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Carbonate deposits from the ancient aqueduct of Béziers, France — A high-resolution palaeoenvironmental archive for the Roman Empire

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ABSTRACT

Carbonate deposits from a Roman aqueduct in Béziers, southern France, record environmental conditions during the late first century C.E. These deposits formed in a steep section of the aqueduct with a high flow velocity, which caused rapid deposition of up to 11 mm of calcite per year over a period of 22–24 years. The microstructure, trace element and stable isotope composition show that regular deposition was interrupted by high-discharge events, probably in response to heavy rainfall during autumn and winter, transporting colloidally- and particle-bound elements and depositing calcite with elevated $\delta^{18}O$ values. Individual autumn high-discharge events coincide with abrupt decreases in $\delta^{13}C$ from −8 to −12‰ giving rise to a saw-tooth profile. In some years, several high flow events persisted throughout the winter, suppressing this profile. Event horizons of micrite capping sparite growth surfaces, enriched in Mg, may represent anomalously low water levels or periods when the channel fell dry. In comparison to carbonate deposits from Roman aqueducts in the Eastern Mediterranean, visible layering is less regular and pronounced in Béziers, reflecting a more complex precipitation pattern.

1. Introduction

The long and ingenious aqueducts built by Roman engineers to supply the cities of the empire with drinking water are some of the most remarkable technical achievements of the ancient world (Hodge, 1992). These aqueducts are not only interesting from a cultural, architectural and engineering point of view, but also contain carbonate deposits that record information on changes in water quantity, temperature and chemical composition for periods lasting up to several centuries and preserving it for 2000 years. A careful study of the deposits allows unravelling of the various factors that influenced carbonate deposition, and provides insights into palaeoclimate, archaeology, palaeoseismology and spring hydrology (Sürmelihindi and Passchier, 2013).

In previous papers (Sürmelihindi et al., 2013a, 2013b; Passchier et al., 2016) we studied aqueducts from southern Turkey, which is an area with a strongly bimodal Mediterranean climate. In this paper, we discuss analytical results from carbonate deposits in the Roman aqueduct of Béziers, a town on the Mediterranean coast of southern France (Fig. 1). This aqueduct is of similar construction and length as aqueducts in Turkey and is also sourced from a karst spring, but the catchment area is located in a Mediterranean climate regime with stronger Atlantic influence. The aim of this study is to investigate the effects of this different climatic setting on the depositional structure and geochemical composition of the carbonate deposits in the Béziers aqueduct and to explore their potential as a high-resolution archive of the palaeoenvironment.

2. Study site

2.1. The Béziers aqueduct

The Roman city of *Baeterra*, modern Béziers, was provided with drinking water by an aqueduct with a total length of 41.2 km, one of the longest in France, built in the second half of the 1st century C.E. (Andrieu, 1990; Andrieu et al., 1994; Esperou and Roques, 2009). The aqueduct was fed by three karst springs at 168, 170 and 150 m altitude located in the hills north of Béziers that were joined into a single channel and transported water to the city at 67 m a.s.l. (Fig. 1; Andrieu, 1990; Andrieu et al., 1994; Esperou and Roques, 2009). The aqueduct was built as a buried masonry channel, covered with a vault and locally by stone cover slabs (Fig. 1b). Although several bridges and tunnels and one inverted siphon have been located, only few remains of the aqueduct are presently visible. Much of the aqueduct was destroyed by erosion and agricultural activity in the area. The first 4 km of the aqueduct are relatively well preserved and have been previously investigated (Andrieu et al., 1994; Esperou and Roques, 2009). From these observations, Esperou and Roques (2009) reconstructed the trace and slope of the aqueduct (Fig. 1). The slope is steepest in the first 4 km of the channel profile. From the dimensions and slope of the channel and the height

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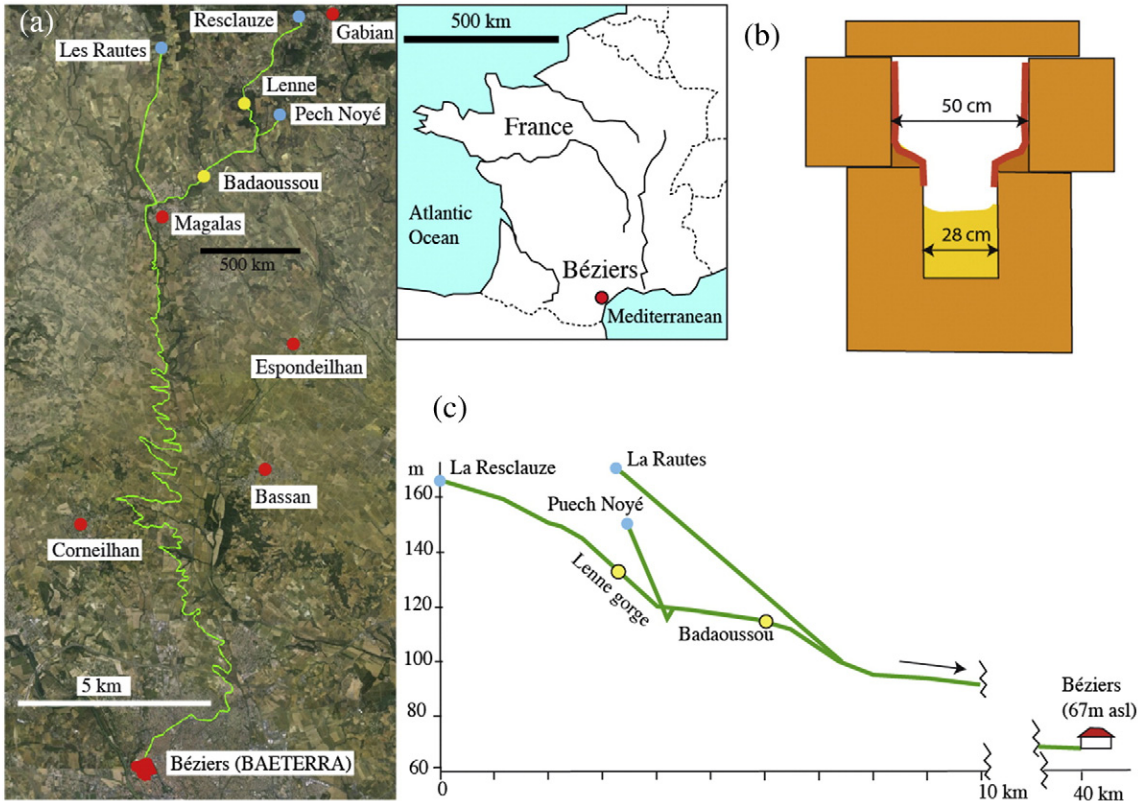

Fig. 1. (a) Map of the Béziers aqueduct, indicating the main spring (Resclauze) and the two other springs, indicated as blue dots. Satellite image from GoogleEarth 7.1. Locations where carbonate deposits were observed in this study are indicated by yellow dots. The map to the right shows the location of the study area in France. (b) Schematic section of the aqueduct channel, showing the two stages of construction. *Opus signinum* waterproof mortar (red line) is only present in the upper part of the channel. Studied carbonate samples are indicated in yellow. (c) Longitudinal section of the Béziers aqueduct, its springs and side branches as well as sampling points (yellow dots). (b) and (c) after Esperou and Roques (2009).

of carbonate deposits on the channel walls, it was possible to determine that the aqueduct transported 1300–7000 m^3 water/day to the city of *Baeterra* (Andrieu, 1990; Andrieu et al., 1994; Esperou and Roques, 2009).

Carbonate deposits have been observed in excavations of the channel in the first section of the aqueduct between 1 and 7 km from the Resclauze spring, and these deposits are thickest between 1 and 4 km from the spring (Fig. 1; Andrieu et al., 1994; Esperou and Roques, 2009). No carbonate deposits were found in the first kilometer of the channel (Esperou and Roques, 2009). Such a pattern is common in aqueducts, since water is usually undersaturated with respect to calcite in the proximal part, and only reaches supersaturation by degassing of CO_2 at some distance from the spring (Sürmelihindi and Passchier, 2013). During the excavation of channel sections, Esperou and Roques (2009) observed that between km 1 and 4 from the Resclauze spring, the channel was built in two phases. The first phase was built as a masonry channel with an inner diameter of 27–28 cm, while in the second stage the channel was enlarged by adding two sidewalls on top of the original walls, creating a channel 50–56 cm wide (Fig. 1b). The second phase was lined with *opus signinum*, Roman waterproof cement, while the first channel was not plastered in most excavated sections (Fig. 1b; Andrieu et al., 1994; Esperou and Roques, 2009). The additional walls were built after the original channel had been partly filled, although subsequently the wider channel also became clogged. The reason for the enlargement seems to have been rapid clogging of the first channel by carbonate deposits (Esperou and Roques, 2009), and widening of the new channel was probably undertaken as a measure to alleviate the impact of renewed carbonate deposition on the channel performance.

2.2. Carbonate deposits

We observed carbonate deposits at two sites along the aqueduct. Deposits in the upstream, steepest part of the aqueduct are massive, laminated and dense, while those at the downstream site at *Badaoussou* at km 6 (just before the junction with the La Rautés branch, yellow circle in Fig. 1c) are 6–9 cm thick, porous and weakly laminated. Ambert and Gilly (1990) reported that downstream from the junction of the La Rautés branch, carbonate deposits decrease rapidly in thickness and are only 1 cm thick at the bottom of the channel near the junction. In this paper, we discuss observations on the dense carbonate deposits of the upstream section in the Lène Gorge, which show the highest potential for preserving palaeoenvironmental records.

2.3. Location and setting of the investigated sample

A large block of carbonate deposits was found in the Lène Gorge, a steep and 20-m-deep valley, 3.3 km from the Resclauze source at 43° 29.510′ N, 3° 14.823′ E at 135 m altitude (Fig. 3; Esperou and Roques, 2009, Fig. 51). The block is 1.3 m long, 30 cm wide and 22 cm thick, and lined by minor remains of Roman water-proof cement (*opus signinum)* (Fig. 3b). Although it was found in upright position, the block is slightly displaced from its original position and the original sidewalls and cover are gone. Because of the uncertainty of its position, no attempt was made to measure its present-day slope. Since the block is 30 cm wide, it is thought to belong to the oldest phase of the aqueduct with a narrow channel. The *opus signinum* surface of the channel bottom is not flat but irregular, which is reflected by the wavy pattern of the bottom layering.