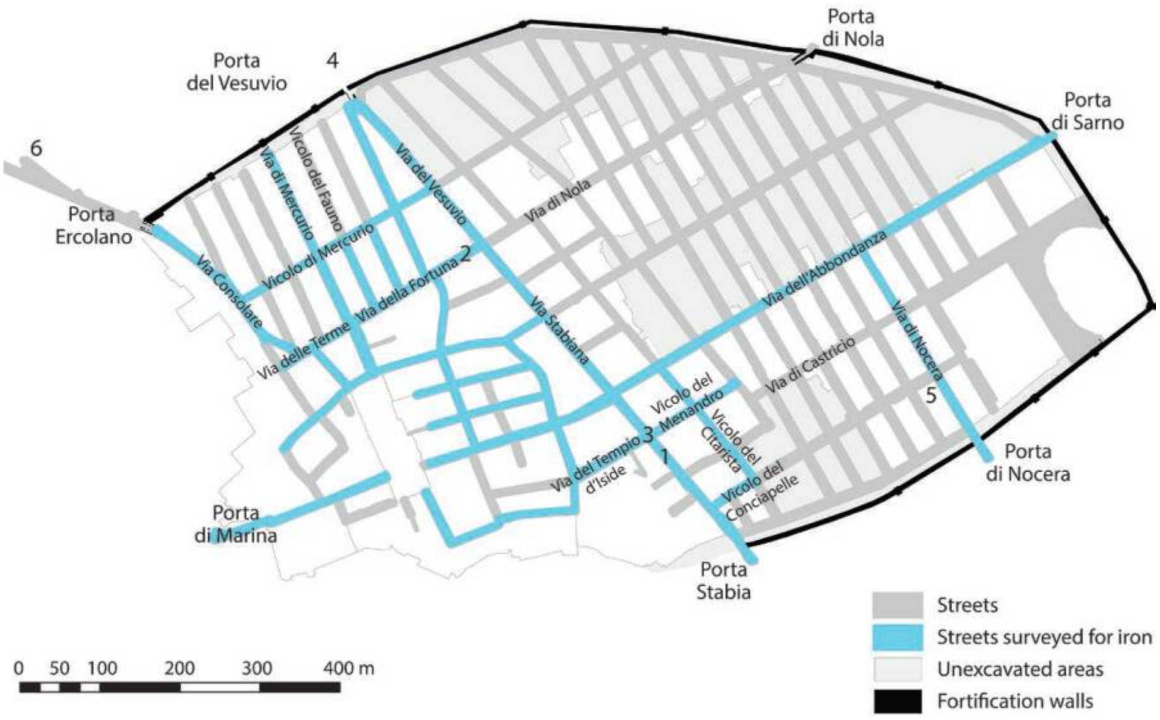

FIG. 2. Plan of Pompeii with streets and points of interest mentioned in the text labeled.

by the breakage on each of the stones surrounding the point of entry.[15] This breakage may have occurred at the end of the process of driving the iron into place, as the hammer likely hit the stones while making the iron flush with their surface. A few solid iron pieces found lower than the street level might have been countersunk with another device,[16] but often the poor condition of the iron suggests that it has eroded down to its present elevation. Examples of molten iron can be identified by the irregular shapes of the remaining solids that conform to the contours of the surrounding lava-stone pavers.

Type 2: Solid with Staining

Those examples in which a solid iron mass is found accompanied by staining make it abundantly clear that most iron pieces in the streets, including many Type 1 deposits, were in fact originally poured into place (fig. 5). In these 78 examples, an obvious iron stain can be observed on the stones adjacent to the solid iron piece and directly connected with it, indicating that the stain and the solid represent a single event.[17] An instructive example on Via Stabiana (fig. 6) shows not only how the molten iron/iron slag stained the three stones surrounding the rut it was poured into but also how the solid iron reflects the plasticity of its molten state. The stain's undulating, flowlike surface adheres and conforms to the particular contours of the lava stones and the rut cut into them. These examples are clearly distinct from smears of iron on paving stones, stepping stones, or curbstones caused by the passage of wheeled vehicles with iron tires, even when such smears are near solid iron deposits in the street.[18]

In another example of Type 2 (solid with staining), a dark red-to-purple stain (fig. 7) is preserved only within the small pockmarks on the surface of one paving stone at the intersection of four paving stones. There are no stains on the surfaces of the other three stones, though staining does appear on a small capping cobble within the intersection of the pavers. A solid remnant of iron/iron slag remains in the junction between the pockmarked stone and the adjacent paver.

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[15] ID_044, ID_127, ID_307.

[16] E.g., ID_273. It is not certain, however, that this deposit was driven in as a solid.

[17] E.g., ID_046, ID_221, ID_257, ID_280, ID_328, ID_381.

[18] Poehler 2017, 130, and supplemental images, figs. 5.15–18, at https://works.bepress.com/eric-poehler/.

FIG. 3. Example of Type 1, solid without staining, Supplementary Table, ID_044, Via Stabiana (ID = iron deposit). The damage to the paving stones around the iron suggests that the iron was pounded into the junction.

FIG. 5. Example of Type 2, solid with staining, Supplementary Table, ID_381, Via Stabiana. Note the irregular form of the iron and the inconsistency of its oxidization.

FIG. 4. Example of Type 1, solid without staining, Supplementary Table, ID_297, Via Stabiana. Note the solid iron at the bottom of a deep rut and degraded iron filling between paving stones.

FIG. 6. Example of Type 2, solid with staining, Supplementary Table, ID_328, Via Stabiana. Note the undulating surface of the iron and the adjacent stains.

These observations demonstrate that an iron-rich material was poured on the surface of the pockmarked stone and was then redirected into the interstices among the pavers. One might be inclined to explain the fact that the stain no longer covers the entire area on the top of the paving stone by subsequent rutting from regular use, but the pavement had only recently been repaired.[19] It is clear, therefore, that these small

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[19] Poehler and Crowther 2018, online Supplementary Table 1: PE_090 (PE = paving event), https://works.bepress.com/eric-poehler/102/.

FIG. 7. Example of Type 2, solid with staining, Supplementary Table, ID_157, Via della Fortuna. Note the ferric materials filling the junction between paving stones and the stains in the pockmarks on top of one paving stone.

depressions on the stone left by chiseling to create its flat surface are stained by (rather than filled with) this iron material because that material was not allowed to set in place. Finally, this solid mass of iron/iron slag and staining are accompanied by, but not in physical contact with, two individual droplets on an adjacent stone.[20] These droplets (discussed in more detail below) document the events associated with introduction of the iron/iron slag into the street as a liquid.

Type 3: Staining at Pour Point

It might be argued that iron staining in the street can be explained by a solid iron object that, having been abandoned in the street prior to the eruption (or after excavation), oxidized and stained the surrounding stones. Three modern stains on the paving stones near the Porta Stabia that were created by the placement of a modern metal stairway,[21] later removed, help test and disprove this hypothesis. Although their colors are not significantly different from ancient stains, these stains are distinct both because they retain the form of the previous objects' linear and rectangular shapes and because they rest in the middle of a paving stone (fig. 8). Conversely, the irregular shapes of ancient stains supports the notion of their fluid state at the time of deposition. Finally, unlike the modern stains, ancient staining—excluding droplets or splatters of droplets (discussed below)—occur only at the abutments between paving stones and not in the middle of a paver.

In the case of iron stains interpreted as pour points, molten ferric materials were apparently poured into gaps between paving stones to repair the spaces between and below them. As the molten material was poured, it covered the adjacent stones and flowed into the gap, but when the material hardened, it did not fill the gap up to the level of the street surface. Such stains occur both in the junctions between two stones and in the intersections of three or more stones. Ancient stains range in color from a light reddish-orange to a dark purplish-gray and differ in intensity and consistency from faint enough to be partially transparent to sufficiently thick to retain a metallic sheen.[22] The color of a stain can differ even within a single pour point.[23] One of the best examples of this comes from a deeply rutted section of Via Stabiana where the undulating edges of an orange-to-purple stain can be seen to flank the junction between two paving stones between which the molten material seeped (fig. 9). Although this stain is relatively large at more than 30 cm in length, some stains are exceptional in size, covering five paving stones and reaching over a meter in length.[24]

Most stains do not cover all the stones at a pour point. Instead, it is common that only one side of the pour point is stained, indicating that a guide was used for directing the molten iron/iron slag (fig. 10).[25] The flat face of an iron spade would work well not only to perform this function but also to push or scrape any sufficiently inviscid material on surrounding stones into the cavity (as in the example of Type 2, solid with staining; see fig. 7). If molten iron/iron slag hardened on the surface of a street, a spade also could be used to

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[20] ID_158.

[21] ID_004–6.

[22] Examples of reddish-orange stains: ID_027, ID_163, ID_308; purplish-gray stains: ID_008, ID_231, ID_324; with metallic sheen: ID_001, ID_218, ID_423.

[23] E.g., ID_027.

[24] E.g., ID_322.

[25] E.g., ID_107, ID_191, ID_308.

FIG. 8. Modern example of Type 2, solid with staining, Supplementary Table, ID_004, Via Stabiana. The stains were made by the feet of modern steps that have now been removed.

FIG. 9. Example of Type 3, staining at pour point, Supplementary Table, ID_432, Via Stabiana.

FIG. 10. Example of Type 3, staining at pour point, Supplementary Table, ID_008, Via Stabiana. Note that the iron materials stain only one stone of the junction.

break up errant material for collection and reuse. The 70 examples of Type 3 testify to the high liquidity of the material that was poured onto the street and flowed even into small cracks.

Type 4: Droplet

The liquidity of the material staining the streets is also demonstrated by the 86 instances of individual droplets of iron or iron slag that we found in Pompeii. We documented droplets in all areas of the streets, including inside deep ruts and on the top of paving stones. This distribution supports the obvious conclusion that droplets were not an intentional part of the deposition of material but are instead accidentally produced, and they serve as evidence for that material's presence in and movement through the streets. Droplets are identified by a red-orange to purple-gray stain and/or by a more three-dimensional form accompanied by a metallic sheen (fig. 11).[26] In the former instance, the droplet had either been scraped up at the time of deposition, leaving only a stain, or had been partially worn away by the movement of vehicles over its position.[27] In the latter instance, the droplet remained largely in its original form.

One example of Type 4 on Via del Vesuvio is a droplet that had landed on the steeply sloping face of a deep rut. The molten iron material not adhering to the stone sagged to the bottom of the stain and formed a small

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[26] Droplets with metallic sheen or three-dimensional quality: ID_074, ID_087, ID_316, ID_423.

[27] It is conceivable that many droplets were eroded in modern times, which would leave only a stain as evidence of their deposition.

FIG. 11. Example of Type 4, droplet (with staining), Supplementary Table, ID_316, Via Stabiana. Note the coronal shape and metallic sheen of the edge of the droplet.

lip (fig. 12). Such examples of droplets found inside ruts are especially instructive as they demonstrate that either the duration of time or the volume of traffic was not sufficient to wear away these accidental deposits of iron/iron slag before the eruption in 79 C.E. The position of droplets inside ruts, where the wheels of vehicles would grind over them, would make them highly susceptible to erosion.[28] That they remain, and remain in some cases with little to no evidence of wheel wear, leaves one with the inescapable conclusion that the droplets were landing on the streets in Pompeii in the final weeks or days before the eruption.[29]

Type 5: Splatter

A splatter is defined as either a collection of droplets or a large, irregular iron staining not directly connected to an instance of solid iron/iron slag or a pour point. Splatters differ from pour points because they are not necessarily located at the seam between paving stones and because they have more than one point of deposition. The 38 examples of splatters appear to result from accidental spillage. For example, a collection of droplets could be created by molten material that dripped unintentionally near a pour point. Like water dripping from a glass that is only slightly tilted, the molten material might have run down the outside of its container, collected at its base, and then dripped onto the pavement near the actual pour point. One stain has a particularly linear appearance, as though molten iron/iron slag had dribbled onto the stone as this container was transported above and across it (fig. 13).

FIG. 12. Example of Type 4, droplet (with staining), Supplementary Table, ID_081, Via del Vesuvio. Note that the droplet adhered to the vertical sidewall of a rut, and some of the molten material collected at the bottom of the stain in a raised lip.

Alternatively, a large splash of iron might cover a large number of paving stones. The weight of the material and its container, the difficulty in carrying and manipulating them, and the heat of both would have been hard enough to manage even if they did not have to be transported over deeply rutted streets. Sometimes, it seems, the ironworkers simply spilled their load. Large splatters of iron staining are rare, as any accident should be, but it is perhaps surprising that trips and slips were not more common. Indeed, the largest concentration of splatters was spilled over at least five

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[28] On the interior of ruts: e.g., ID_128, ID_188, ID_211; on the sidewalls of ruts: ID_071, ID_099, ID_123, ID_162, ID_174, ID_319, ID_367. One droplet was even found on top of a stepping-stone: ID_229.

[29] Unsurprisingly, Pompeii produces many examples of evidence for activities ongoing at the moment of the eruption. For example, cutting beam pockets (Quadriporticus, VIII 7, 16; Poehler and Ellis 2013, 11), painting in a house (Casa dei pittori al lavoro, IX 12, 9; Varone 1998), bread left in the oven (Casa del Fornaio [Modestus], VII 1, 36; Benton 2014, 80, 266–68), and the paving of streets (Vicolo del Conciapelle; Poehler and Crowther 2018, 596–97).

FIG. 13. Example of Type 5, splatter (with staining), Supplementary Table, ID_429, Via Stabiana. Note the linear arrangement of staining and droplets across the paving stone.

stones in a well-rutted (and subsequently disturbed) section of Via Stabiana. These stains, some still retaining a clear metallic sheen, cover comparatively large portions of the paving stones and appear to represent a particularly egregious accident and not a large pour point.[30]

Unfortunately, this section of Via Stabiana was significantly disrupted by the aqueduct built by Domenico Fontana in 1592, which cut directly across the street (see fig. 2[1]).[31] Additionally, interventions for the infrastructure of the modern tourist site have disturbed this part of Via Stabiana with the removal of some ancient paving stones, the addition of some modern stones, and the repositioning of some ancient pavers without regard to their original organization.[32] Nonetheless, even in their disturbed state, these remaining ancient pavers record an event, or perhaps several, in which a large amount of molten, ferric material was accidentally deposited onto the street. Had this section of Via Stabiana not been disturbed, it might have been possible to deduce more precisely how that event transpired.

Type 6: Repair with Composite Materials

In 29 instances, the quantity of the iron and iron slag in the street is far greater than in any individual instance among Types 1–5. It is clear in these examples that the intention was to repair the deeply rutted and failing stone surfaces using molten materials. Undoubtedly, the most dilapidated sections of street in Pompeii are on Via della Fortuna west of its great intersection with Via del Vesuvio, Via di Nola, and Via Stabiana where most examples of such large-scale repairs are found (see figs. 2[2]; 14). One particularly long rut along the north curb was filled by several meters of iron repair materials, of which significant portions survive for examination (fig. 15). Several features are immediately apparent. First, iron and iron slag were not the only materials used in the repair. In every example, additional materials were used, including stones of varying sizes, ground-up pieces of terracotta and ceramics, and in some examples, small pieces of white limestone. Second, the iron substances were poured directly into the rut, covering it throughout its length but not deeply in all places. In fact, in one rut, as it passes over the top of a single stone, the preserved height of the material is little more than a centimeter or two in ruts that are 10–20 cm deep. This indicates that the objective was to prevent further damage, not to fill the rut completely and restore a flat surface. On the other hand, it seems that these materials were meant to penetrate more deeply into the gaps below the surface and between paving stones that were nearly or entirely cut through by ruts. Specifically, with these repairs of composite materials in place, something of the original compression between paving stones was reproduced, and at the same time, a kind of bridge was created for vehicles to cross over the now-filled gaps.

Even if we allow for a layer of repair only 2 cm deep within a much deeper rut and estimate that 50% of its volume consisted of nonferric materials, the volume of ferric material is considerable. Our calculations indicate that more than 70 liters of molten iron/iron slag was poured onto this section of Via della Fortuna to repair it.[33] How deeply these repairs might have pen-

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[30] ID_426, ID_427, ID_429, ID_431.

[31] Images from the late 19th and early 20th centuries show the external curve of a vaulted channel that Fontana had cut through Via Stabiana prior to its excavation. See Poehler and Crowther, 2018, online Supplementary Figure 1: https://works.bepress.com/eric-poehler/99/. The same channel is still in place across Via di Nocera in the eastern portion of the city. See Via di Nocera street views: http://pompeiiinpictures.com/pompeiiinpictures/Streets/Via_di_Nocera p2.htm.

[32] In this area, some paving stones have a rut on one edge, but the adjacent stone does not have the other half of that rut. In other examples, ruts now run (impossibly) perpendicular to the street.

[33] This calculation is based on an estimate of the area of the street rutted between the stepping stones in the middle of this

FIG. 14. Deeply rutted section of Via della Fortuna containing remnants of many repairs.

etrated below the surface when filling a pothole or a large gap between the stones rather than a rut in the street's surface can be explored thanks to an excavation beneath Via Stabiana just south of its intersection with Via del Tempio d'Iside and Vicolo del Menandro (see fig. 2[3]). In 2011, a short report was published on work by the superintendency to capture and redirect rainwater from Via Stabiana into the Domenico Fontana aqueduct, thereby transforming the early modern water channel into the present site's sewer.[34] Interestingly, at approximately 80 cm below the current surface, the excavators found an earlier lava-stone surface, which, as we have argued elsewhere, was likely one of Pompeii's first lava-stone surfaces.[35] Because the focus of the report was on the efforts to improve the surface drainage of the modern site, a detail crucial to our discussion was omitted: more than 10 rectangular storage trays (or ca. 33 liters) of ferric, composite repair materials were recovered and preserved from an excavation less than 4 m^2 in area.[36]At the time of writing, these materials had not yet been studied by a specialist. Visual examination of the contents shows that a significant amount of iron/iron slag was poured into a cavity that was already partially filled with a number of other materials, including relatively large fragments of lava stone, terracotta and ceramics, and several instances of

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segment of paving (segment identified in Poehler and Crowther 2018 as PE_129). Measurements between the stepping-stones and the curbs were multiplied by a length of 10 m to find the total rutted area, which was then multiplied by a percentage of the area that was deeply rutted. For example, the area between the center and southern stepping-stones was 49 cm wide and, over the course of its length, was deeply rutted over 50% of its area.

[34] Rispoli and Paone 2011.

[35] Poehler and Crowther 2018, 588–89.

[36] The authors are grateful to Dott. Catello Imperatore for alerting us to the existence of these materials from his excavation. Our calculation of volume is as follows: 10 trays (55 cm x 33 cm x 11 cm), filled two-thirds full contain 133.8 liters. We estimate that the material is 75% nonferric fill, which leaves 33.4 liters of ferric materials.

FIG. 15. Example of Type 6, repair with composite materials, Supplementary Table, ID_168, ID_169, Via della Fortuna. Note that the deposit contains ceramics, including terracotta, as well as pieces of marble or white limestone, and it fills only the bottom of the rut.

what appears to be copper based on the familiar green tint of its oxidized form.[37]

This excavation reveals the depth to which some of the iron/iron slag fills penetrated below the street surface as well as the very large quantities of material deposited. Indeed, only a few meters south of the superintendency's trench, another repair can be seen filling a large gap between the paving stones, and we can conjecture that the material of the repair continued for some distance below (fig. 16). It is probable that the depth of the repairs on Via Stabiana is unusual, and we should not think that such great volumes of molten material disappeared into the seams between paving stones wherever there is a stain nor that each solid iron piece is the tip of a much larger iceberg.[38] Nonetheless, the volume of material at only these two locations (i.e., Via della Fortuna and Via Stabiana)—in addition to the wide distribution of the supporting evidence in Types 1–5—demonstrates the commitment Pompeians had made to the use of iron for street repairs and the scope of the problems they had hoped to solve by it.

FIG. 16. Example of Type 6, repair with composite materials, Supplementary Table, ID_422, Via Stabiana. Note that the deposit (ca. 40 cm x 20 cm) includes large stones and that it fills a large gap between paving stones.

Distribution and Quantification

Having described the deposits of iron material in the streets of Pompeii, we now turn to more quantitative and spatial analyses to reinforce the four main points introduced above, that (1) the iron materials in the street are ancient; (2) most were applied in liquid from; (3) their purpose was to repair the streets; and (4) many (if not all) repairs were made not long before the eruption of Mount Vesuvius in 79 C.E. Moreover, we further elaborate on the notion of street repair, as

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[37] Slag heaps from Populonia show layering of iron (Roman) above copper (Etruscan) smelting activities (Benvenuti et al. 2000). Mixing of these slags might account for the presence of copper in these deposits.

[38] That these materials were poured into Via Stabiana rather than used as fill in the construction of the street is supported by staining elsewhere on this street and by the absence of slags being used as a bedding layer anywhere else in the city, including in the repaving of Vicolo del Conciapelle, which was ongoing in 79 C.E. Additionally, it is tempting to wonder if these deep fills of iron materials below Via Stabiana relate to the earlier street surface having acted as a barrier to water soaking into the soils, which consequently eroded the fills supporting the final surface.

these analyses reveal two different mechanical properties understood and deployed by the Pompeians.

Support for all four points comes from examining the specific locations of deposition, which show where iron materials were used and where they were not, as well as how different types of iron materials were employed. At any particular location, we found iron deposits on a single stone, in the junction between two stones, or in the intersection of three or more stones. When combined with the type of iron material present, detailed information about the location of the deposits offers important insights. First, more than two-thirds of the observations record the presence of liquid iron through staining evidence, even though solid iron without staining (Type 1) is the single largest category at 31% of the total. Solid iron pieces were most commonly found in the intersections among stones, while staining was most often identified on a single stone.

The specific locations of iron staining reveal how carefully (despite the minor loss of material from droplets and splatters) the Pompeians seem to have poured this material. When pouring iron/iron slag at an intersection of three or more stones, they stained only one stone in 51% of the deposits, two stones in 37%, and three or more stones in only 12%. The percentages are even stronger at pour points identified at the junctions of two stones only—seven out of 10 times they stained only one of the two stones. As argued above, these figures indicate that some kind of guide, perhaps a spade, was used when pouring the material. Such patterning in the placement supports our belief in both the antiquity and liquidity of the material. That is, if such staining were to be imagined as iron objects left in the street to corrode away over decades or centuries,[39] it stretches credulity to explain how such lost items would have—92.8% of the time—fallen or been placed not only at the seams between paving stones but also on alignment with those seams.[40] The consistent positioning of staining is further supported by the 132 solid iron objects, all of which are found in the seams between paving stones.

These data also demonstrate that two different concepts of force were applied to repair Pompeii's streets. First, where greater compression was needed, a few iron tangs were wedged between the pavers (sometimes damaging the stones in the process) to increase the pressure across the surface of the street. Second, and most frequently, Pompeians poured liquid iron materials to fill holes and gaps, especially into those spaces that could otherwise be reached only by removing the paving stones, and so bound the streets below by adhesion as well as compression. In perhaps the most dilapidated street section, the eastern portions of Via della Fortuna (see fig. 2[2]), ruts had almost completely cut through the paving stones, and it is here that just over half of all repairs using composite materials were found.[41] But even those ruts that contain only a small amount of iron reveal a strong relationship between ruts and iron materials: 21% of all iron and iron staining were found specifically within a rut, but more than 84% of all iron deposits were found in street sections having deep ruts (as defined by Tsujimura; table 1). Moreover, in streets with little to no rutting,[42] 66% of the iron deposits identified were droplets or splatters rather than repairs, probably the result of spills during the transit of molten iron material to locations with deep ruts.[43] A related correlation is the strong relationship between the age of the pavement and the likelihood of its having received iron repairs: 65.1% of all iron deposits are found within sections of paving that were more than 79 years old at the time of the 79 C.E. eruption (table 2).

These statistics demonstrate that the Pompeians targeted deeply rutted streets, regardless of age, for this novel repair process. Additionally, the fact that some iron repairs were applied to streets paved or repaved in the last decades before the eruption shows how late in the life of the city this process was introduced.[44] For example, the short stretch of pavement on Via della Fortuna (18.5 m) between two particularly deeply rutted sections, which represents a repair made in the period

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[39] For example, modern stains (supra n. 21).

[40] Of the 70 examples of Type 3 (staining at pour point), only five appear on a single stone.

[41] ID_141, ID_142, ID_147, ID_148, ID_168–71, ID_173, ID_175–79, ID_182.

[42] That is, in Tsujimura's (1991) shallow, faint, and no rut categories.

[43] The likelihood that deposits were unintentional spills, rather than repairs, decreases as rut depth increases: droplets and spatters account for 71% of deposits in streets with no ruts, 61% in those with faint ruts, 50% in those with shallow ruts, and only 23% in those with deep ruts.

[44] It is conceivable, of course, that this use of iron was applied in early periods and continued until the eruption. There is, however, no evidence to support such an argument, and that supposition is made less likely due to the consistent use of stone for street repairs in previous eras.

TABLE 1. Iron Deposits by Depth of Ruts (as defined in Tsujimura 1991).

	No. of Iron Deposits by Rut Depth			
Iron Deposit Type	Deep	Shallow	Faint	No Rut
Type 1: Solid without staining	123	3	3	3
Type 2: Solid with staining	75	2	–	1
Type 3: Staining at pour point	58	6	6	–
Type 4: Droplet	52	13	13	8
Type 5: Splatter	34	2	1	1
Type 6: Repair with composite materials	25	4	–	–
Total	367	30	23	14
% of all iron deposits	84.6	6.9	5.3	3.2

following the earthquake of 62/3 C.E., received at least nine iron deposits that must date after that event.[45] But it is the small stains and droplets within ruts—deposits that could easily have been eroded away by the passage of vehicles—that indicate that this remarkable experiment was likely still occurring in the last weeks if not days before the eruption in 79 C.E.

COULD THE ROMANS MELT IRON?

The evidence for repairs using molten iron material raises technical questions. It has been, and indeed remains, a common assertion that Romans lacked the technical ability to reach the temperatures required to liquefy iron, especially in its pure forms.[46] This question was a subject of intense debate in the first half of the 20th century, and skeptics pointed to the general absence of both the blast furnace and cast-iron objects from the archaeological record.[47] Equally important were the assumptions underlying these arguments, including a unilineal model of technical evolution and a rejection of the idea that Romans could produce cast iron because they rarely used the resulting metal.[48]

TABLE 2. Iron Deposits by Age of Pavement (using phases of paving activity in Pompeii as defined in Poehler and Crowther 2018).

Phase of Paving Activity	No. of Iron Deposits	% of All Iron Deposits
Phase 1 (100–20 B.C.E.)	16	3.9
Phase 2 (20–1 B.C.E.)	253	61.3
Phase 3 (1–20 C.E.)	47	11.4
Phase 4 (21–40 C.E.)	56	13.6
Phase 5 (41–62/3 C.E.)	32	7.7
Phase 6 (62/3–79 C.E.)	9	2.2

These empirical and theoretical concerns have come to be better understood in recent decades as new excavations, more focused metallurgical study, and experimental archaeology have been brought to bear on questions regarding molten iron in antiquity.

The simplest challenge to dispel is the claim that there is an absence of cast iron in the archaeological record.[49] More than a century ago, indisputable examples of cast iron were recognized and published from Hengistbury Head and Warrington in England.[50] These early objects and excavated furnaces required the ad-

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[45] Poehler and Crowther 2018, online Supplementary Table 1: PE_090. The iron interventions on this paving event, however, are found near to the repairs of the particularly damaged sections: seven of nine iron deposits (ID_151, ID_153–55, ID_157–59) are located within a few meters of the deeply rutted sections, which had dozens of iron deposits in each.

[46] Supra n. 9.

[47] Craddock (1995, 259) notes that ironworking furnaces of all types are rare in the archaeological record.

[48] Craddock 2003, 231. See Forbes (1966, 78, fig. 14) for the linear "evolution of the metallurgical furnace."

[49] For the most recent review of the evidence, see Pleiner 2000, 247–49.

[50] May 1904, 26; Gowland 1915, 76–7.

mission that melting iron was not impossible using Roman technology, and May went so far as to argue that cast iron was being intentionally produced and refined.[51] Unfortunately, subsequent scandals of misidentification[52] and outright forgeries[53] led the scholarly community away from the question. Throughout the middle of the 20th century, it was the *communis opinio* that "cast-iron must be considered unknown to Antiquity,"[54] and even direct references to iron casting by Aristotle, Pausanius, and others were explained away.[55] Scholars tended to dismiss the few unimpeachable artifacts that were discovered as the by-products of an accidental overheating, an idea bolstered by the repeated claim that most cast iron was found in slag heaps because it was deemed useless.[56] Yet, this narrative sets aside the fact that some of the earliest items known were not discarded lumps of misfired bloom.[57] Intentionally formed objects include a cauldron rim fragment from Brading Roman Villa on the Isle of Wight, a small block of cast iron from Wilderspool (Warrington), and a small iron bar from the Roman industrial area at Tiddington.[58] If this last piece was a billet, it could support the Roman origin of larger cast-iron ingots from Dordogne, France, the date of which are in question.[59] Even those scholars who accepted this evidence for intentional objects, such as Aitchison, continued to argue that cast iron was unintentionally produced and resulted from the "freakish behavior" of some "run-away" furnaces.[60]

Experimental archaeology has added additional relevance to these pieces as well as those found on slag heaps by demonstrating that the Roman shaft (bloomery) furnace could produce cast iron with only slightly more human effort. Reconstructed furnaces have shown that Romans did regularly and necessarily achieve temperatures above 1400°C, sufficient to liquefy some iron ores, and could surpass 1600°C, which is beyond the melting point of pure iron.[61] More recent experiments indicate that "cast iron should be regarded as an inevitable by-product of bloomery smelting,"[62] which "was easily made if wanted,"[63] and not the result of a mishap. It is, moreover, not necessary to conclude that cast iron found in slag heaps was regarded as useless by Roman ironworkers. According to Crew et al., remains of cast iron instead usually would have been recycled in subsequent smelts, and pieces recovered in slag heaps only represent the remains that smelters failed to reuse.[64] This observation is significant as it suggests that our corpus of cast iron finds both does not reflect the amount of this material produced by the Romans and masks their contemporary understanding of its significance for their activities. By the end of the 20th century, Tylecote could state that examples of Roman cast iron are "innumerable" (though still denying their significance), and Pleiner could list eight objects of intentionally produced cast iron.[65]

Today, the claim that Romans could not melt iron cannot be sustained.[66] Moreover, the claim misconstrues Roman technical preferences as technical incompetence. Cast iron was too brittle for most purposes, so the idea in smelting was to cause the iron to bloom, not to liquefy. It was not the case that Romans could not create cast iron; it was instead their common intention not to do so. For this reason, current discussions of Roman metallurgy more often focus on why they preferred the bloomery process,[67] their experi-

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[51] May 1904, 21–9.

[52] On the so-called Hallstatt ring, see Coghlan 1977, 49.

[53] For example, Dawson's Beauport Park Statue. Charles Dawson was a master forger and perpetrator of the great Piltdown Man hoax. For the story of the forgery, see Russell 2003, 34–8; for metallurgical analysis see Craddock 2009, 477–79. Coghlan (1977, 49) lists other statuettes that have been found and discounted because of poor provenance.

[54] Forbes 1950, 407. Aitchison (1960, 205) and Schubert and Ingen Housz (1957, 57), among others, repeat this formulation.

[55] Pleiner (2000, 139–40) discusses the ancient sources except Pausanius and Zosimos, for whom see Forbes (1950, 408) and Craddock (1995, 279; 2003, 243–44), respectively.

[56] Collingwood and Myres 1936, 233; Forbes 1950, 407–8; Craddock 2003, 234; Rihll 2013, 57–8.

[57] Coghlan (1977, 47–9) admits these as examples of intentional Roman cast iron while maintaining their unimportance.

[58] Fieldhouse et al. 1931; Cleere 1958, 72–4; Aitchison 1960, 205, table 19.

[59] Wertime 1961, 46. Another pig-iron lump is catalogued at Bonn: Meier-Arend 1984, 368 n. 74.

[60] Aitchison 1960, 205. See also Coghlan 1956, 73.

[61] See Morton and Wingrove 1970, 6; Tholander and Blomgren 1985, 417; Pleiner 2000, 133–37 (citing Tholander 1987); Sim 2011, 85–6.

[62] Crew et al. 2011, 258. Although these experiments replicated a 14th-century furnace, its design is unchanged from Roman bloomeries.

[63] Rehder 2000, 127.

[64] Crew et al. 2011, 258.

[65] Tylecote 1986, 168 (followed by Craddock 2003, 249); Pleiner 2000, 248–49.

[66] Note the absence of this claim in Lang 2017.

[67] Rehder 2000, 141.

ments within and beyond it,[68] and what such empirical knowledge might have taught them in the absence of (modern) theoretical constructs.[69]

If most Roman smiths lacked a technical ability, it was how to decarburize the cast iron they regularly produced to make it less brittle and so appropriate for use as tools. Once again, however, there is a growing body of evidence that some Roman blacksmiths were learning how to refine high-carbon and cast irons for use.[70] There are today a few indisputable examples of evidence and an evolving sense that these practices were more common than previously understood.[71] It is clear that there was a range of Roman ironworking practices and competencies as well as many socioeconomic incentives and disincentives to employ them.[72] It is worth pointing out that we see such variation in the application of many Roman technologies, with cutting-edge and lagging examples often existing side-by-side. For example, Pompeii's architectural environment had long benefited from the pozzolanic bonding agents locally available for use in mortars, yet at the time of the eruption, few buildings had taken full advantage of the boom in cement construction that was revolutionizing Roman architecture at Rome and beyond.

While it is now beyond doubt that the Romans could and did melt iron and were perhaps learning to use the resulting products, it is important to remember that the process of pouring a molten ferric material into the streets at Pompeii did not necessarily require the same level of effort or expertise. In the first instance, the process at Pompeii was almost certainly a secondary event of melting some material in a crucible furnace, perhaps one not unlike that shown in the frescoes from the Casa dei Vettii (fig. 17)[73] at Pompeii or the Catacombs of Domatilla[74] at Rome. It was not the primary action of reducing raw ore into an iron bloom. This secondary process did not involve concern about overheating since melting and even superheating the material was the desired result. Secondly, the Pompeian workers might have used many varieties of iron and iron-rich materials with a significantly lower melting point than pure iron. Some iron ores, such as bog ores (limonite) and lake iron, are rich in phosphorus and consequently have a melting point closer to 1200°C. Similarly, cast iron and iron-smelting slags have a melting point between 1100°C and 1200°C, which makes both good candidates to be identified as the materials in the streets at Pompeii.[75] Since slag is a waste product and cast iron is a less desirable (if recyclable) by-product of smelting than pure iron, these lesser materials would also have the benefit of cost effectiveness in addition to their lower melting points, a point we will return to below.

HOW DID POMPEIANS REPAIR THEIR STREETS WITH MOLTEN FERRIC MATERIALS?

How the Romans introduced liquefied iron material into the streets at Pompeii remains a mystery. The process must have included obtaining the necessary raw materials (e.g., iron and iron slag, charcoal), assembling the facilities and tools (furnaces, crucibles, tongs, hammers), and transporting the liquefied materials (vehicles, manpower, insulating and pouring devices). Fortunately, archaeological research on Pompeii's industrial landscape and on the primary metal-producing regions of the Roman world allows an attempt at reconstructing the process of making iron repairs at Pompeii. To be clear, our description is speculation, but, like any good argument built on circumstantial evidence, it puts the plausible, if not the actual, in place of the absent.

Unfortunately for our reconstruction, metalworking at Pompeii is a surprisingly understudied subject, especially when it comes to iron. In 1988, Gralfs published her thesis on the 11 identifiable sites of metal

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[68] Fluzin 2000; Craddock 2003, 249–51; 2008, 109; Cech and Rehren 2014. See especially Lang's (2017, 863) discussion of Roman steel.

[69] Crew 2013. Stewart (2002, 114) remarks that "the ability of pre-historic and Roman smelters to feel the way empirically towards such results, without knowing the reasons, is to be respected."

[70] Craddock 2008, 107–8.

[71] See Crew et al. (2011, 258) for additional bibliography.

[72] Earlier scholars deserve credit for expecting such variability from limited evidence. As early as 1950, Forbes (1950, 407) pointed out that "even in the sixteenth century primitive and more sophisticated methods of metalworking were used side by side and different forms of smelting furnaces were adapted to the peculiar characteristics of local ores. No wonder that our picture of Roman and pre-Roman iron smelting is far from clear."

[73] See Monteix (2016, 204–5) for the most recent technical description.

[74] Kelleher 1982, 225, no. 144.

[75] On the melting points of iron and slag, see Cleere 1971, 205; Rehder 2000, 103–12; Stewart 2002, 91, fig. 4.22.

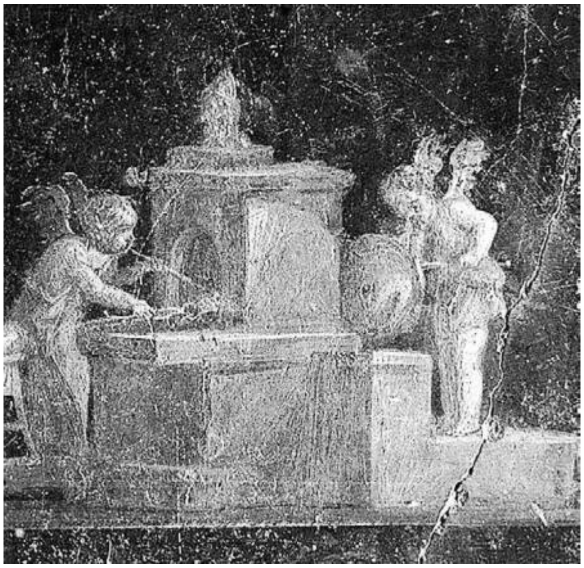

FIG. 17. Wall painting depicting a crucible furnace, Casa dei Vettii, Pompeii, Room q, south wall (© DAI Rome, neg. D-DAI-ROM 31.2736).

production within Pompeii, proving that the city's capacity was far greater than previously understood. Still, metalworking was not a robust industry and operated mainly as small businesses.[76] On the other hand, some of the tools demonstrate that Pompeian smiths were apprised of cutting-edge techniques and that local consumption could support some larger-scale bronze producers.[77] Perhaps the most illustrative of these small-scale smithies is the so-called fondo Barbatelli, located just outside the Porta del Vesuvio (see fig. 2[4]), where smiths produced a wide range of objects in bronze, iron, and lead including statues, serving vessels, and furniture parts.[78] Although it was never fully excavated and was subsequently reburied, the organization of space, the metalwork implements, and the objects produced at the "fondo Barbatelli" represent the wide technical abilities of the Pompeian metal industry and the limited scale at which it operated. Therefore, this workshop cannot be the site of production for Pompeii's iron street repairs. Even though the workshop had ironworking tools, a crucible forge in its front room,[79] and "a formless mass of iron"[80] that Gralfs believes could have been slag,[81] the scale of the process to repair Pompeii's streets with iron is far beyond the capacity of this locale. Because Gralfs could identify only two other primary ironworking facilities within Pompeii, both of which were still smaller in size,[82] the production site for the street repairs must have been located elsewhere, probably beyond the city walls.

An extramural location fits the pattern for other heavy industries at Pompeii. For example, the pottery industry at Pompeii in 79 C.E. was limited to two workshops at the urban periphery, one inside the Porta di Nocera (I 20, 4) and the other outside the Porta Ercolano (see fig. 2[5, 6]).[83] While these facilities appear to have been capable of serving Pompeii's daily ceramic needs, none of the kilns known at Pompeii were capable of creating larger vessels such as amphoras and dolia. Still, fabric analysis of stamped amphoras and tiles indicate that, at least in the last quarter of the first century B.C.E., the workshop of L. Eumachius was producing these ceramics, though its location is unknown.[84] If these larger materials were produced locally, they must have been fired at an external production facility.[85]

A similar phenomenon can be identified in Pompeii's fish-salting industry. Although Pompeii was famous for its garum production, nearly every street-front facility with a fish-processing vat—and there must have been scores of them spread across the city—had been transformed by the beginning of the first century C.E. into a food and drink shop.[86] Yet the garum industry did not disappear along with its small-scale, intraurban production sites. In fact, one leading industrialist, Umbricius Scaurus, continued to profit from fish sauce, exporting it around the Mediterranean until

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[76] Gralfs 1988, 107. For a brief review of ironworks, see Pleiner 2006, 139.

[77] Gralfs (1988, 71–6, 102–3) includes two workshops in her discussion of the Casa delle Forme di Creta: VII 4, 59–60, and VII 4, 61–2.

[78] Gralfs 1988, 12–48.

[79] Sogliano 1900, 599.

[80] Sogliano (1899, 444): "un amasso di ferro informe."

[81] Gralfs 1988, 18.

[82] I 6, 1, and VI 3, 12–13.

[83] A comprehensive overview of the evidence for the final decades at Pompeii can be found in Peña and McCallum 2009a, 64–76. A third facility is possible, though unlikely, at II 3, 8. Placing kilns in marginal locations seems to have been a feature of the early city as well. See Peña and McCallum 2009a, 58; Dicus 2014; Ellis et al. 2015, 2–5.

[84] Peña and McCallum 2009a, 77; 2009b, 176–79.

[85] It is possible that a large production facility remains buried in the unexcavated areas of Pompeii.

[86] Ellis (2011) discusses five vats in his excavations and reports 11 more vats in Pompeii, all out of use in 79 C.E.

Pompeii's final days.[87] Once again, we have a market for the products and evidence of the products themselves but not the site of their production.

Therefore, if Pompeii had a large iron-production facility, or if a new site was created specifically for the repair of streets, it almost certainly had to be located outside of the city. Whether there was one large facility or several smaller ones, any such production area would have needed areas dedicated to the storage of (1) the iron materials; (2) charcoal for fuel, which might have itself been produced there rather than purchased requiring still more space; (3) the waste materials produced; and (4) the vehicles and animals that would transport all these materials. Although we do not yet know the full volume of materials poured into the streets, some notion of the scope of the project can be gained if we assume some minimum figures for the iron deposits. For example, if each of the 309 locations where iron materials (including solid iron but excluding droplets and splatters) were identified represents only one deposition of an average-sized, melted iron billet,[88] such as those found at Newstead (lgth. 30 cm x diam. ca. 6 cm, wt. 6.65 kg)[89] or those from the shipwrecks at Saintes-Maries-de-la-Mer (lgth. 29.5 cm x wdth. 10.5 cm x ht. 5.2 cm, wt. 6.79 kg),[90] then no less than 2,000 kg of iron was needed. In some cases, the amount of iron that is currently visible suggests that less than an entire billet was required, but many of the iron stains indicate that at least this amount was used. Given what we know from excavations below Via Stabiana discussed above where perhaps 30 times the volume of a single billet was deposited at one location, this estimate for the total amount of ferric materials used at Pompeii might be quite conservative indeed.[91]

Similarly, although melting cast iron or iron slag requires a lower temperature for a shorter duration than does smelting iron from raw ore, the estimated fuel requirements and heating times would still have been significant. For smelting iron at Populonia, Saredo Parodi estimates that between six and 10 kg of charcoal were needed to reduce a single kilogram of iron (i.e., 127 cm^3, which is a cube merely ca. 5 cm on a side).[92] This high ratio was required within the shaft furnace in order to separate the iron from the rock. Melting iron in a crucible furnace would have been more efficient. If melting the iron required only half the amount of charcoal, the 6.65 kg billet described above would require 20–33 kg of charcoal, or 6,000–9,990 kg for all the observed deposits. In terms of space, each melt would require a cube of charcoal approximately 50 cm on a side, or at least 29.7–49.0 m^3 (a cube ca. 3.0–3.5 m on a side) for all the observed deposits.[93] None of the known locations of metalwork seems to have sufficient facilities (furnaces), space (dedicated storage areas), or forms of access (ramps, stables, and corridors) for these processes, even if all these materials were not present at once.

Still, the furnaces could not have been located very far outside the city because the most difficult aspects of this operation would have been transporting a substantial volume of molten iron material into Pompeii, maintaining its heat (and thus its liquidity), and then pouring it out at specific locations across the city.[94] Even if the foundry were located only 150 m outside the Porta del Vesuvio near the "fondo Barbatelli,"[95] the distance from the Porta del Vesuvio to some of the nearest concentrations of deposition in the streets was 250 m farther, with the most distant being over a kilometer away. Conveying these materials at a moderate walking pace (3.2 km/h) would require approximately 10 minutes or more to reach most places in the city. Since the difference between the ambient temperature and that of the molten metal will always be more than 1100°C, any molten material exposed to the air rapidly begins to solidify outside of the furnace.[96] To maintain its liquidity, which would be close to that of water, the molten materials would likely have been both superheated (raised to temperatures above the melting point

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[87] Curtis 1988; Ellis 2011.

[88] On an "average-sized" billet, see Tylecote 1986, 167–68; 1987, 254–55; Pleiner 2006, 40–3.

[89] Curle 1911, pl. 65.

[90] Pagès et al. 2008, 265–66, figs. 2, 3; Type 6C, SM6_10.

[91] Supra n. 35.

[92] Saredo Parodi 2013, 39, 42.

[93] These calculations are based on a specific gravity of 208 kg/m^3 for charcoal.

[94] We considered the possibility that the Pompeians had used a mobile furnace, but we have not pursued the idea because of a lack of evidence and because the volume of such a small-scale furnace might have been insufficient to produce the documented repairs.

[95] The distance to the pottery facility outside Porta Ercolano is 167 m.

[96] Solidification rates of metals, as defined by Chvorinov's Rule, are a function of temperatures, properties of the metal and mold materials, and mold shape. The average rate for steel to become completely solid is expressed as four minutes per square centimeter of mold surface area.

to compensate for heat loss in transit) and insulated (to prevent heat loss in transit). At a minimum, a lid for the crucible would be required to prevent rapid solidification of the exposed top surface of the materials.[97] Maintaining fluidity, however, is not the only reason to insulate the crucible. To protect the workers during transport and pouring, it seems very likely the crucible was placed within another container such as a modified transport amphora, perhaps partially filled with lapilli or sand.

In this reconstruction, the total weight of the melt of a single billet of 6.65 kg (850 cm^3) in a ceramic crucible of 2 kg placed in an insulating, sand-filled container weighing 10 kg would be 18.7 kg, which is manageable to transport and manipulate in pouring. Yet, several of the repairs of composite materials are so large that they might require dozens of trips if each pouring was less than a single liter. Multiplying the volume of the molten material even by five would increase the load to over 45 kg, a weight that would begin to test the strength of a single man, and a tenfold increase would tax even two men.[98] For comparison, consider that a Dressel 20 amphora filled with oil weighs about 105 kg and carrying one is depicted by the Romans as a two-man job (fig. 18).[99] This comparison, however, leaves out of consideration the very high temperature of the iron materials, which, even when insulated, would require porters to keep their distance. It therefore seems best to assume that, regardless of weight, insulated crucibles were carried on poles between a pair of porters in a manner similar to the representations of other objects being carried.

Finally, using the evidence available, we can also begin to reconstruct how the pouring was accomplished. It is first important to note that, when molten, metals are highly inviscid, flowing almost as easily as water. Molten slags are also quite fluid, even at lower temperatures; slags are as much as five times more fluid than motor oil at 1200°C.[100] These facts fit the evidence in the street that the ferric materials flowed quickly into desired locations and at times escaped to form accidental depositions. As mentioned previously, it is clear that some type of guide was used to direct the iron materials into the cavities below and between the paving stones. At the same time, the large number of droplets and splatters demonstrate that pouring from the crucible was a challenge that made the small losses of material common and larger accidents not uncommon.

FIG. 18. Terracotta plaque at VII 4, 16, in Pompeii depicting porters carrying a large amphora on a beam. Note that the porters use staffs, apparently for balance.

There are no firm answers about how the iron repairs were made, as there is no direct evidence beyond the repairs themselves. Nonetheless, we have attempted to circumscribe the possibilities in the context of what is known. The economic forces acting on other heavy industries suggest that our iron facilities were extramural. The high weight, temperature, and cooling rate of the iron materials further suggest that individual deliveries were of limited volume and that the process of pouring was difficult.

WHY DID POMPEIANS REPAIR THEIR STREETS WITH MOLTEN FERRIC MATERIALS?

Despite hundreds of observations of iron in the streets, the technical capabilities of the Romans, and a plausible reconstruction, the uniqueness of this phenomenon drives the skeptical mind to search for a simpler solution. Why did the Pompeians use iron materials to repair their streets? To answer this, we must first better understand the circumstances in which they employed this novel procedure. There must have been some reason for rejecting the ordinary ways of maintaining their streets in favor of a method that was per-

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[97] On crucibles, see Forbes 1966, 75–6; Tylecote 1986, 95–101; 1987, 183–92; Bayley and Rehren 2007.

[98] Rihll (2013, 58) suggests that 50 kg was the limit for metalworkers to lift and manipulate. She estimates 15 kg for the crucible and pouring apparatus.

[99] Peña 2007, 305.

[100] Rehder 2000, 111.

haps completely unprecedented. That impetus is best found in the history of street repairs at Pompeii and in the cost in time, money, and opportunity involved in paving and repaving lava-stone streets.

Beginning in the late second or early first century B.C.E. and continuing until the city's destruction, Pompeians transformed their beaten-ash streets (*battuti*) into a network of lava-stone pavements that over time became deeply rutted. The process of paving Pompeii was gradual and, though characterized by periods of intense activity, was never fully completed. More than half of the lava-stone pavements were laid for the first time in the Augustan period, probably together with the water system, as part of a grand infrastructural project.[101] Short extensions of lava-stone pavements off the main thoroughfares and onto side streets indicate that Pompeians expected to expand these pavements. Instead, the need to repair the main streets diverted attention and resources during the middle of the first century C.E.; less than a quarter of all the pavements laid between 20 C.E. and 62 C.E. expanded the total area of stone-paved streets at Pompeii. Other pavements from this period were repairs to the Augustan, and earlier, lava-stone surfaces, and although repairs were necessary, they were also continuous and disruptive. On average Pompeii witnessed one or two paving events every year that interrupted traffic for weeks, while the transportation of materials for these repairs undoubtedly added to the traffic (and the ruts) on streets not under repair. By 79 C.E., a third of the city streets were still made of beaten ash.

During the nearly two decades between the earthquake(s) and the eruption, street repairs were secondary to rebuilding the city's architecture. Only 12 sections of street were repaired during this time, and these likely clustered in the 70s rather than the 60s C.E. Evidence for the delay in street repairs is found in what was occurring on the day of the eruption, when four paving projects were underway simultaneously. Three projects were repairs in important east–west thoroughfares across the southeast of the city,[102] while the fourth was paving a street in the northwest, almost certainly for the first time.[103] This means that, on average, paving in 79 C.E. was almost six times more intense than in the previous 17 years and more than double the average of the last century.[104] Equally important, however, are the streets that were not repaved even though some sections were in desperate need of repair. Via Stabiana was nearly cut through by ruts, and the easternmost section of Via della Fortuna was more rut than road. Why these streets languished in the plans for street repair is best explained, ironically, by their essential nature in the street network. In fact, the intersection of Via Stabiana and Via degli Augustali/Via Mediana, near the center of the city, is the most heavily trafficked location in the entire city. A recent network analysis of pedestrian movement at Pompeii shows that more than 91% of all the possible routes across the city use this intersection. The four-way intersection of Via del Vesuvio, Via della Fortuna, Via Stabiana, and Via di Nola, ranked in the top 15% of streets in volume of traffic, is not far behind.[105] It is in the Via del Vesuvio, Via della Fortuna, and Via Stabiana that the most intense use of molten iron/iron slag was documented, amounting to 81.1% of all iron deposits. The concentration of iron materials in these locations suggests that these repairs were a temporary, emergency procedure for streets that were too important for the city's post-earthquake recovery to be ripped up for repaving in stone.

The decision to repair these most-used streets with iron materials and not to refit them with stone as was being done at the same time in other, less crucial streets indicates that the most important factor in developing the use of iron materials was time. Consider the deeply rutted northern half of Via Stabiana between Via dell'Abbondanza in the south and Via della Fortuna/Via di Nola in the north. Assuming that the stone masons could cut, shape, and closely fit two or three rows of stones across the street each day (i.e., an area 5 Roman feet long by ca. 13 Roman feet wide), it would require 169 days (almost half a year) to repave the entire section if they worked from one end to the other, or 84 days if teams worked from both ends inwards simultaneously, or 42 days if additional teams worked outwards from the middle as well. By contrast, one gang making 10 deposits a day (one hour per pour, 10 pours per day) could complete the 154

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[101] Poehler 2017, 54. Our chronology of paving is based on Poehler and Crowther 2018.

[102] Via di Castricio and Vicolo delle Conciapelle.

[103] Vicolo del Fauno.

[104] Poehler and Crowther 2018, table 1.

[105] Poehler 2016, 186–91, figs. 6.10–13.

iron repairs[106] in this same section in just less than a third of the time estimated for the fastest repaving with stone.[107] If we imagine two gangs each making 12 pours a day, the repairs would be complete in less than a week. Most importantly, this iron repair work could be done without ever having to do more than stall traffic on those streets. These estimates make the iron repairs between 2.7 and 26.4 times more efficient in terms of repair time. When one factors in the difference between causing a momentary delay versus a weeks-long detour, the savings in repair time is enormous.

Perhaps the weightiest reason for the iron repairs was their relative cost. Finished raw iron is cheaper and stone pavements are more expensive than one might expect. Evidence from inscriptions provides a good baseline for the cost of stone pavements, which Duncan-Jones has found to average 22.5 sestertii per Roman foot.[108] However, because this average is derived from extramural streets and does not consider the varying widths of urban streets, we have created a formula to calculate the real costs of paving based on area.[109] For example, we estimate that the northern section of Via Stabiana described above cost nearly 14,000 sestertii,[110] which is nearly three times what the public paid in the same period for the monumental basin in the Forum Baths.[111] Furthermore, this deeply rutted pavement on Via Stabiana was the replacement of an earlier lava-stone surface, and in 79 C.E. it was in need of paving for a third time. In fact, across the entire city the total cost of repaving (ca. 250,000 sestertii) was approaching the cost of the initial pavings (360,000 sestertii).[112] In view of the costs in time and money, the desire to find an alternate solution must have been strong indeed.

To an average Pompeian, however, iron was expensive, too. Closely contemporary documents from Vindolanda indicate that the price of refined iron billets was 4.4 sestertii/kg.[113] To put that price into the Pompeian economic context, such a billet (6.65 kg, valued at 29 sestertii) weighed the same as a modus of wheat, which would have fed a man for a week but which cost a quarter as much (7 sestertii). To a working Roman, a billet was worth about a week of wages.[114] Translated into iron poured (or pounded) into the streets, that same billet could have been sufficient to make no more than four small plugs 6 cm in diameter and 7 cm deep (about the size of a teacupful of iron). Many examples, however, show large areas of staining that suggest the entire contents of a crucible. For this estimate, we will assume that an average repair used one billet. In this section of Via Stabiana, then, the iron materials for the 154 repairs (excluding droplets and splatters) would have cost a minimum of 4,460 sestertii. For all the iron repairs we have documented, the cost would have been at least 8,960 sestertii. The cost of fuel (charcoal) has not been figured in here but can be considered negligible. No price for charcoal has been recorded, but estimates have assumed it to be of very low value.[115] On the other hand, if we assume that the workers were paid (not the only option) and apply the time estimated above, then employing 15 men—five men to run the furnaces and five in each of two gangs to pour—for 10 days would add another 2,000 sestertii to the cost of the iron used for Via Stabiana. Still, the total cost (6,460 sestertii) is less than half the cost of a new stone pavement.

The estimate of the volume of material used, however, does not fully take into account the many repairs in the street where ruts and holes were filled by an iron-rich slurry of slag, terracotta, ceramics, and stone. Such repairs demonstrate not only that there was much more material poured into the streets at Pompeii than is included in our estimate but also that there are other materials with different costs to consider. Unlike iron, there is no known valuation for slag, but there is good reason to believe it was cheap, even free, while still

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[106] This number includes solid iron as well as staining and excludes droplets (24) and splatters (15).

[107] Craddock (1995, 245–46) remarks that a single 19th-century Indian furnace could yield three blooms in a working day, which seems to have been the norm. If a crucible furnace were only twice as efficient, Pompeii would have needed only two or three to support the iron repairs project.

[108] Duncan-Jones 1982, 124–25.

[109] Poehler and Crowther 2018, 599–600.

[110] On Via Stabiana, see Poehler and Crowther 2018, online Supplementary Table 1: PE_006.

[111] *CIL* 10 817.

[112] Poehler and Crowther 2018, 600.

[113] Bray 2010. We may wonder if this price is artificially low because of the proximity of Vindolanda to iron sources and the purchasing power of the army. As it relates to our purposes, however, it might not matter, as Pompeii, too, was well connected by sea to the iron-producing areas, and if bought by the municipality, the city would have had its own leverage in negotiations.

[114] Hawkins 2016, 169 n. 118.

[115] Landels 2000, 31–3. Carrier (2017, 233 n. 757), however, believes Landels underestimates the price of charcoal, especially in Alexandria.

being a desirable commodity for traders to transport.[116] Much usable iron was still encased within the slag of the original ore.[117] Romans knew about these remnant metals; slag from gold production was reprocessed,[118] slag collectors (*scaurarii*) were active at Roman mines in Iberia,[119] and metallurgical research on stratified slag heaps has sometimes found the latest materials to be the lowest in iron content, suggesting they might have been reprocessed.[120] In addition, as a commodity, slag was not subject to import and export taxes. The *Lex Portorii Asiae*, reinscribed in 62 C.E., reads: "Whatever is no longer useful, in respect to stone or rock, whatever has been mined in order to extract gold, silver, [copper?], iron, lead, orichalcum, or whatever anyone may carry of these, he is not to pay customs."[121] This clause suggests that ships departing from metalworking areas could make a commodity of their ballast and bring slags to places like Pompeii where they might be in demand.

Although slag itself has not been found in shipwrecks, other evidence from wrecks has demonstrated that Romans were entrepreneurial in their approach to finding salable materials for ballast and for dunnage (packing material), just as early modern sailors were.[122] Millstones and querns, building materials including brick, tile, timber, and blocks of stone, other raw materials such as coal and glass, and even foodstuffs have all been named as ballast or dunnage in ancient cargoes.[123] Indeed, bricks have been offered as the ballast for the return trips in the iron ore trade.[124] Of course, iron itself was a commodity shipped across the Mediterranean both as ore and as finished iron bars.[125] In fact, the eleven ships wrecked off Saintes-Maries-de-la-Mer (dating from the first century B.C.E. to the first century C.E.) carried 500 tons of iron bars among them.[126] For evidence closer to Pompeii, there is the report of Diodorus Siculus that raw iron blooms were brought from Populonia in Tuscany to Puteoli for refining and for trading elsewhere.[127] This Elban ore is likely where Pompeii got its iron, at least until the end of the first century B.C.E.[128] After that time, as one of the largest and most long-lived sites in the Mediterranean, Populonia became a prolific source of slag. It is estimated that between two and three million tons of slag were produced in antiquity, with as much as 80% of that having been reprocessed in the early 20th century.[129]

With mounds of slag available for collection and free of customs duties, it is possible that merchants sailing south from Tuscany, even if they already carried blooms of iron, might want to make use of and commodify this material. Once in the Bay of Naples, these ships would be emptied of both cargo and ballast and would be in need of both for their next voyage. One of the wrecked ships excavated at San Rossore, Pisa, though half a century earlier than the ironwork at Pompeii, offers a potential clue about the full cycle of this exchange. Ship B was laden with amphoras containing wine, fruit, nuts, and olives that were packed using small stones of lava, tuff, and lapilli as dunnage. These materials, along with amphoras filled with sand also from Ship B, are all sourced to the Vesuvian region.[130] With iron and iron slag sources nearby at Elba and on the mainland, perhaps ships trading up and down the Italian peninsula brought wine up from the Adriatic

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[116] Van Oss (2014) found slag sales in 2013 to have averaged $17/ton. Van Oss (2002) found prices ranged from $3/ton for domestic air-cooled slag to $35/ton for imported slags and $57/ton for granulated slag.

[117] Supra n. 4.

[118] Plin., *HN* 33.69.

[119] Pérez Macias et al. 2014, 19–22.

[120] In this argument, the slag heap represents the discard from a second smelting, which buried the higher iron content slag from earlier activities. Forbes (1950, 396–97), however, suggests "this should be confirmed by further analyses."

[121] Translated in Bernard 2014, 182.

[122] On profitable ballast, see Gill 1988, 2. Martin Frobisher's arctic voyage in 1577 carried as ballast 500 Russian "iron stones" that could be used for barter or as an emergency source of iron (McGhee 2001, 169–71). Perhaps the strangest form of ballast was that of animal mummies exported from Egypt in the 19th century (Morgan and McGovern-Huffman 2008, 585).

[123] Millstones: Buckland and Sadler 1990, 116; Alfonsi and Gandolfo 1997, 69; Sidebotham 2008, 313 n. 30. Querns: Allen and Fulford 1999, 176. Documented and expected building materials include vaulting tubes (Vann 1993, 34), bricks (Tchernia 2011, 159 n. 12; Bang 2016, 92), and tiles (Parker 2008, 187). Coal: Smith 1997, 319. Glass: Stern 1999, 475.

[124] Darvill and McWhirr 1984, 250.

[125] Parker (1992, 185, 381) reports a mass 25 m x 15 m of high-quality iron ore in the Fuenterrabia wreck and slag as a possible cargo in the San Vicenzo A wreck. Taylor (1998, 117) and Mattingly et al. (2001, 80) argue for iron ore as "saleable ballast."

[126] Pagès et al. 2008; Pagès et al. 2011.

[127] Diod. Sic. 5.13.1–2.

[128] Saredo Parodi 2013, 25.

[129] Saredo Parodi 2013, 18–22.

[130] On Ship B, see Bruni (2000, 42–5) for an overview, Mattioli et al. (2000, 131–41) on the amphoras, and Giachi and Pallecchi (2000, 350) and Pecchioni et al. (2007, 18–9) on the dunnage materials.

coast packed in Vesuvian materials[131] and later returned south balanced by Tuscan iron and slag. It appears that these traders had opportunistically commoditized their dunnage using building materials from near Naples for sale farther north, and it seems unlikely that they would have neglected to monetize their ballast for return trips south.

CONCLUSION

There is still much to do on this topic at Pompeii, especially surveying the remaining streets and chemically testing the iron and slags. Researchers must also look for this new paving technology beyond Pompeii. Like the drainage and traffic systems identified at Pompeii,[132] this infrastructural technology was probably not unique to that city. Indeed, we have noted one example of Type 2 (solid with staining) at Paestum, at the junction of the cardo and decumanus. The present results, however, do have potentially important implications. Beyond documenting a novel method of street repair, our research disproves the lingering misconception among nonspecialists that Romans did not, or could not, melt iron. Our results represent the first large-scale attestation of the Roman use of molten iron and shows that we might have misunderstood the Romans' relationship to this technology. Evidence for molten iron is infrequent not because the Romans lacked the technology to produce it, but because they lacked appropriate applications for it. It was not a goal they were unable to achieve, it was an opportunity they did not know they desired. At Pompeii, we now have one such opportunity and application.

Although the process of remelting and pouring out ferric materials onto dilapidated thoroughfares was probably rare in antiquity, Pompeii would not be alone in reusing ballast materials to pave their streets.[133] John Leyland, writing in 1546, remarked that the volume of Icelandic cobbles from the cod trade was sufficient "to pave the whole of Kingston from one end to the other."[134] In 18th-century New York City, streets were paved in flat pieces of Belgian granite, and during World War II, rubble from the destruction of Bristol crossed the Atlantic as ballast and served as the foundation for New York's FDR Drive.[135] Slag was also a common ballast material in the early modern period; San Juan, Puerto Rico, has a long history of paving its streets in blocks cut from European furnace slag.[136] Such instances of ballast being repurposed for construction material,[137] for street surfaces, and even for paving streets in reused slag are historical parallels for Pompeii. Like the transatlantic trade of the early modern period, the boom in Mediterranean shipping in the early imperial period not only increased the actual amount of ballast materials[138] but also made them more noticeable. Surely, their conspicuous presence made experimentation likely.

Indeed, related experimentation was already taking place in Roman construction. It is difficult to separate the contemporary revolution in the Roman use of concrete from the idea at Pompeii of repairing streets with another liquefied material. As the Domus Aurea and the Domus Flavia demonstrate, by the 70's C.E. Roman architects had become expert in designing and building structures of poured concrete. In the Pompeian context, filling ruts and the voids below paving stones was another experiment in the use of liquefied solids, one in which the force of adhesion was added to compression. In fact, remnants of *opus signinum* found adhering to the inside of ruts on Via di Mercurio suggest earlier attempts to apply similar concepts.[139] In

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[131] Volcanic materials from southern Campania were transported around the Mediterranean to be used as building materials and bonding agents, most famously to Caesarea Maritima where more than 17,000 m^3 (or 13,000 tons) of pulvis puteolanus was delivered in at least 45 ships. See Arnaud (2014, 168) as well as Jackson et al. (2014, 154–59) on the sourcing of this material, along with other elements of mortars. Lancaster (2015, 30) notes that Vesuvian scoria were essential in the construction of the Pantheon, the Baths of Trajan, and the Baths of Carracalla, and that Sardinian scoriae similarly piggy-backed on the trade in millstones with Carthage. Marra et al. (2013) have chemically traced construction materials at Rome to the Pompeian region.

[132] Poehler 2012, 2017.

[133] Burström 2017, 51–9.

[134] Quoted in Peacock et al. 2007, 28.

[135] Burström 2017, 61–7.

[136] These silvery-blue blocks are called *adoquines*. Pabón-Charneco 2016, 81, fig. 5.1.

[137] In the 18th and 19th centuries, buildings in La Rochelle, France, were made of substantial quantities of Canadian granite (Peacock et al. 2007, 29).

[138] The Shipwrecks Database of the Oxford Roman Economy Project shows the greatest number of shipwrecks occurring in the century between 50 B.C.E. and 50 C.E. http://oxrep.classics.ox.ac.uk/databases/shipwrecks_database/.

[139] Especially between the middle stepping-stones on Via di Mercurio between VI 8, 22, and VI 10, 6. Why Pompeians did not use cement for their street repairs is unknown, though it was likely a combination of factors including (1) the duration of curing cement compared to iron or even stone repairs; (2) the high

Early Imperial architecture, stonecutters were increasingly replaced by carpenters and bricklayers. At Pompeii, it seems *silicarii* were sometimes supplanted by charcoal makers and blacksmiths who discovered that they could pour molten iron material into inaccessible spaces, binding the paving stones from below and fusing together the iron streets of Pompeii.

Eric E. Poehler
Classics Department
527 Herter Hall
University of Massachusetts Amherst
Amherst, Massachusetts 01003
epoehler@classics.umass.edu

Juliana van Roggen
1642 NE 3rd Avenue
Camas, Washington 98607
juliana.vanroggen@gmail.com

Benjamin M. Crowther
Classics Department
University of Texas at Austin
2210 Speedway, Stop C3400
Austin, Texas 78712
bcrowther@utexas.edu

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viscosity of cement, which would not allow it to penetrate small cracks in the pavement; and (3) the growing Roman awareness of cement's lesser tensile strength and concern over its durability in this context.

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