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Evidence of active tectonics on a Roman aqueduct system (II–III century A.D.) near Rome, Italy

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Abstract

In this paper we describe evidence of strong tectonic deformation affecting two aqueducts of Roman age (II–III century A.D.). The channels are located approximately 20 km northeast of Rome along the ancient Via Tiburtina. Brittle and ductile deformation affects these two structures, including extensional joint systems, NE-oriented faults, and horizontal distortion. This deformation is consistent with right-lateral movement on major N-striking faults, and represents the first evidence that tectonic deformation took place in historical times in the vicinity of Rome, with local strike–slip movement superimposed on a regional extensional fault system.

Keywords: Strike–slip tectonics; Active tectonics; Geo-archaeology; Rome; Italy

1. Introduction

The ancient Via Tiburtina was one of the consular highways of imperial Rome and connected the city to Tibur (nowadays known as Tivoli). Along the modern Via Tiburtina, approximately 20 km from Rome, recent archaeological excavations have uncovered a system of aqueduct tunnels and the remains of a necropolis that can be dated to the Middle Imperial era (II–III century A.D., Moscetti, 2001; Di Sante and Presen, 2002). We have discovered evidence of tectonic deformation affecting portions of the aqueduct system (Fig. 1), which is the first evidence of active tectonic deformation in the vicinity of Rome during historical times.

These findings shed light on the orientation of the dominant local stress field associated with recent tectonics, as evidence from two competitive stress-fields has reported. A transcurrent regime, characterized by a NW striking $\sigma3$ has been suggested to be representative of the most recent tectonic deformation (Faccenna and Funiciello, 1993; Faccenna et al., 1994a,b). Alternatively, seismic data show a common NE-striking T-axis for all the recent seismicity of this area, which supports NE–SW directed regional extension (Montone et al., 1995; Basili et al., 1996; Marra, 1999).

2. Tectonic and seismological setting

Rome is located on the margin of the Tyrrhenian Sea, at the convergence of a series of major structural lineaments (Fig. 2). The Latium Volcanoes (Vulsini, Vico, Monti Sabatini and Alban Hills) are aligned NW–SE along the strike of extensional structures that formed at the rear of the Apennine fold-and-thrust belt (Funiciello et al., 1976; Locardi et al., 1977; Funiciello and Parotto, 1978). The continuity of the northern-central Apennines is interrupted along the Olevano–Antrodoco line, a N-striking thrust front across which the Umbria–Marche Basin thrusts eastward over the Latium–Abruzzi Carbonate Platform (Parotto and Praturlon, 1975; Salvini and Vittori, 1982). A few kilometers west of this line is the Sabina Fault, a N10–20° striking shear zone (Alfonsi et al., 1991).

Recent seismological studies (Amato et al., 1994; Amato and Chiarabba, 1995; Montone et al., 1995; Basili et al., 1996) show that focal mechanisms around Rome have a NE oriented T-axis. This direction is parallel to that of the minimum principal stress ($\sigma3$) associated with long-term extension that has affected the Tyrrhenian margin of Italy since Messinian time (Patacca et al., 1991). However, a

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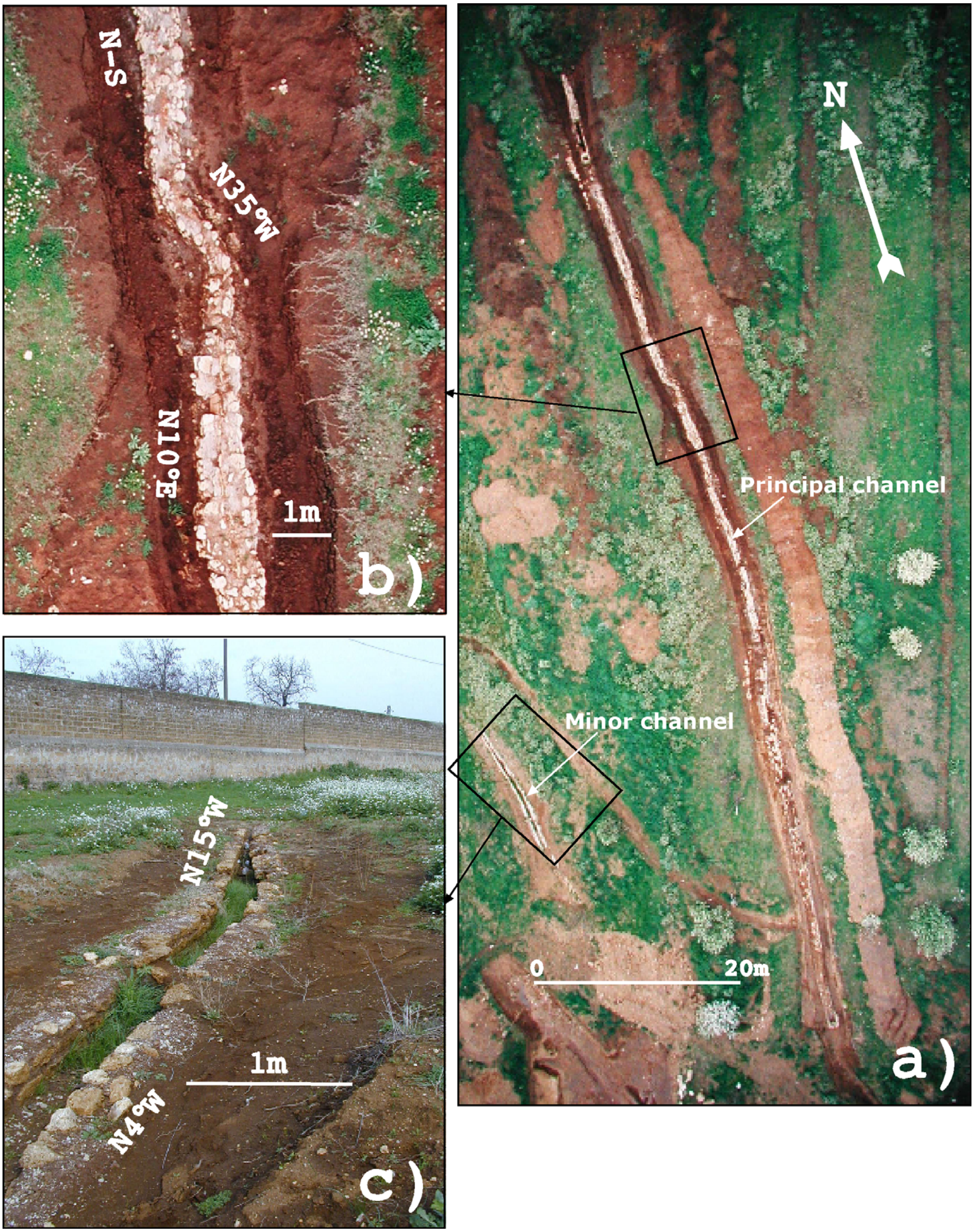

Fig. 1. Aqueducts constructed by Roman engineers during the II–III century A.D. (a) Low altitude photo showing horizontal deformation of the two (originally) linear aqueducts. (b) Detail of a twisted portion of the aqueduct. (c) Ground view of the minor channel.

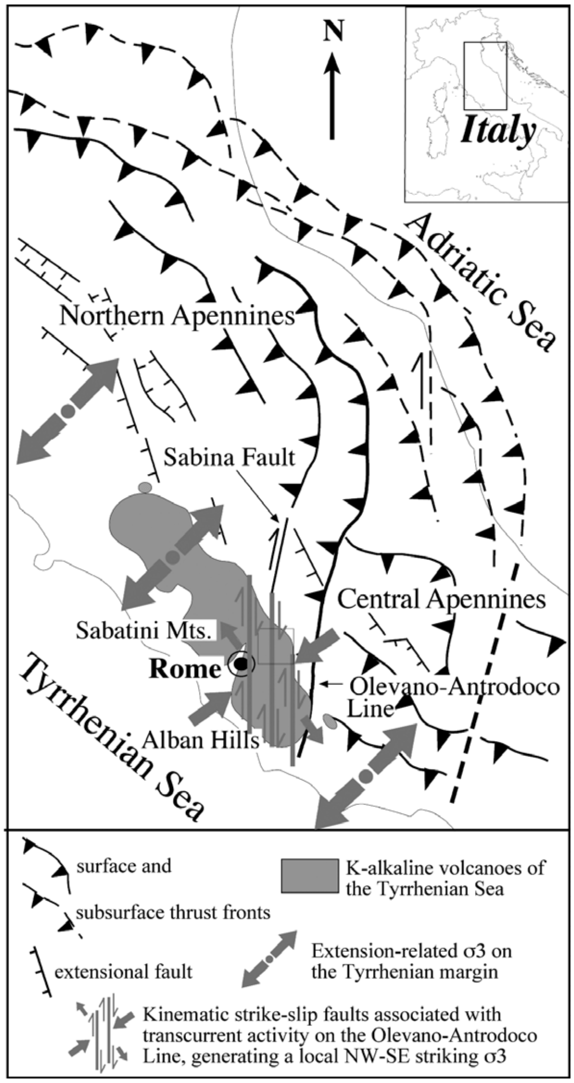

Fig. 2. Structural scheme of Central Italy (modified from Marra, 1999).

competitive stress field, characterized by a NW-striking $\sigma3$, was superimposed locally on these extensional features in the area of Rome during the Quaternary period (Marra, 2001). This tectonic regime was characterized by strike–slip faulting from Pliocene through middle–late Pleistocene times, and manifested in the area of Rome through a series of N-striking right-lateral en échelon fault segments at the southern end of the Sabina Fault (Faccenna and Funiciello, 1993; Faccenna et al., 1994b). A kinematic effect linked to the presence of a crustal discontinuity along the Sabina Fault has been suggested as the causal mechanism for concurrent strike–slip and extensional tectonics around Rome (Marra, 1999).

3. Geology of the area

The archaeological site is located inside the Acque Albule basin (Fig. 3). Here, a travertine plateau of upper Pleistocene age and with a maximum thickness of approximately 60 m covers a sedimentary sequence of clay, sand and conglomerate of Pliocene–Pleistocene age. The Acque Albule basin is bordered to the south and east by pyroclastic products from the Alban Hills volcanic district situated ~20 km to the south. The Alban Hills were characterized by an intense explosive activity in the time span 561 ± 1–355 ± 2 ka (Karner et al., 2001a), followed by a strombolian/effusive phase between 300 and 250 ka and a more recent phreato–magmatic phase that, perhaps, should not even be considered completely extinct at this time (Karner et al., 2001b). The northeast edge of the basin consists of middle Pliocene age clay deposits, while along the eastern border Mesozoic–Cenozoic age carbonate rocks associated with the central Apennines thrust-and-fold belt are exposed.

The Acque Albule basin has been interpreted as a rhombic shaped pull-apart basin of approximately 4 × 7 km, created by strike–slip faulting within a N–S oriented shear zone that crosses the Rome area (Faccenna et al., 1994a). Its formation and evolution are attributed to middle–late Pleistocene time. Isopachs of the travertine deposit are N–S elongated and mimic the trend of the isotherm lines associated with the Bagni Albule thermal spring in the area where the travertine reaches its maximum thickness (Fig. 3). The drainage system in the surrounding area is mainly N–S oriented, suggesting that the local morphology is controlled by N–S oriented tectonic displacement. Accordingly, N-striking fault segments, mainly with a right-lateral component, N30°E oblique-to-normal faults and N30–60°E extensional joints, represent the main fault systems recognized in the area of the Acque Albule basin. This fault and joint system displaces both the travertine plateau and the surrounding pyroclastic rocks. In particular, the U-series ages of calcite that fills fractures and faults in the Pliocene-age deposits range from 49 (±8) to 178 (+66/−44) ka, whereas the formation age of travertine that was affected by strike–slip faulting is 28 (+16/−15) ka (Faccenna et al., 1994a). This deformational pattern defines a strike–slip tectonic system acting on principal N–S right-lateral fault segments and is characterized by a minimum stress tensor ($\sigma3$) oriented N50–60°W.

4. Site geology and structure of the aqueducts

The archaeological site is located at the western margin of the Acque Albule basin (Fig. 3) and is partially covered by travertine deposits. One particular necropolis associated with a Roman villa dating from the II–III century A.D. was identified following an excavation that completely removed the recent, 1–1.5-m-thick travertine cover. The tombs were originally dug in the pyroclastic rock beneath the travertine layer, which verifies that this travertine mantle was deposited after the abandonment of the settlement, probably around the 5th century A.D. The two aqueduct channels, in which tectonic deformation was identified, are located

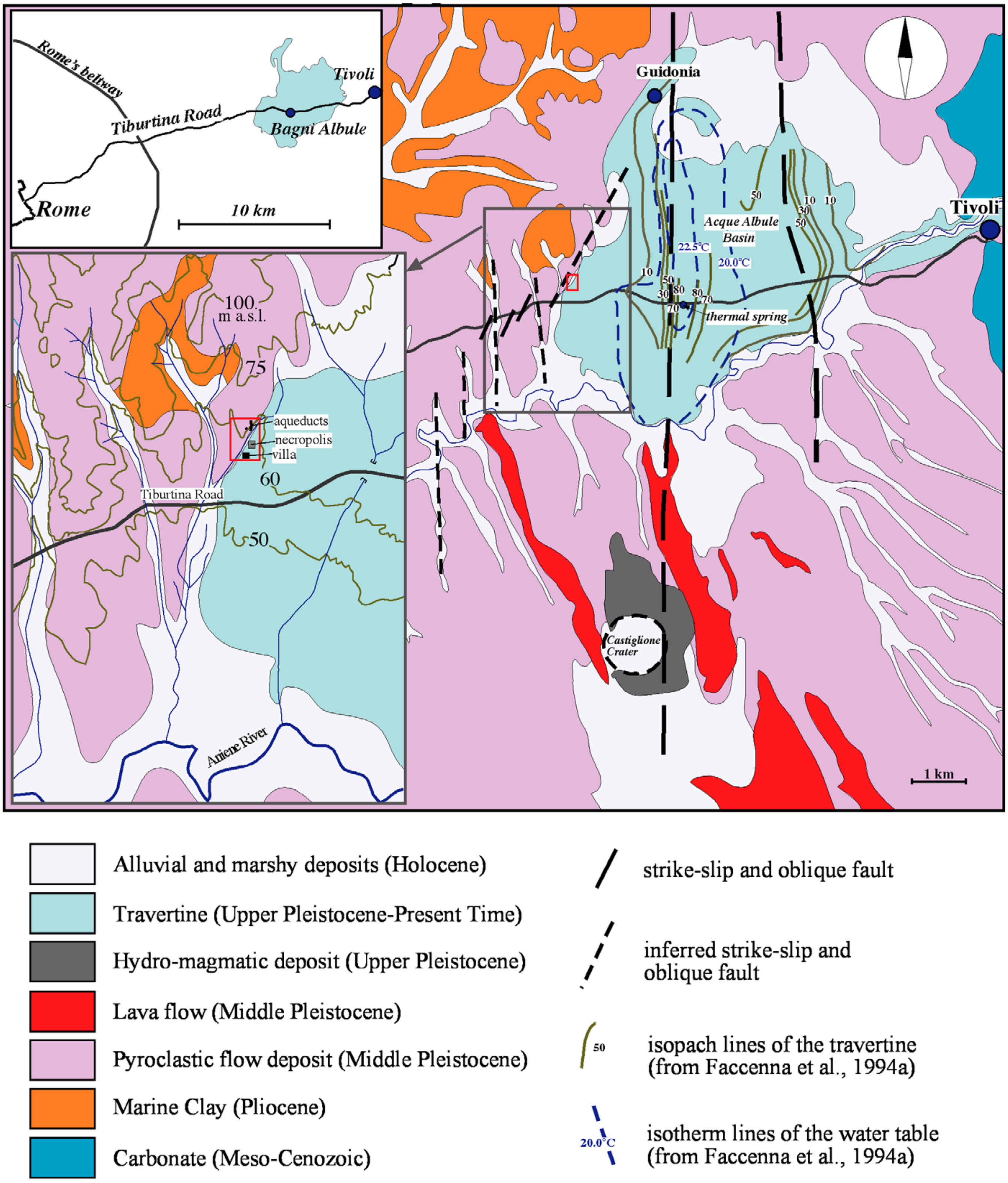

Fig. 3. Location and geological map of the investigated area (redrawn from De Rita et al., 1998). The archaeological site is located at the western margin of the Acque Albule basin.

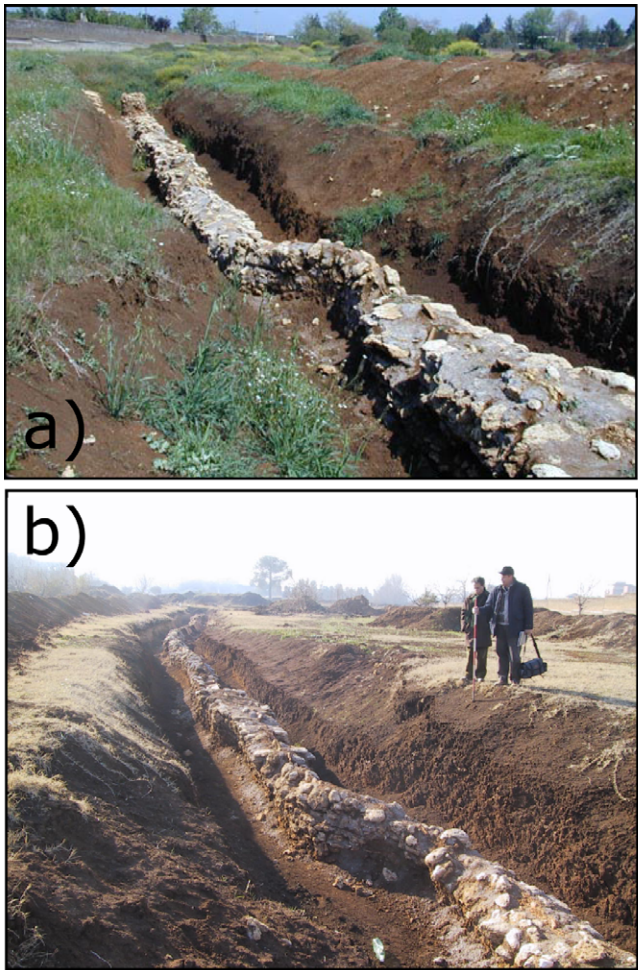

Fig. 4. Post-construction ductile deformation of the principal channel. (a) View from south. (b) View from north.

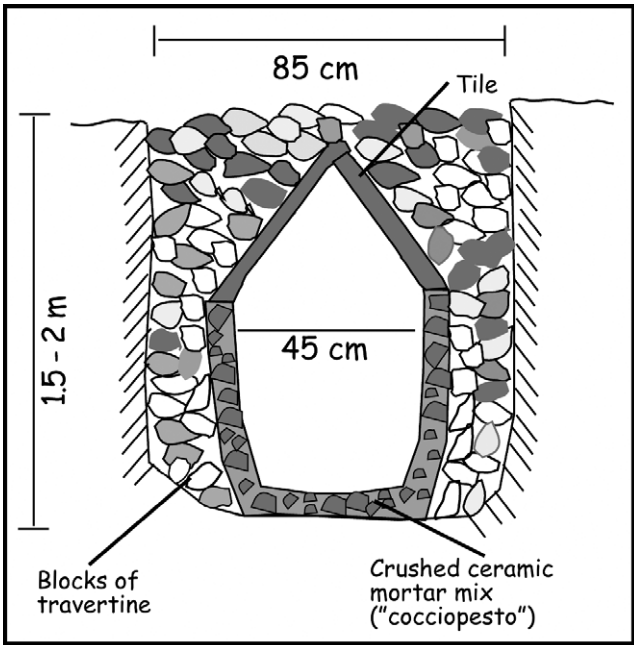

Fig. 5. Cross-section showing the structure of the aqueduct channel.

immediately to the north of the travertine plate edge, on pyroclastic rock pertaining to the 'Pozzolane Rosse' eruption (457 ± 4 ka; Karner et al., 2001a). Of these two structures, the principal N–S channel shows evidence of both brittle (extensive) and ductile (compressive) deformation (Fig. 4), whereas the shorter channel to the southwest shows predominantly ductile deformation. Both channels were constructed of the same materials and have cross-sectional dimensions of about 85 cm wide and 150 cm high (Fig. 5). The foundation trench for the aqueducts had followed the natural slope of the land. The walls of the aqueduct channel were made with irregular blocks of travertine held together with a cement mortar mix ('malta pozzolanica'). The base and sidewalls of the tunnel were sealed with crushed ceramic mortar mix ('cocciopesto') that rendered them impermeable. A ridged tile system ('cappuccina') covered the length of the structure with the peak at par with the surrounding ground level. The remaining space between the tiles and the ground level was backfilled with blocks of travertine (Fig. 5).

Today, the longer channel is in a better state of preservation as it had remained completely buried prior to recent exhumation. Oriented more or less N–S the channel extends for 118 m and displays a difference in elevation of approximately 1.5 m (portable GPS measurement) between the northern and southern ends (Fig. 6a). The average gradient of 1.6% (~2°) across the total length is comparable with the topographical gradient along the natural ground surface. A variation in the gradient (solid blue lines in Fig. 6a) is evident approximately at the middle of the aqueduct's length. The archaeological excavation was carried out to a width of approximately 2 m and to depths varying from a minimum of 1 m to a maximum of 3 m in the northernmost part. Here there is evidence of a thick accumulation of sedimentary material covering the aqueduct subsequent to its construction (Fig. 6a). Such an accumulation indicates that differential subsidence has occurred since construction. However, subsidence on the order of 1 m cannot alone explain the horizontal distortion of the aqueduct that is principally manifested through horizontal displacement, resulting in an estimated total offset of approximately 4 m (Fig. 6b). Numerous extensional joints and faults were surveyed all along the archaeological excavations of the principal channel (Fig. 7). Open fractures from between 0.5 and 4 cm are filled with alloisite (an argillaceous mineral derived from alteration of the pyroclastic rock). Such tectonic features (Fig. 7b–b′) are more concentrated along the southern portion of the excavation (first 30–40 m), whereas the rocks to the north do not show such deformation. In fact, at least four different lithological facies are observed along the course of the excavation (Fig. 6). In the southern part of the channel a pristine facies of pyroclastic rock (Pozzolane Rosse) crops out. This is a scoriaceous ash-tuff of weak coherency, compact and with small number of fractures (<1 fracture/5 m). About 20 m

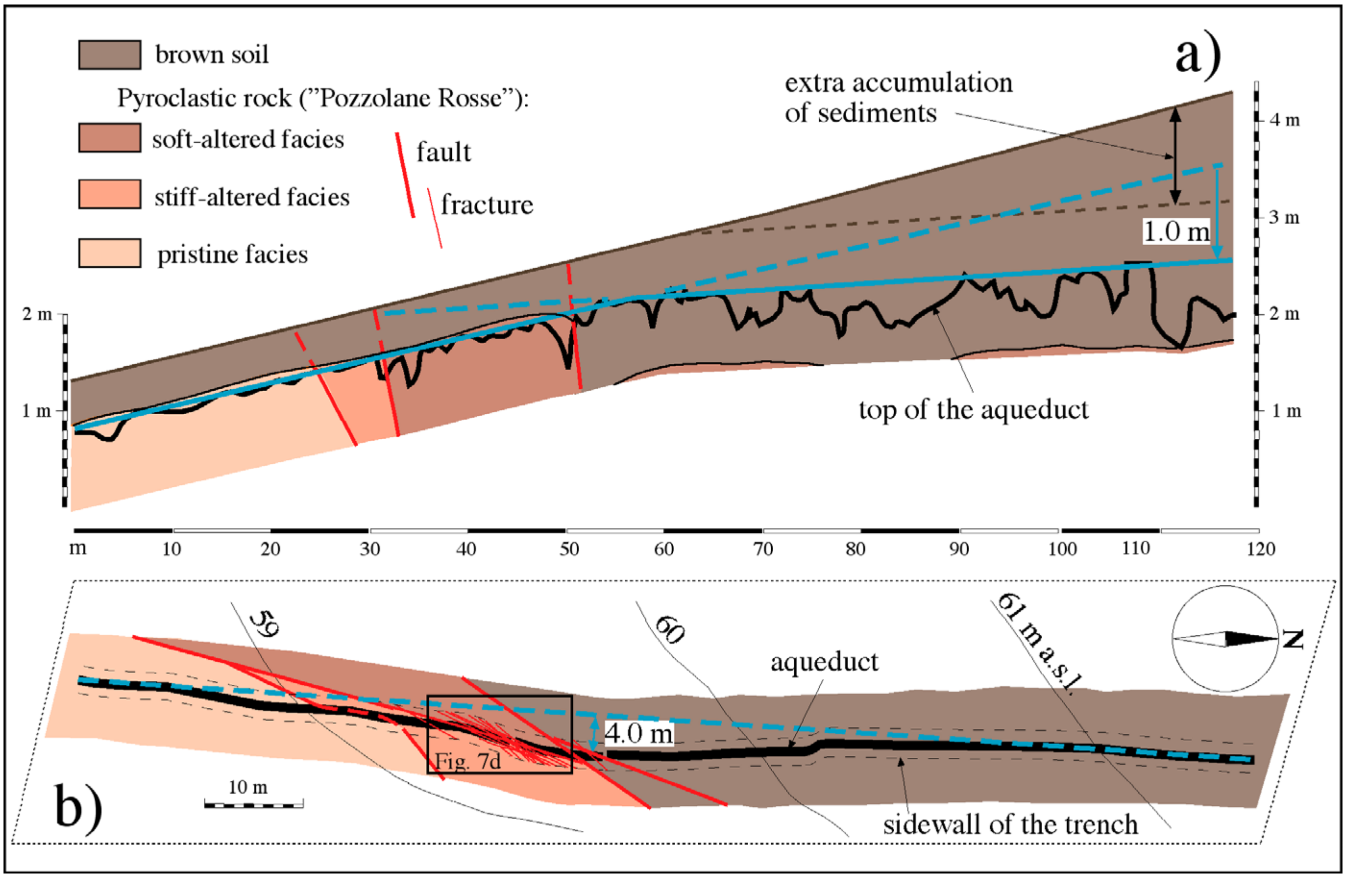

Fig. 6. Geology of the area surrounding the principal channel. (a) Longitudinal profile: elevation detected by GPS measurements. Tectonic subsidence of ~1 m with respect to a constant gradient (blue dashed line) is evident. (b) Map view of the principal channel showing geology and structural information. Horizontal displacement of ~4 m with respect to the original linear trend (blue dashed line) is evident.

further north, a N30°E oriented fault, dipping 65°NW (Fig. 7c), marks the contact between the zone of pure 'Pozzolane Rosse' pyroclastic deposits and a transitional zone of their zeolitized facies (zeolith is a phyllosilicate formed during the devitrification process of the amorphous silica that constitutes the matrix of pyroclastic rocks). This latter is semi-lithified and characterized by a greater degree of fracturing (approximately 1 fracture/0.5 m). Based on the numerous faults and fractures found at the site, the origin of this particular zeolithic facies can be attributed to an increase in circulation of hydrothermal fluids from the nearby Acque Albule basin area. A different lithological facies resulting from a stronger alteration of the pyroclastic deposits become evident approximately 10 m further north, once again at the point where a fault (approximately N15° oriented and dipping 85°W) intersects the channel. This facies introduces a lack of coherency and represents a portion of deposit that has endured a partial process of pedogenesis as well as an alteration occurring through fluid circulation similar to that of the semi-lithic zeolithic facies. Also in this case there is a high degree of fracturing that seems to end as the lithological alteration increases. In fact, this highly altered facies grades upwards into a brown soil, gradually increasing in thickness from about 0.5 m to more than 2.5 m as the channel progresses northwards, making brittle elements no longer recognizable. This later section of the channel excavation effectively reveals a change in the deformation style, with considerable evidence of ductile deformation. Tectonic elements concerning outcrops of Pozzolane Rosse, with the same orientation and characteristics as those observed along the course of the excavated channels, are also found in concentrated zones throughout the entire archaeological area. A total of 30 meso-structural tectonic elements were surveyed (Fig. 7d). The greater number of these are extensional joints with a lesser number of faults.

Whereas these faults are identifiable by the abrupt facies changes of the Pozzolane Rosse, kinematic data are less clearly recognizable. Faint horizontal striations along fault planes developed through the alloisite alteration material suggest a prevalent strike–slip motion. A stereonet projection indicates a preferential strike of N30–40°E and a dip ranging between 70 and 90° SE in most instances (Fig. 7d).

The detailed survey of the principal channel shows that its course has been segmented, with individual segments striking between N10°E and N10°W, and with one particular section oriented at N35°W (Fig. 1b). The points where the

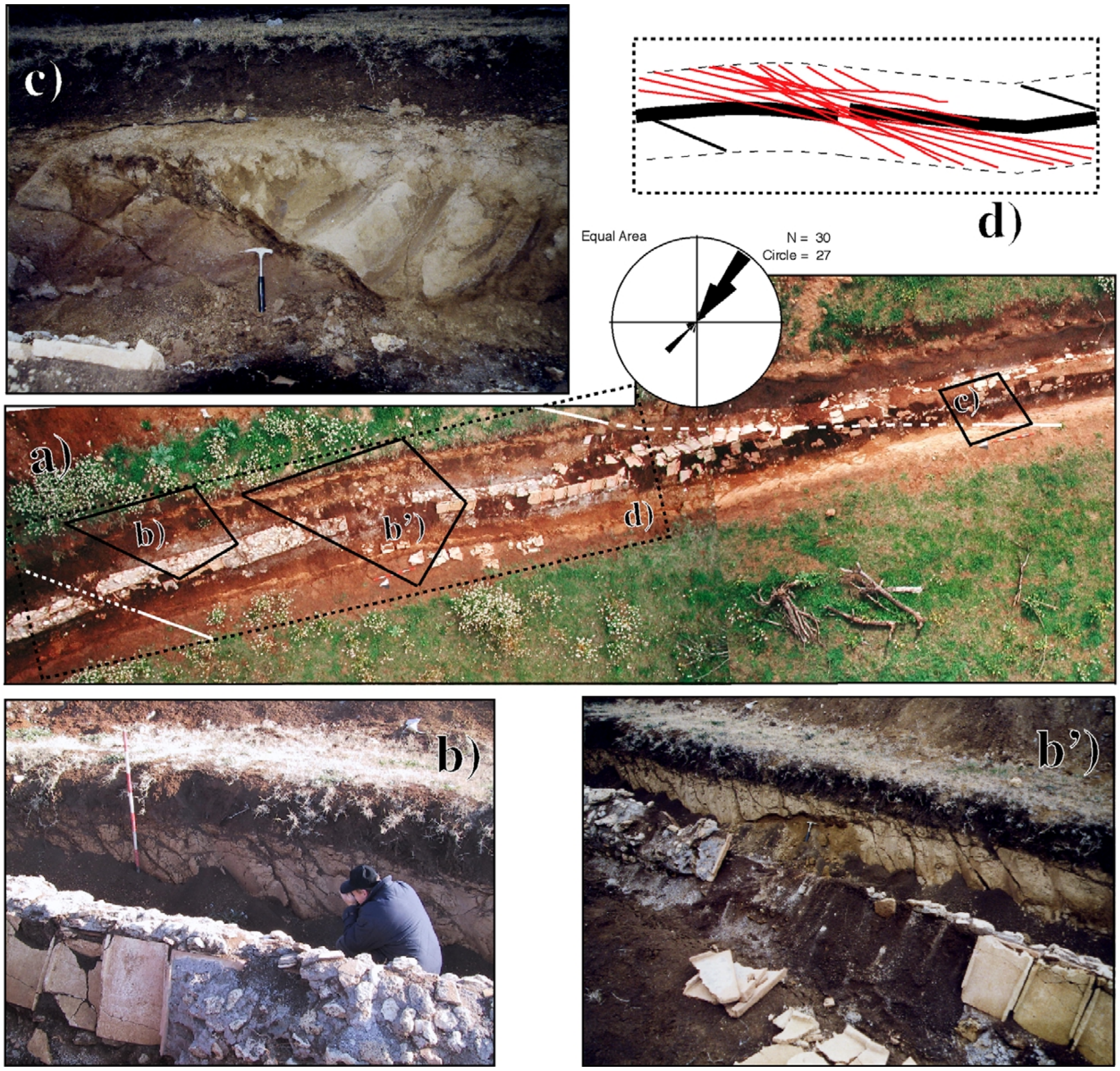

Fig. 7. Most tectonic elements affecting the rock surrounding the principal channel are concentrated in the central portion. (a) The aqueduct is seriously damaged at the location of the major structural elements. (b)–(b′) Detail of the fracture system that affects the ground along the twisted portion of the aqueduct. (c) N30°E striking, 65°NW dipping fault that marks the contact between the volcanic rock and the travertine. (d) Detail of most strongly deformed section and stereonet diagram with orientations of the surveyed joints and faults.

various segments vary direction often coincide with a break and a slight dislocation (less than 50 cm offset) in the structure (Fig. 7a). A few segments, however, appear to be deformed in a more ductile manner. For example, a section approximately 2 m in length curves N35°W (Fig. 1b), but has not undergone brittle deformation. Perhaps the cause of this more ductile behavior is that the rock surrounding the aqueduct here is very altered Pozzolane Rosse and soil. The smaller channel (Fig. 1c) situated to the southwest of the principal excavation is cut back to approximately half its depth, probably due to modification of the original topography by agricultural development. Deformation of this second channel can essentially be explained by transverse compression resulting in a restriction of the inner trough (from 45 to 15 cm) and rotation of the structure.

5. Tectonic deformation affecting the aqueducts

A necessary component of our study is to evaluate the possibility that the observed anomalies in the structure of the aqueduct are due to defective construction or to the unforeseen presence of underground obstacles, rather than to deformation of an originally straight structure.

The investigated portion of the aqueduct is only 120 m long and is excavated in a flat field, and through an extremely soft pyroclastic unit. Given this information it is highly unlikely that Roman engineers of the Middle Imperial age were unable to excavate a straight trench; the only possible obstacles could have been trees. Additionally, the aqueduct is curved both on large and small scales (Fig. 1a). If intentionally built in this manner, the aqueduct section that we have investigated would have been constructed differently than all other aqueducts that date to this time. Trees did not stop Roman engineers from the Middle Imperial age from building straight aqueducts.

Fig. 8c–c′ and d–d′ shows additional proof that the original structure of the aqueduct is strongly deformed after its initial construction. As shown in Fig. 8c and d, the aqueduct at this distorted portion has collapsed. Fig. 8a and b shows that the aqueduct was originally 85 cm wide, with an inner trough of 45 cm, but Fig. 8c and d shows that the width of the entire section of the aqueduct is reduced to ~40 cm in this twisted portion; the inner trough is completely missing here (Fig. 8g). The tiles that formed the roof of the aqueduct have buckled between the two courses of blocks that form the sidewalls of the aqueduct. This fact is evidence that the structure experienced normal compression that caused the complete sealing of the inner trough (Fig. 8g).

Other evidence of deformation is visible immediately south of the twisted portion, where a tract of the aqueduct shows an enlarged section where the roof has fallen down, forming a ~15 cm vertical step at its top (Fig. 8e). Even further to the south, the aqueduct narrows again (width ~70 cm), and the tiles are buckled upwards.

Fig. 8c–c′ and d–d′ shows that the concrete that held the travertine blocks in the twisted portion of the aqueduct has crumbled, allowing for the semi-ductile deformation observed here. In contrast, the travertine blocks have been displaced without significant fracturing, moving one to each other within the granular matrix formed by the crumbled concrete. Differently, the tiles of the roof experienced brittle deformation at this point and appear completely crumbled (Fig. 8c′ and d′). Elsewhere in the aqueduct where less deformation occurred, there is significantly less brittle deformation of the roof tiles (Fig. 8f).

Finally, the ~2 m of soil above the roof of the northern portion of the aqueduct (Fig. 6a) shows that this portion of the aqueduct experienced differential subsidence with respect to the southern end of the aqueduct, where only ~0.5 m of soil is present. As noted above, this type of aqueduct originally was excavated into the ground and the roof was placed immediately below the ground level (Fig. 8a); the inspection wells extended upward about 1 m above ground level. Today, the top of the inspection well at the northern end of the aqueduct is found below ground level (Fig. 8b). Based on all the above-mentioned considerations, we conclude that the present irregular shape of the aqueduct is the result of strong post-construction deformation.

To evaluate the possible tectonic contribution to the observed deformation, we have also investigated the morphology and the lithological characteristics of the area, in order to exclude any possible gravitational cause (i.e. by landslide). Fig. 9 shows a detailed contour map (contour interval is 1 m) based on a topographic survey performed during the archaeological survey of the aqueduct. Contour lines are superimposed on an aerial photograph (Flight 'Tivoli', 1995). Comparison with an older 1:10.000 topographic map created in 1962 allowed us to reconstruct recent modifications of the site topography. Fig. 9 shows that the aqueducts are located in an area with a ~2° slope to the southeast (from an elevation of 61–58.5 m a.s.l.) where this broad plain terminates at a NE-striking streambed. This area was originally bordered to the northwest by a N60°E striking scarp with ~4 m of vertical displacement. A large portion of this scarp has been removed or otherwise altered by anthropogenic causes (Fig. 9: the original morphology is represented with dashed contour lines). Also the course of the stream has been modified slightly in order to channel it straight across the field. The original streambed was located at a geologic boundary that separates the volcanic rocks to the NW and the recent travertine deposit to the SE. Based on the parallel strike of the scarp and the stream bed that borders the travertine plateau, we infer the presence of a ~N60°E striking fault located at the foot of the morphological step. We suggest that movement of this fault was responsible for formation of the scarp, and also for the subsidence of the southeastern end of the field and its subsequent flooding with deposition of travertine.

The gentle slope of the area where the aqueducts are located and the lithological features of the rocks that constitute the substrate allow us to rule out the possibility that a landslide may be the cause of the observed deformation. Actually, inclination of ~2° is too small to trigger a ground movement even in the most sensitive clay. It is very unlikely that rocks having an inner friction angle of 35–40° (like the volcanic rocks and the Pliocene clay bedrock that are present here) may fail under such conditions.

6. Seismicity of the area

In June–July, 2001, a low magnitude seismic sequence occurred in the northern Acque Albule basin (Fig. 10; Gasparini et al., 2002). It was characterized by several small events with a maximum Md = 2.7, whose epicenters were located in the town of Guidonia. and showed a NE–SW distribution (Fig. 10), parallel to the northwestern edge of the travertine plateau of Acque Albule. Hypocenters were very shallow (0.5–1.0 km). The small magnitudes prevented the calculation of reliable focal mechanisms. It is notable that the first M = 2.3 shock significantly reduced the flow rates of the Bagni Albule thermal spring. Regular flow rates resumed only after a second M = 2.7 shock occurred.

The June–July seismic sequence has a peculiar feature with respect to the local seismicity that has been described for the area of Rome (Molin et al., 1986; Riguzzi and Tertulliani, 1993). Historical records indicate that three moderate earthquakes (Io = VI–VII MCS) occurred in 1812, 1895 and 1909. While the epicenter of the 1812 event has been located to the NW of Rome, the more recent ones

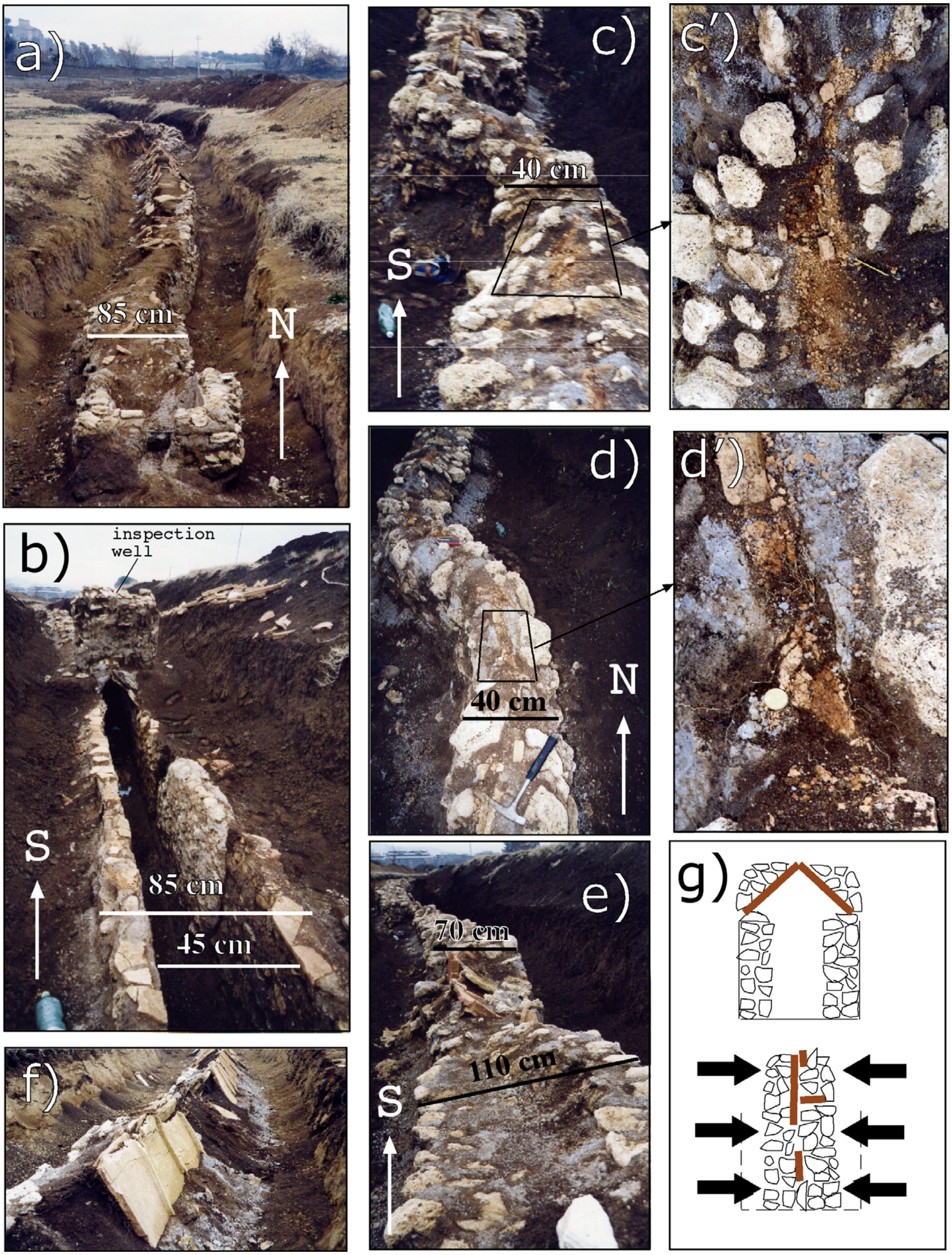

Fig. 8. Photographs showing details of the deformation that affects the principal aqueduct channel (see text for explanations).

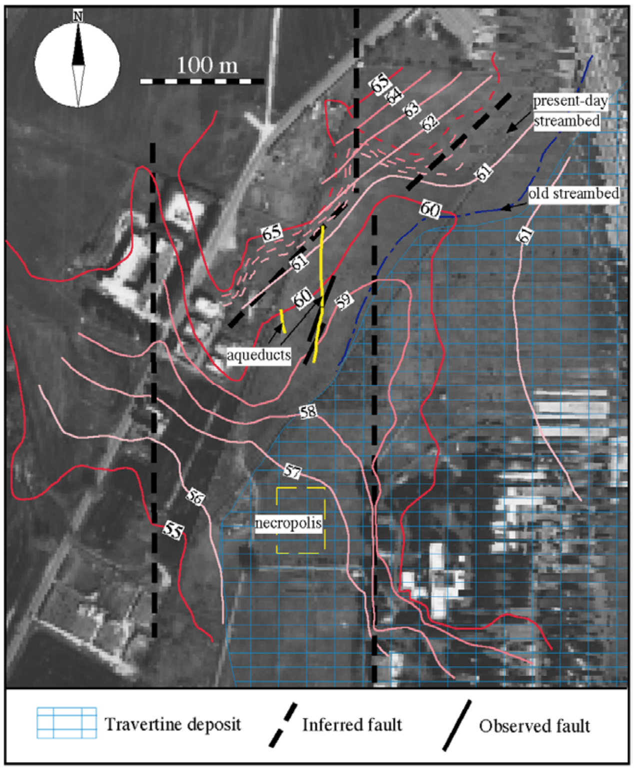

Fig. 9. Aerial photograph (Flight 'Tivoli', 1995) of the investigated area. Superimposed contour lines (interval = 1m) are obtained from a regional 1:2000 scale map plus more detailed topographic data from survey performed by archaeologists. An older 1:10,000 scale topographic map from a 1962 survey enabled us to reconstruct the original topography (dashed contour lines) prior to anthropogenic modification.

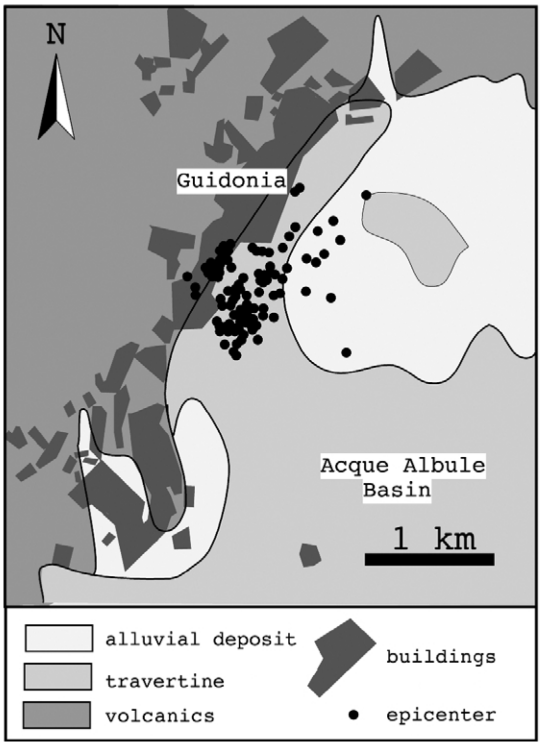

Fig. 10. Epicenter of June–July 2001 seismic sequence that occurred at the northwestern border of the Acque Albule basin (modified from Gasparini et al., 2002).

are located to the south, where another M = 3.6 earthquake recently occurred on June 16, 1995 (Basili et al., 1996). Based on a hypocentral depth of ~15 km and a focal mechanism showing a NE-oriented T-axis for this latter event, the low-magnitude seismicity of Rome has been interpreted to be linked with extensional tectonics (Marra, 1999). The different characteristics of the Bagni Albule seismic sequence may be suggestive of a different, local tectonic context.

7. Discussion and conclusion

The observations mentioned above illustrate that deformation of the aqueduct was caused by tectonic activity during the last 1500 years (assuming the site was abandoned around the 5th century A.D.). The N30–40°E orientation of the joints and faults, the presence of sections deformed in a ductile manner that are now oriented N35°W with evidence of transversal compression, the segmentation of the two channels into tracts rotated in different directions on a horizontal plane, and ultimately, the narrowing of the inner trough of the smaller channel oriented N15°W, are all elements consistent with a local stress field characterized by a tensor of maximum stress ($\sigma 1$) oriented northeast on the horizontal plane, and a tensor of minimum stress ($\sigma 3$) oriented northwest (see Fig. 11). Thus, the geometry of the deformational pattern and the brittle deformation affecting the surrounding rock are consistent with strike–slip

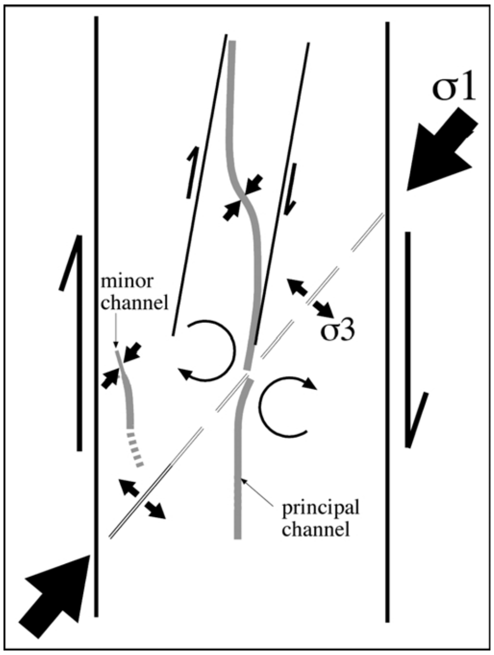

Fig. 11. Tectonic model for the Acque Albule basin: the deformation is consistent with shear tectonics confined between right-lateral N-striking faults, implying a horizontal NE–SW oriented maximum stress tensor $\sigma 1$).

tectonics creating a pull-apart basin at Acque Albule. In particular, ~N20–30°E striking oblique–slip faults and associated fractures located at the northwestern border of the travertine basin (see Fig. 3) highlight a right-step in the major N–S lineament that crosses the area. Evidence of travertine deposits flooding the archaeological site since the 3rd century AD indicates a westward growth of the sedimentary basin and suggests that strike–slip movement of the border faults and associated collapses of the basin occurred during historical times.

Based on the absence of significant local earthquakes in the historical records (Molin and Guidoboni, 1989), we believe that the described deformation should be attributed to aseismic fault creep. Our inability to resolve any kinematic indicators from the 2000–2001 seismic events of Bagni Albule prevents us from showing any direct linkage with the strike–slip tectonics responsible for the deformation of the aqueduct channels. However, the variation of the hydraulic capacity of the Bagni Albule thermal spring in coincidence with the seismic sequence suggests a possible interaction between this shallow seismicity and the tectonic structures that control the basin and that constitute preferential pathways to the circulation of thermal fluids.

Also in the absence of significant related seismicity, the observed deformation linked with the strike–slip regime is a potential factor of hazard with respect to human settlements in the area of the Acque Albule basin. With respect to a few years ago, when the Roman volcanoes were considered extinct and with no signs of tectonic activity present in the area, it seems today that the Eternal City is not still destined—geologically speaking—to eternal rest!

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