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Palaeomagnetic results from an archaeological site near Rome (Italy): new insights for tectonic rotation during the last 0.5 Ma

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Abstract

Approximately 20 km north-east of Rome, along the modern trace of the Tiburtina road, recent archaeological diggings have brought to light a system of aqueduct galleries constructed by Roman engineers. This site falls inside the Acque Albule Basin, a travertine plateau, upper Pleistocene in age that has been interpreted as a rhomb-shaped pull-apart basin created by strike-slip faulting within a N-S shear zone that crosses the Rome area. This study provides evidence that two narrow water channels of this aqueduct system were significantly deformed by tectonic movement that occurred subsequent to their construction (II-III century A.D.). The geometry of the deformation pattern is compatible with that expected for a shear zone bounded by N-S oriented, right-lateral faults. The palaeomagnetic study of the volcanic formation («Pozzolane Rosse» Formation, 457±4 ka) containing the Roman aqueduct system evidences significant clockwise rotation around sub-vertical axis, consistent with the above-mentioned tectonic style.

Key words *palaeomagnetism – block rotation – active tectonics – Rome – Italy*

1. Introduction

Along the modern trace of the Tiburtina road, approximately 20 km north-east of the city of Rome (fig. 1), recent archaeological diggings have brought to light a system of aqueduct galleries constructed by Roman engineers during the II-III century A.D. Geological and structural data collected and presented by Marra *et al*. (2004) along two narrow water channels of this aqueduct system (fig. 2a-d) evidenced deformations due to tectonic movement that occurred subsequent to their construction.

The archaeological site falls at the western edge of the Acque Albule Basin (AAB in fig. 1), a travertine plateau, Upper Pleistocene in age with a medium thickness of approximately 60 m. AAB has been interpreted as a rhomb-shaped pull-apart basin (7 km long, 4 km wide) created by strike-slip faulting within a N-S shear zone, whose evolution is attributed to Middle-Upper Pleistocene times (Faccenna *et al*., 1994). The water channels were excavated in the pyroclastic terrain («Pozzolane Rosse» Formation, 457±4 ka, Karner *et al*., 2001) emplaced by the eruptive activity of the nearby Colli Albani Volcanic District southwest of the basin (fig. 1) (De Rita *et al*., 1988, 1995; Karner *et al*., 2001).

The principal N-S water channel is affected by both brittle (extensive) and ductile (compressive) deformations, whereas the shorter

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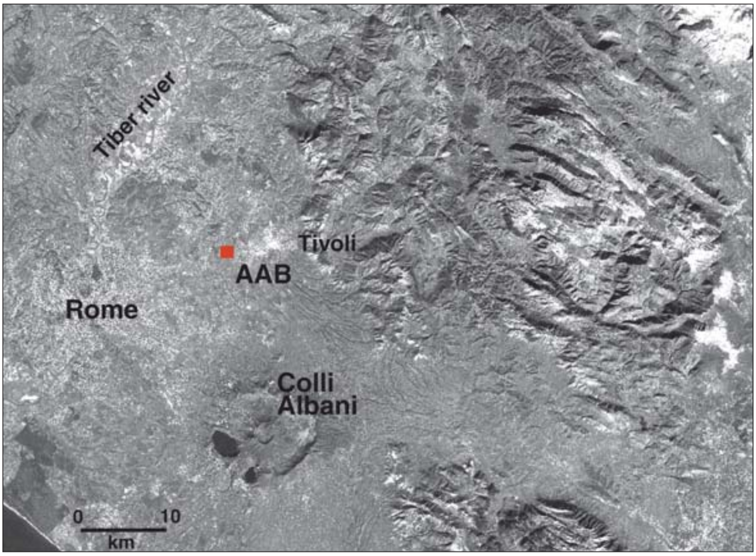

Fig. 1. SPOT image showing the location of the study area. AAB: Acque Albule Basin. The red box indicates the location of the studied area.

channel to the south-west reveals predominantly ductile deformations linked to transverse compression resulting in a restriction and rotation of the structure (fig. 2a). Several elements compatible with strike-slip tectonics have been identified, including: i) the deformation pattern and the brittle structures affecting the aqueducts and the surrounding rock; ii) the presence of sections deformed in a ductile manner (fig. 2b); iii) the segmentation of the two channels into tracts rotated in different directions, the narrowing (up to a complete sealing in some instances) of the portions of their internal section oriented ~NW (Marra *et al.*, 2004). In particular, the observed deformation is consistent with that expected for a shear zone bounded by N-S right-lateral faults. Such tectonic deformation is commonly characterised by horizontal rotations of single domains bounded by faults, as widely reported in the literature (*e.g.*, Sonder *et al.*, 1994). In order to provide additional quantitative support for the structural data, and to determine vertical axis rotations, a palaeomagnetic analysis was carried out in the «Pozzolane Rosse» Formation.

2. Structural investigation

Both channels have a similar structure with a 85 cm width and a depth of about 1.5 m (fig. 2c,d). The original excavations had followed the natural slope of the land; the base and sidewalls were sealed with a crushed ceramic mortar mix (*cocciopesto*) that made them impermeable, and a ridged ‘hood-like’ tile system (*cappuccina*) covered the length of the structure with the peak at par with the surrounding ground level. As sketched in fig. 2d, the lateral area of the structure was backfilled with blocks of travertine held together with a cement mortar mix (*malta pozzolanica*). According to the ar-

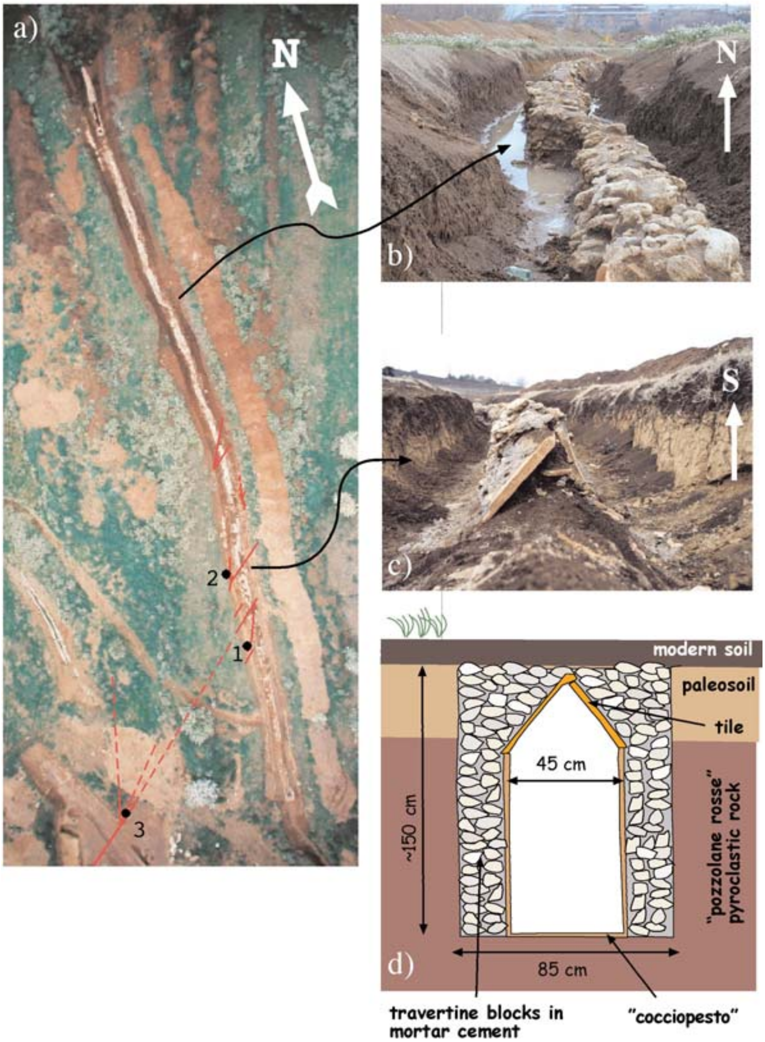

Fig. 2a-d. Aqueducts constructed by Roman engineers during the II-III century A.D. a) Low altitude photo showing horizontal deformation of the two originally linear aqueducts; b) detail of a twisted portion of the aqueduct; c) detail of channel structure with the typical ridged 'hood-like' tile system (*cappuccina*); d) sketch of aqueduct structure.

chaeologists (Moscetti, *personal communication*) the water channels were built following a rectilinear trend by Roman engineers and were characterised by a homogeneous gradient. In particular, the marked s-shaped change in direction that occurs at the principal channel (fig. 2b) cannot have any hydraulic or constructive reason.

Decisive to evidence the post-constructive deformation of the main aqueduct is the marked restriction of the section of the aqueduct in correspondence of the distorted portion. Figure 2c and d show that the aqueduct was originally 85 cm wide, with walls 20 cm wide and an inner tunnel of 45 cm. At present, the entire width of the aqueduct appears reduced to ~40 cm close to the twisted portion (fig. 2b). It descends that the inner tunnel is completely missing in this portion of the aqueduct. The tiles that formed the roof are vertically clutched in between the two courses of blocks that form the side walls of the aqueduct. This fact discloses that the structure suffered a transversal compression that caused the narrowing of the inner light, leading to its complete sealing (fig. 3a-c). It is therefore apparent that the two aqueducts underwent strong deformation after their construction that is dated around II-III century A.D. (Moscetti, 2001).

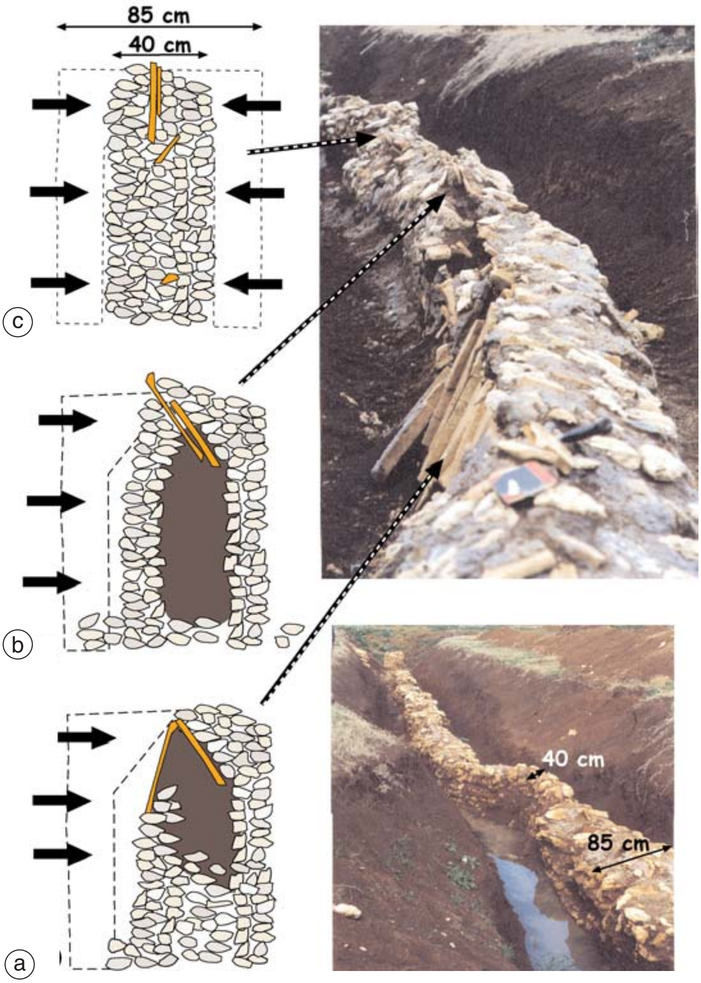

Fig. 3a-c. Details of most strongly deformed sections. The structure has suffered a transversal compression that caused the narrowing of the inner light up to its complete sealing. The tiles (in yellow) that formed the roof are vertically clutched in between the two courses of blocks (a, b, c).

Oriented approximately N-S the principal channel runs for 118 m (fig. 2a) and displays a difference in elevation of about 1.8 m, N-side down (portable GPS measurement) between its edges (see fig. 6 in Marra *et al.*, 2004). The average gradient of 1.5% along the total length is comparable with that of the topography. In the northern part of the channel a conspicuous accumulation of sedimentary soil gives testimony to the occurrence of one or more instances of subsidence following the time of construction. However, subsidence levels in the range of one metre cannot alone explain the distortion manifested through horizontal displacement, resulting in an estimated total offset at the southern end of the principal aqueduct, of approximately 8 m and a consequent clockwise rotation of approximately 10°. A clockwise rotation in the same range also affects the minor aqueduct channel.

A detailed survey (Marra *et al.*, 2004) of the principal channel indicates a segmented course of the entire structure, with orientations ranging between N10°E and N10°W, and with one section oriented at N35°W. Numerous extensional joints and faults were surveyed all along the archaeological excavations of the principal channel. Elaboration by way of a circular diagram reveals a preferential orientation on N30°-40°E and a dip ranging between 70° and 90° towards the SE (in most instances) rather than towards the NW (see fig. 7 in Marra *et al.*, 2004).

Fig. 4. Sites 1 and 2 along a limited outcropping of the Pozzolane Rosse Formation, containing the Roman aqueduct system.

3. Palaeomagnetic investigation

In order to detect possible horizontal rotations linked to strike-slip tectonics, we drilled 35 cores in 3 sites along a limited outcrop of lithified, fine grained portion of the Pozzolane Rosse pyroclastic-flow deposit (fig. 4). This is a massive, poorly cemented, scoriaceous ash deposit erupted 457±4 ka (Karner *et al.*, 2001) by the Alban Hills Volcanic District, whose petrographic features are well distinguishable with respect to other pyroclastic-flow units of the same volcanic district (De Rita *et al.*, 1988; Karner *et al.*, 2001).

We used a petrol-powered portable drill, and the cores were oriented *in situ* using a magnetic compass. Sampling was adjusted to avoid intervals with pebbles and scoriae that characterize this Formation. The magnetic measurements were made in the shielded room of the palaeomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia, INGV (Rome). All the samples were measured on a 4.5-cm small access pass-through 2G cryogenic magnetometer. Alternating Field (AF) demagnetization was systematically used. Peak fields were set at 10 milliTesla (mT) increments to 40 mT, then at 20 mT increments up to 120 mT. The maximum peak field was set at 150 mT.

For 77% of the samples, stable palaeomagnetic behaviour was evident in the vector component diagrams (fig. 5) with characteristic remanence (ChRM) directions that generally

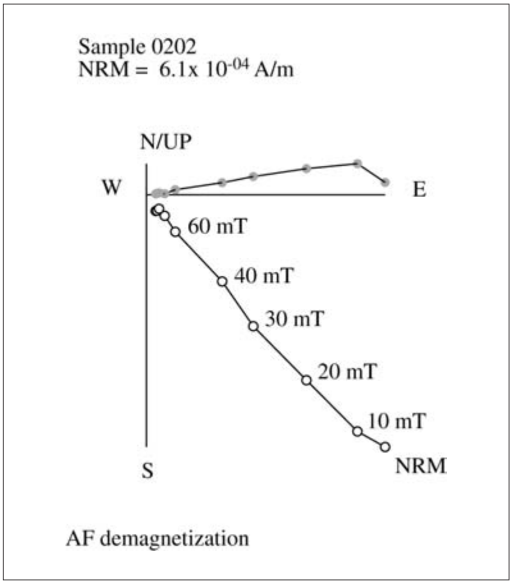

Fig. 5. Example of demagnetization behaviour on vector component diagram, in geographic coordinates. White symbols denote projection onto the vertical plane. Grey symbols denote projection onto the horizontal plane. Numbers adjacent to data points indicate Alternating Field (AF) in milliTesla (mT).

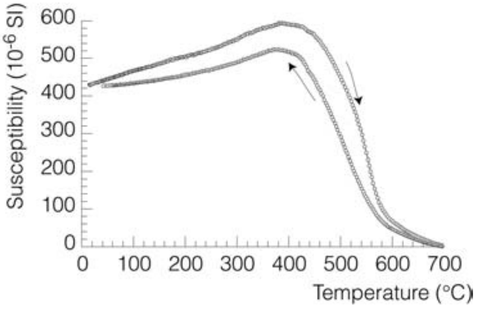

Fig. 6. Temperature dependence of the low field magnetic susceptibility (κ) for a selected sample from site 2.

tended toward the origin. Efficiency of AF cleaning and thermomagnetic analyses (fig. 6) concur to indicate that magnetite is the dominant ferromagnetic mineral. For each samples, the ChRM direction was determined using a best-fit line that was constrained through the origin of the vector component diagram (Kirschvink, 1980). For the remaining samples the demagnetisation data are noisy and it was

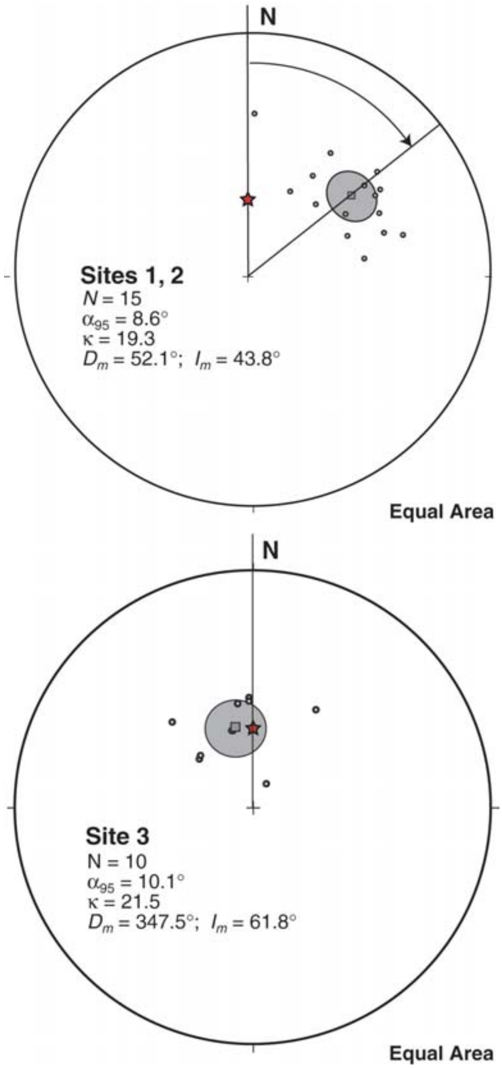

Fig. 7. Equal area projection (lower hemisphere) of ChRM directions for sites 1+2 and 3. Mean declination (D_m) and inclination (I_m) with confidence limit (α_{95}), precision parameter (κ) and number of samples (n) are listed. The star indicates the expected direction for a Geocentric Axial Dipole field (GAD).

not possible to determine a clear ChRM direction. This behaviour is attributable to the presence of lava clasts and scoriaes within the matrix. Site-mean palaeomagnetic directions were calculated using Fisher's (1953) statistics where only stable ChRM were isolated.

The mean palaeomagnetic directions obtained from the three sites are plotted on an equal area projection in fig. 7. All samples from the three sites show normal palaeomagnetic directions. The mean direction obtained from the statistical analysis of sites 1 and 2, close to the distorted portion of the aqueduct, indicates a clockwise rotation of about 50° with respect to the local north (N=15, D_m=52.1°, I_m=43.8°, κ=19.3 and α_{95}=8.6) with an average rotation rate of ~0.1°/ky. In addition, the data from sites 1 and 2 show a significant flattening of the palaeomagnetic vectors, with inclination data that are noticeably lower than those expected for a time-averaged Geocentric Axial Dipole (GAD) field. On the contrary, the mean direction obtained from site 3 is oriented N-S (N=10, D_m=347.5°, I_m=61.8°, κ=21.5 and α_{95}=10.1) and the flattening is absent or negligible (fig. 7). In fact, we cannot exclude the possibility that this N-S direction may arise from a very recent phase of remagnetization.

Finally, we rule out that a significant tilting of the investigated volcanic layer may have caused the observed palaeomagnetic rotation, since no evidence for it is inferred from the textural features of the rock, or from the surrounding structural-geological setting.

4. Discussion and conclusions

Clockwise rotation around sub-vertical axis, as predicted in the theoretical model suggested in Marra *et al.* (2004), may explain the observed deformation on the archaeological structure as well as the geometry and kinematics of the surveyed tectonic elements. The large angle of rotation may be interpreted as a consequence of the small dimensions of the rotated block and of the sum of repeated instances of movement in the time span 457 ± 4 ka-Present (fig. 8).

Several theoretical models for block-rotation induced by strike-slip faults have been pro-

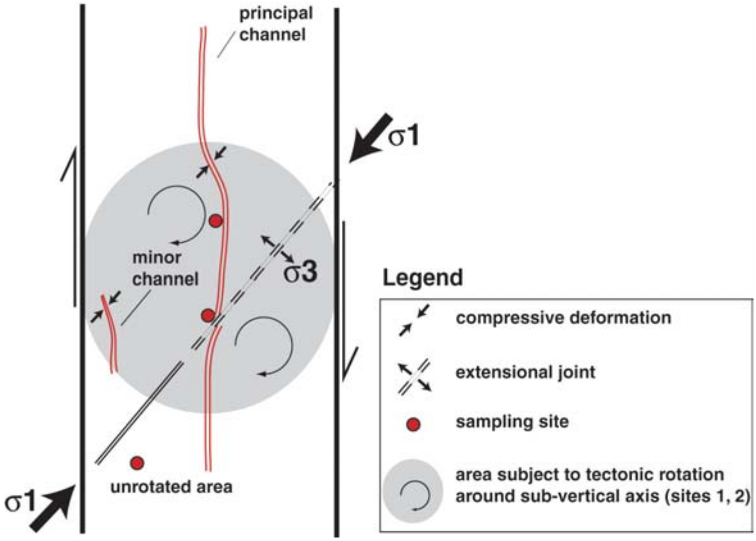

Fig. 8. Schematic tectonic model for the study area (after Marra *et al.*, 2004). A clockwise rotation around sub-vertical axis, could explain the deformation as well as the geometry and kinematics of the tectonic elements.

posed in the literature (*e.g.*, Sonder *et al.*, 1994). Here we suggest that rotation of small (several tens of meters) rigid blocks can occur among overstepping, N-S oriented, right-lateral fault segments. These small blocks must have also a shallow detachment level, in correspondence of major lithostratigraphic discontinuities. Therefore, it is expected that block-rotation in the area of Rome can be observed only in very limited sectors, in the proximity of N-S right-lateral faults.

The activity of right-lateral N-S faults, within the framework of a larger NE-SW extensional tectonic regime (Montone *et al.*, 1995) in the area of Rome, has been interpreted (Marra, 1999, 2001) as a local kinematics induced by a disengagement zone at the eastern boundary of the Northern Apennines. Based on the absence of significant local earthquakes in the historical sources (CPTI, Working Group) and in the instrumental seismicity, we believe that the strike-slip faults in this area are characterized by creeping and are responsible for slow aseismic deformation.

In conclusion, brittle and ductile elements affecting the two water channels and the surrounding rocks are coherent with a local stress-field characterized by a tensor of maximum stress ($\sigma 1$) oriented NE-SW on the horizontal plane, and a tensor of minimum stress ($\sigma 3$) oriented at 90° to the former (fig. 8). Thus, the geometry of the deformational pattern is consistent with strike-slip tectonics previously described in this area (Faccenna *et al.*, 1994) and interpreted as responsible for the «pull-apart» origin of the Acque Albule Basin. Palaeomagnetic data reveal that a prevalently horizontal displacement, causing locally large CW rotation, occurred in agreement with that expected for a tectonic deformation induced by a set of parallel N-S right-lateral faults.

Whereas a generalised CW rotation is expected in the vicinity of right-lateral faults, a more detailed model can be proposed to explain the presence of rotation only at two out of three investigated sites. We suggest that conjugate fracture systems in between the two N-S faults that border the area subject to rotation (as theoretically foresighted in Jones and Tanner, 1995), can originate a polygonal, roughly circular area (fig. 8), that can accommodate the rigid rotation. Differently, the zones outside of this area do not experience any significant rotation. The location of the palaeomagnetically investigated sites and the results are in good agreement with the proposed model. However, such a model requires further verification, with a larger number of tested locations, to be considered a possible deformation style associated to strike-slip faults in the area of Rome.

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