Geological observations of excavated sand (*harenae fossiciae*) used as fine aggregate in Roman pozzolanic mortars

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Introduction to Roman pozzolanic mortars

Early concrete work in Rome consists of coarse clasts of volcanic tuff or lava (*caementa*) laid in a pozzolanic mortar made of granular volcanic ash mixed with lime and water. Despite nearly a century of investigation, the sources of volcanic rock that Romans selected for fine aggregate, or *pozzolane*, in these cementitious materials remain enigmatic.[1] Furthermore, little is known about the preferences of Roman builders in their formulations of the remarkably durable mortars of the Imperial age. Our purpose here is to record some geological observations of the granular volcanic ash deposits surrounding Rome (fig. 1), in order to provide insights into the sources and material characteristics of the fine aggregate used in the mortars of several Late Republican and Early Imperial concrete monuments in the city. These data provide a geological foundation for identifying Roman preferences in the selection of fine aggregate for Roman concrete mortars from the 2nd c. B.C. through the early 1st c. A.D.

Vitruvius (2.4.1) describes the fine aggregate used to mix up mortar (*ad materiem miscendam*) as excavated sands (*harenae fossiciae*).[2] He describes the range of colors and material characteristics of *harenae fossiciae* and explicitly distinguishes them from sands of the riverbed (*fluminibus*) and the seashore (*litore marino*) (2.4.2). The archaeological and historical literature and our petrographic and mineralogical observations of mortars from monuments constructed during or prior to Vitruvius' lifetime confirm that the Romans employed *harenae fossiciae* from the sequence of granular volcanic ash deposits — the Pozzolane Rosse, Pozzolane Nere, and Pozzolanelle ignimbrites[3] — that erupted from the Alban Hills volcanic district between *c.*457,000 and 366,000 years ago (figs. 1-2).[4] For example, the earliest pozzolanic mortars of the so-called Porticus Aemilia (174 B.C.)[5] contain mainly Pozzolanelle fine aggregate (Jackson and Marra 2006). In contrast, mortars of the earliest phases of concrete construction at the Temple of Concord (121 B.C.) and the Temple of Castor and Pollux (117 B.C.) (color figs. 3a, 3c) contain an assortment of mainly volcanic sediments, which were eroded from the landscape hundreds of thousands of years ago and re-deposited in valleys within the area that would become Rome.[6] These mortars correspond to the early, "ashy gray type" described by E. B. Van Deman in her comprehensive observations of Roman concrete monuments (1912a, 244-45). She observed (1912b, 391) that by the late 1st c. B.C. and early 1st c. A.D. the Romans had developed a "dusky red type" of mortar in which "the *arena* consists of red or reddish brown pozzolana, with which a little gray and white are mixed". Petrographic studies (color figs. 3b, 3d) of Augustan concrete renovations to the Temples of Castor and Pollux (A.D. 6) and of Concord (A.D.

1 E.g., Van Deman 1912a and 1912b; Frank 1924; Blake 1947, 1959 and 1973; Lugli 1957; Langton and Roy 1984; Lechtman and Hobbs 1987; Bakos *et al.* 1992 and 1994; Chiari *et al.* 1992 and 1996; Lancaster 2005; Jackson and Marra 2006.

2 The expression *ad materiem miscendam* translates as 'to compose, to make up, to compound mortar'. Giuliani (2006, 216) considers the terms *materia, materies, (h)arentum, and maltha* synonyms of mortar.

3 An ignimbrite is the deposit of a pyroclastic flow (*pyro* = fire, *clastic* = broken in pieces), a hot mixture of gas and particles produced by an explosive eruption.

4 Jackson and Marra 2006; Karner *et al.* 2001; Chiari *et al.* 1996, 24-30; Bakos *et al.* 1992 and 1996. See also De Rita *et al.* 1988 and 1995.

5 In this article we describe the oldest mortars at the base of Porticus Aemilia. Giuliani (2006, 217) believes that it would have taken about 20 years to construct the Porticus Aemilia, given its massive size and the technical challenges of early concrete work. He suggests that construction began in 192 B.C. (Livy 35.10.12) and that the building was inaugurated in 174 (Livy 41.27.8).

6 These include the deposits of the Aurelia and San Paolo Formations (Marra and Rosa 1995; Alvarez *et al.* 1996; Karner and Marra 1998; Corazza *et al.* 2004).