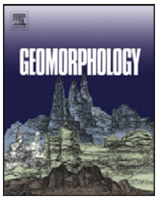
Geomorphology 195 (2013) 13–26

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



The origin and growth of a recently-active fissure ridge travertine over a seismic fault, Tivoli, Italy

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ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form 13 April 2013
Accepted 15 April 2013
Available online 23 April 2013

Keywords:
Fissure ridge
Plateau
Travertine
Earthquakes
Geothermal fluids
Faults

ABSTRACT

An enigmatic, c. 2 km-long and 15 m-high travertine ridge, the Colle Fiorito ridge, occurs in the northwestern sector of the Tivoli travertine plateau, central Italy. The main questions addressed in this paper concern the origin and mode of growth of this prominent ridge. The presence of active structures beneath the studied ridge is inferred by recent and past earthquakes located at shallow depths immediately beneath Colle Fiorito. To understand the surficial structure of the Colle Fiorito ridge and the travertine depositional environment, we constructed a 10 m-resolution DEM, analyzed recent and past aerial photographs, and conducted field surveys and meso- to micro-scale sedimentological analyses. To understand the ridge subsurface structure, we studied a set of 32 stratigraphic well logs available from previous works and from the local decorative stone industry, and realized a 2D electrical resistivity tomography (ERT) across the ridge. Results show a gentle antiformal structure affected by subvertical zones of strata discontinuity. The Colle Fiorito structure is interpreted as a previously-unknown fissure ridge travertine grown at the edge of the Tivoli travertine plateau, perhaps when the volumetric deposition rate reached its climax in the plateau for the abundance of fluid discharge and the rise of the water table. Such a fluid pressure may have activated the faults and fractures beneath Colle Fiorito, thus opening new pathways for the ascension of geothermal fluids toward the surface.

1. Introduction

Thermal (or thermogene sensu Pentecost, 1995) travertines are chemical deposits of $CaCO_3$ precipitated in geothermally-active areas usually around or along geothermal springs and open fissures (Bargar, 1978; Crossey et al., 2006), forming deposit morphologies as different as cascades, apron and channel travertines, fissure ridges, plateaus, and towers (e.g., Scholl and Taft, 1964; Buccino et al., 1978; Chafetz and Folk, 1984; Goff and Shevenell, 1987; Altunel and Hancock, 1993a, b; Benson, 1994; Pentecost, 1995, 2005; Traganos et al., 1995; Ford and Pedley, 1996; Buchardt et al., 1997; Guo and Riding, 1998, 1999; Atabey, 2002; Chafetz and Guidry, 2003; Crossey et al., 2006; Faccenna et al., 2008; Zentmyer et al., 2008; Pedley, 2009; Pedley and Rogerson, 2010; Fouke, 2011). Thermal travertine deposits are known worldwide and have been studied for their numerous insights into paleoenvironment, paleoclimate, neotectonics, geothermics, and several other scientific disciplines and industrial applications such as the industry of decorative stones (e.g., Rihs et al., 2000; Brogi and Capezzuoli, 2009; Brogi et al., 2010; Capezzuoli et al., 2010; Crossey and Karlstrom, 2012; De Filippis et al., 2012; Gratier et al., 2012; Van Noten et al., 2013). The formation of thermogene travertines is connected with the existence of a geothermal circuit of aggressive fluids, which, after interacting with carbonate rocks in the substratum, ascend toward the surface where they release most of their calcium bicarbonate content in the form of travertine deposit. The conduits that allow the calcium bicarbonate-rich fluids to ascend toward the surface are one of the main scientific targets for geologists working on travertines and, in general, on geofluids. The fluids that are at the origin of travertine deposits are, in fact, highly-mineralizing (calcium bicarbonate-rich) and should therefore rapidly obstruct at least the shallowest part of the conduit, thus theoretically hindering the formation of large and long-lived travertine deposits. Contrary to this concept, the longevity of several travertine deposits is known to be on the order of 10^4 years and their volume may be up to 1 km^3 (Uysal et al., 2007; Faccenna et al., 2008; De Filippis et al., 2012; Kampman et al., 2012). It follows that dilational mechanisms connected with tectonics, fluid pressure (usually modulated by the fluid supply and paleoclimate oscillations), or other factors must be invoked to keep the feeding conduits pervious to highly-mineralizing fluids for tens of thousands of years (Hancock et al., 1999; Rihs et al., 2000;

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http://dx.doi.org/10.1016/j.geomorph.2013.04.019

Anderson and Fairley, 2008; Faccenna et al., 2008; Brogi and Capezzuoli, 2009; Uysal et al., 2009; Zampieri et al., 2009, 2010; Brogi et al., 2012; De Filippis and Billi, 2012). Knowing and studying the conduits through which geothermal travertines have been fed may therefore provide insights into the geothermal circulation and into the mechanisms that make this circulation efficient.

One interesting case of long-lived thermogene travertine is the middle to late Pleistocene deposit filling the Acque Albule basin (Tivoli; Fig. 1) close to Rome, central Italy (Maxia, 1950b; Chafetz and Folk, 1984; Pentecost and Tortora, 1989; Pentecost, 1995; Faccenna et al., 2008, 2010; De Filippis et al., in press). This travertine constitutes one of the largest known travertine deposits (plateau) of Quaternary age in the world. Whereas in several other travertine deposits, the shallowest part of the feeding conduit is known from the occurrence, for instance, of subvertical open fissures partly mineralized by subvertical bands of sparry travertine (banded travertine; Bargar, 1978; Uysal et al., 2007; De Filippis et al., 2012), in the case of the Tivoli travertine plateau such evidence is probably buried beneath the travertine itself. Moreover, in several other travertine deposits, the surface expression of the feeding conduits is marked by a prominent vertical growth of the deposits (see for instance the fissure ridge travertines and the travertine towers; Bargar, 1978; Buchardt et al., 2001; Ludwig et al., 2006; De Filippis and Billi, 2012), whereas the Tivoli travertine is characterized by a substantially flat upper surface (Fig. 1). One viable hypothesis for the feeding conduit of the Tivoli travertine is that the geothermal fluids ascended along a central conduit controlled by an active strike–slip to transtensional fault system (Fig. 1). Along this fault system, in fact, the thickness of the travertine deposit is considerably larger (at depth) than that aside from the fault system (see cross-sections in Fig. 1) and a series of fossil and active geothermal springs and vents align on top of the fault system (Faccenna et al., 2008, 2010). Nevertheless, to the northwest of the Tivoli flat travertine plateau, a ridge of bedded travertine occurs in the Colle Fiorito area (Fig. 1). The Colle Fiorito ridge, which is the unique prominent structure over the flat travertine plateau, is an elongated and curved travertine mound about 15 m high, 2000 m long (i.e., the long axis in map view), and 400–500 m wide (i.e., the short axis). The ridge is intriguing because recent earthquakes occurred right below the ridge (Gasparini et al., 2002) and, on its top, evidence of recently-active degassing structures such as small vents was signaled already several years ago (Maxia, 1950b).

In this paper, we study the Colle Fiorito ridge in the Acque Albule basin (Fig. 1) with a multidisciplinary (geomorphological, geological–sedimentological, and geophysical) approach to understand its prominent morphology over the flat Tivoli plateau and to contribute to the comprehension of whether this prominent structure is the surface expression of a travertine-feeding conduit (similar to fissure ridges; e.g., Brogi and Capezzuoli, 2009; De Filippis et al., 2012) or whether it is the result of a different mechanism. The occurrence of recent earthquakes below this structure and gas vents on its summit make the Colle Fiorito ridge an interesting structure to understand the relationships between travertine ridge growth, geothermal outflow, and faulting, which have been and are being studied also elsewhere (e.g., Uysal et al., 2007, 2009; Zentmyer et al., 2008; Zampieri et al., 2010; Brogi et al., 2012).

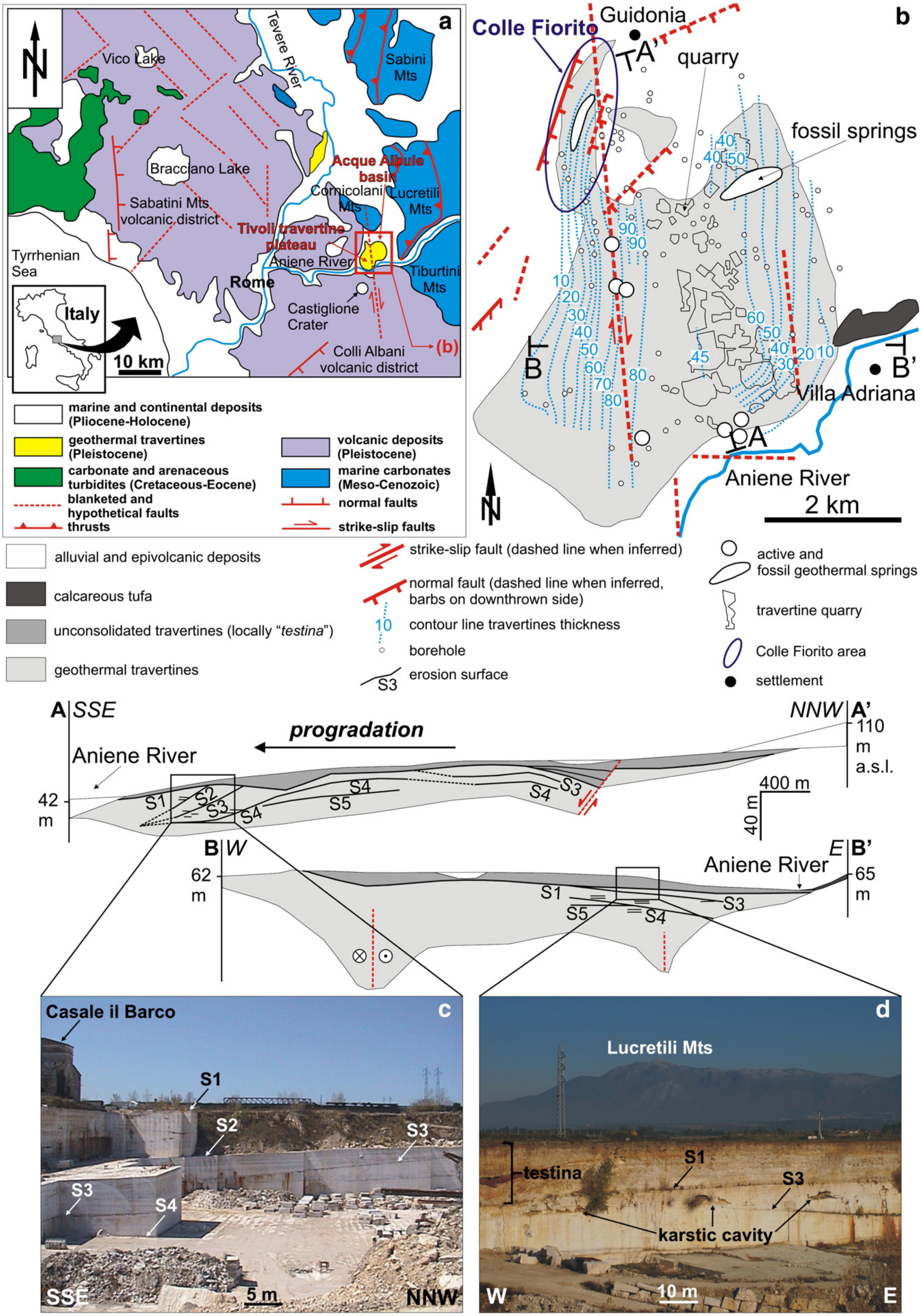
2. Geological setting

The Pleistocene Acque Albule basin is located in central Italy, 30 km to the east of Rome (Fig. 1). The basin is bounded by the Neogene Apennines fold-thrust belt to the north and east (i.e., the Cornicolani and Lucretili Mountains), by the Pleistocene Colli Albani quiescent volcano to the south, and by the present Tiber valley and the post-orogenic (Pliocene–Quaternary) Tyrrhenian extensional domain to the west. The Acque Albule basin pertains to this latter extensional domain. The Aniene River, which is a tributary of the Tiber River, flows across the southern portion of the Acque Albule basin toward the southwest. The central Apennines fold-thrust belt, which developed with an eastward piggy-back sequence of thrust sheets during late Miocene–Pliocene time, underwent a post-orogenic extension since about Messinian–Pliocene times connected with the opening, toward the west, of the Tyrrhenian back-arc basin (Cosentino and Parotto, 1986; Patacca et al., 1992; Cavinato and DeCelles, 1999; Billi and Tiberti, 2009). In the Tuscan, Latium and Campanian margins of the Tyrrhenian basin, reduced thickness of the lithosphere, active or recently-active volcanoes and extensional basins, and a high heat flow (average values between 100 and 200 mW/m^2; Mongelli and Zito, 1994) are the results of the Neogene–Quaternary back-arc and post-orogenic extensional processes (Locardi et al., 1977; Barchi et al., 1998; Jolivet et al., 1998; Chiodini et al., 2004; Acocella and Funiciello, 2006).

The Acque Albule basin has developed during Pleistocene times within this post-orogenic framework. The activity of the extensional faults (mostly NW-striking) along the Tyrrhenian margin of central Italy was accompanied by the activity of transverse (NE-striking) or oblique (N-striking) strike–slip faults usually acting as accommodation structures between adjacent extensional compartments undergoing differential kinematics (e.g., Faccenna et al., 1994a; Acocella and Funiciello, 2006). One of these strike–slip faults has been active through the study area with a right-lateral kinematics along a N–S direction since at least the late Pleistocene (Faccenna et al., 1994b) and it is still seismically active (Gasparini et al., 2002; Frepoli et al., 2010). The activity of this fault has been accompanied by the activity of NE-striking normal and transtensional faults, which have caused at least part of the subsidence of the Acque Albule basin through a pull-apart mechanism (Faccenna et al., 1994b). The bottom of the pull-apart basin is constituted by Mesozoic–Cenozoic subsided marine carbonate bedrock, which outcrops in the adjacent Cornicolani and Lucretili Mountains. The carbonate bedrock is covered by marine Pliocene–Pleistocene blue-gray clays and clayey sandstones, which are exposed on the hills located to the north and northeast of the Acque Albule basin, and by volcanic products coming from the adjacent volcanic districts of Colli Albani and Monti Sabatini. The infilling deposits of the basin are then mainly composed of late Pleistocene thermogene travertine, whose average thickness is c. 40-50 m, but may reach even 85–90 m (Maxia, 1950a; Faccenna et al., 2008; Fig. 1). The deposition of this thermogene travertine has been contemporaneous with the final activity of the adjacent Colli Albani Volcano, which is still classified as quiescent for the emplacement of degassing-driven maar deposits during Holocene and historical times (Funiciello et al., 2003; De Benedetti et al., 2008).

In the Acque Albule basin, the Regina and Colonnelle hydrothermal springs (c. 2000 l/s; Capelli et al., 1987; Fig. 1) and several minor hydrothermal sources (c. 300 l/s; La Vigna et al., 2012, 2013) distributed over the basin provide evidence for the ongoing hydrothermal activity (Petitta et al., 2011; Carucci et al., 2012). The fluid discharge in the Acque Albule basin is, at present, particularly abundant, namely around 2000–3000 l/s. The source of the $CaCO_3$ (and CO_2) forming the travertine deposit is principally the subsurface Meso-Cenozoic carbonate succession (Manfra et al., 1976; Maiorani et al., 1992; Minissale et al., 2002; Billi et al., 2007). The presence of these carbonate rocks below the

Fig. 1. (a) Geological map of the Roman area, central Italy, including the Acque Albule basin, where the Tivoli travertine plateau grew during late Pleistocene time. (b) Geological map of the Tivoli travertine plateau and related cross-sections (modified from Faccenna et al., 2008). Note the location of the Colle Fiorito ridge to the northwest of the Tivoli travertine plateau. In the A-A′ cross-section, note the southward progradational pattern of the travertine strata. (c) Panoramic photograph from the southern portion of the Tivoli travertine plateau. Note the presence of horizontal to shallow erosional surfaces (S1, S2, S3, and S4) across the travertine benches. (d) Panoramic photograph from the central portion of the Tivoli travertine plateau. Note, in the travertine benches, the karstic cavities that are usually associated to the erosional surfaces. These cavities normally occur below the erosional surfaces.


a
Vico Lake
Tevere River
Sabini Mts
Bracciano Lake
Sabatini Mts volcanic district
Acque Albule basin
Cornicolani Mts
Lucretili Mts
Tivoli travertine plateau
Aniene River
Tyrrhenian Sea
Rome
Tiburtini Mts
Castiglione Crater
Italy
10 km
Colli Albani volcanic district
(b)
marine and continental deposits (Pliocene-Holocene)
geothermal travertines (Pleistocene)
carbonate and arenaceous turbidites (Cretaceous-Eocene)
blanketed and hypothetical faults
thrusts
volcanic deposits (Pleistocene)
marine carbonates (Meso-Cenozoic)
normal faults
strike-slip faults
b
Colle Fiorito
Guidonia
A'
quarry
fossil springs
B
B'
Villa Adriana
A
Aniene River
2 km
10 20 30 40 45 50 60 70 80 90
alluvial and epivolcanic deposits
calcareous tufa
unconsolidated travertines (locally "testina")
geothermal travertines
strike-slip fault (dashed line when inferred)
normal fault (dashed line when inferred, barbs on downthrown side)
contour line travertines thickness
borehole
erosion surface
S3
active and fossil geothermal springs
travertine quarry
Colle Fiorito area
settlement
A SSE
NNW A'
progradation
Aniene River
110 m a.s.l.
42 m
S1 S2 S3 S4 S5
400 m
40 m
B W
E B'
62 m
65 m
Aniene River
S1 S3 S4 S5
c
Casale il Barco
S1
S2
S3
S3
S4
SSE
5 m
NNW
d
Lucretili Mts
testina
S1
S3
karstic cavity
W
10 m
E

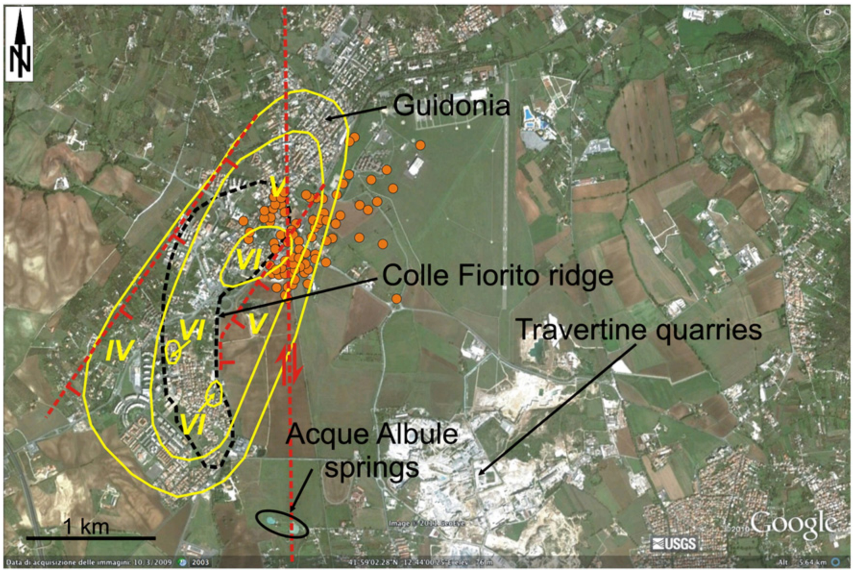


Fig. 2. Aerial photograph of the Tivoli and Colle Fiorito area (after Google Earth) with isoseismal curves (curves of equal damage or felt seismic intensity) drawn by Gasparini et al. (2002) for the 7th November 2001 earthquake occurred right beneath the Colle Fiorito ridge. Orange dots are earthquake epicenters for the 2001 seismic sequence from Gasparini et al. (2002).

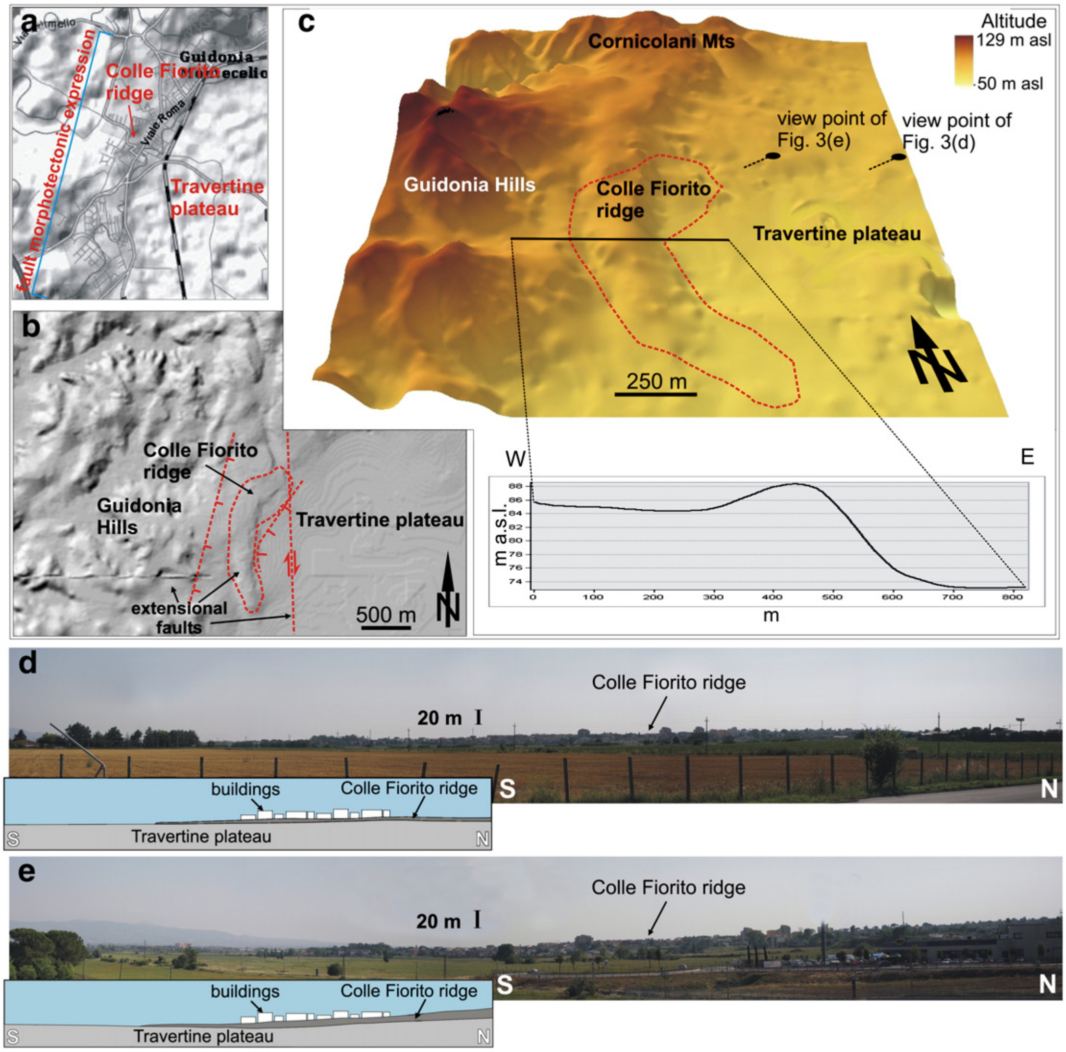


Fig. 3. (a) Digital elevation model (DEM, 20 m resolution; after IGMI). Note the morphological contrast between the Tivoli plateau (Acque Albule basin) and the adjacent slightly-prominent Colle Fiorito ridge. (b) DEM (20 m resolution, after ESRI) showing a NNE-trending lineation to the west of the Colle Fiorito ridge coinciding with an active fault documented also in Faccenna et al. (1994b) and Gasparini et al (2002). (c) Perspective view of a DEM (10 m resolution, 10× vertical magnification) showing the Colle Fiorito ridge. The topographic cross-section is through the middle portion of the Colle Fiorito ridge and was obtained from the DEM. (d) and (e) Lateral panoramic photographic views (from east toward west) of the Tivoli travertine plateau and Colle Fiorito ridge. See the view points in Fig. 3(c).

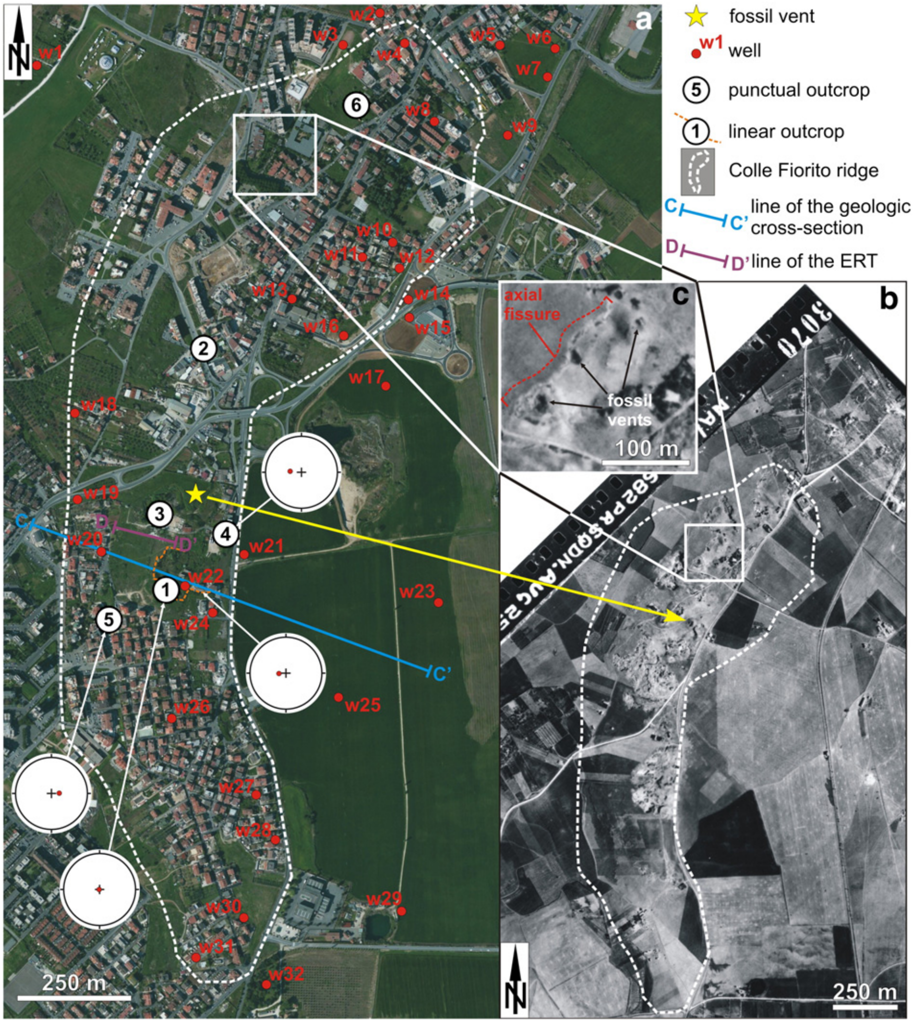


Fig. 4. (a) Aerial photograph (from Bing Maps) of the Colle Fiorito ridge with location of several geological features used in this work (see Supplementary Material 1). Polar diagrams (obtained using the Daisy software, Salvini et al., 1999) are Schmidt nets (lower hemisphere) showing poles to bedding (red dots). (b) Aerial photograph of the Colle Fiorito ridge taken by the Royal Air Force (RAF) in 1943 before the massive development of buildings in the area (compare Fig. 4a and b). Note the presence of presumably-recent cones and small vents on top of the Colle Fiorito ridge. (c) Detail from (b) showing a crestal fissure along the axial region of the Colle Fiorito ridge.

nearby Colli Albani volcano is known from geophysical and volcanic evidence (e.g., Funiciello and Parotto, 1978). C- and O-isotope data from the Tivoli travertine and other calcite deposits in the area show that the origin of these deposits is through spring waters heated during transit in a high heat-flow area and enriched by a large quantity of CO_2 derived mainly from decarbonation of limestones in the substratum, and also from a deeper source (Chiodini et al., 2012). In this circuit, while a temperature increase must have reduced the solubility of carbonates (depending on the temperature), this same solubility must have been strongly increased by the CO_2 enrichment. During their upward rise, the warm CO_2-rich waters must have intercepted the colder shallow aquifer mainly recharged by meteoric precipitation. The meteoric cold waters lowered the temperature of the rising deep waters and reset the oxygen isotopes of the travertine during diagenetic processes (Manfra et al., 1976; Minissale et al., 2002).

The Tivoli travertine plateau consists of well-organized benches of diagenetically altered, very compact travertine strata with a sub-horizontal to gently southward dipping attitude. In particular, the travertine strata are characterized by an obvious (at the hectometric-to-kilometric scale) progradation pattern (Faccenna et al., 2008; Fig. 1), with strata progressively steeper and also slightly thicker toward the south (i.e., progradation direction). The travertine benches are cut and bounded by evident erosional surfaces (Fig. 1), which are usually accompanied by brownish clayey paleosols and karstic features (Faccenna et al., 2008, 2010). This evidence is symptomatic of episodic lowering of the water table in the Acque Albule basin during the travertine growth.

The Tivoli travertine plateau has been partly dated through U-series methods. The oldest age so far known for this travertine deposit is about 116 ka, whereas the youngest one is circa 29 ka (Faccenna et al., 2008). Also the travertine exposed at the summit of the Colle Fiorito ridge has been dated; the resulting age (28 + 16 / −15 ka), however, is affected by a large error due to the detrital Th fraction in the sample (Faccenna et al., 1994b).

3. Recent seismicity

The Acque Albule basin is characterized by a low seismicity (Frepoli et al., 2010) although stronger earthquakes from the adjacent seismically-active domains of the central Apennines and Colli Albani volcano are usually clearly felt in the basin (e.g., La Vigna et al., 2012, 2013). In the Acque Albule basin, localized or areal subsidence processes are also active, possibly in connection with geothermal fluid circulation and sinkhole development (Billi et al., 2007). Gasparini et al. (2002) studied the recent local seismicity of the Acque Albule basin. In

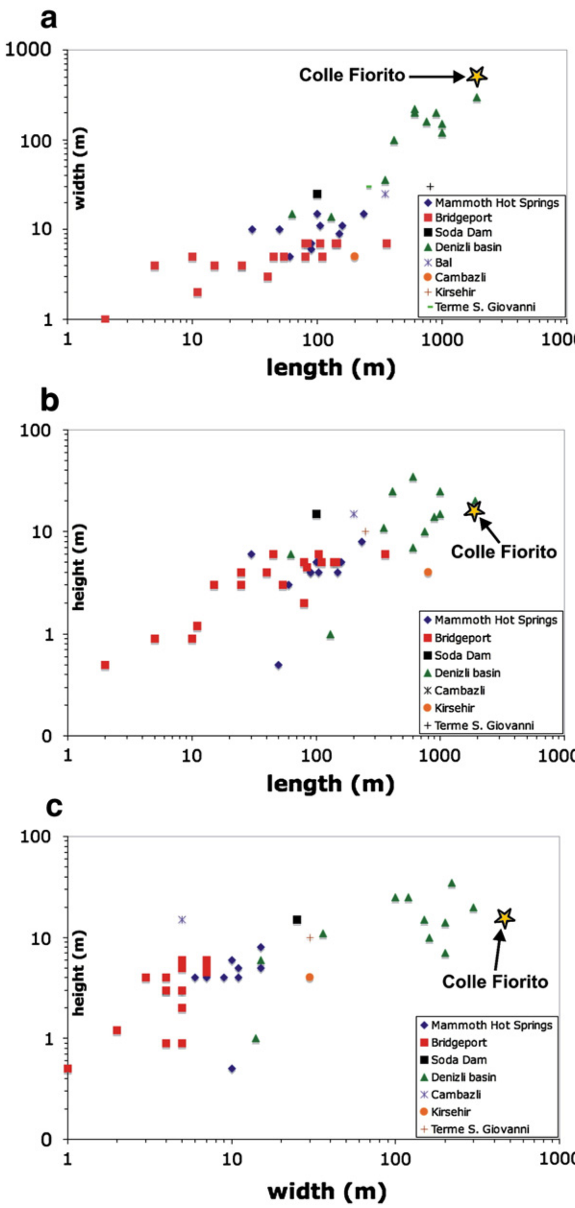


Fig. 5. Aspect ratio (length vs. width vs. height) diagrams for most known fissure ridge travertines in the world (after De Filippis and Billi, 2012). Yellow stars indicate aspect ratios of the Colle Fiorito ridge.

particular, they studied the seismicity beneath the Colle Fiorito ridge, providing the following information.

17th century: The oldest information concerning the seismicity (and similar or possibly related phenomena) of the Acque Albule basin dates back to the second part of the 17th century about a certain area of Colle Fiorito, which, at that time, was named Valle Stregata (Enchanted Valley) due to the fact that the inhabitants used to perceive loud noises from the subsurface.

1972: On the 22nd of May, 1972, at 1:15 a.m. (GMT), a seismic event was felt by the population of the Acque Albule basin. Some municipal officers reported that the event was felt by everybody including those sleeping at that time of the night. The event caused cracks and mild damage to some buildings and no victims or injured people (MCS maximum intensity = VI in Guidonia located 1 km to the northeast of Colle Fiorito). A loud underground noise was heard by several inhabitants.

1989: A seismic sequence particularly felt in the Colle Fiorito area occurred in January 1989 with four main events between the 11th and 14th. The affected area was small and narrow with a MCS maximum intensity = V in the Colle Fiorito area.

1999: On the 27th of June, 1999, at 5:12 a.m. (GMT), an earthquake was felt in the eastern sector of Montecelio (located 2 km to the northeast of Colle Fiorito) with a MCS maximum intensity = IV–V. The event was not recorded by the national seismic network probably because it was too shallow and mild.

2001–2002: A seismic sequence occurred in the Acque Albule basin during 2001–2002. Gasparini et al. (2002) installed a local seismic network during this sequence and studied in detail both the sequence and some main events pertaining to this sequence (Fig. 2). The sequence included shallow (less than 1.5 km deep), low magnitude (less than Ml 3.0) earthquakes accompanied by rumbles and, in places, strong vibrations of the ground. In particular, the national seismic network recorded seven main events with Ml between 2.1 and 2.7 between June 2001 and January 2002. After processing the data from the local network and constructing maps with isoseismal curves (Fig. 2), Gasparini et al. (2002) concluded that the seismic sequence was characterized by very shallow hypocenters sourced by two main steep causative faults: a N-striking fault running across the middle portion of the Acque Albule basin (i.e., below the main travertine deposit) and a NE-striking fault located right beneath the Colle Fiorito area. In particular, results from the macroseismic investigation (i.e., for the seismic event occurred on 7th November 2001) show a good correspondence between the isoseismal lines and the Colle Fiorito ridge (Fig. 2); this result is, however, at least partially influenced by the presence of several residencies right on top of the Colle Fiorito ridge (Fig. 2), whereas buildings are substantially absent over large part of the Tivoli travertine plateau, where several travertine quarries are active.

2009: It is finally interesting to report that the waves radiated by the 2009 L'Aquila earthquake (Mw 6.3; Chiarabba et al., 2009) provoked piezometric variations in the Acque Albule basin probably connected with transient changes of permeability (La Vigna et al., 2012, 2013). Moreover, in the same occasion, a remarkable transient increase of degassing from the Acque Albule geothermal springs (in particular, from the Colonnelle and Regina lakes) was observed. Due to the gas hazard, in fact, the area of the geothermal springs was strictly forbidden to people for a period of a few days after the 2009 L'Aquila earthquake, whose epicentral area is located c. 70 km to the northeast of the Acque Albule basin.

4. Methods and results

4.1. Geomorphology

To constrain the main geomorphological features of the Colle Fiorito ridge, we used three digital elevation models (DEMs): two models at a resolution of 20 m provided by ESRI (Environmental Systems Research Institute; Fig. 3a) and by IGMI (Istituto Geografico Militare Italiano; Fig. 3b), and a third one at a resolution of 10 m (Fig. 3c). This latter DEM, in particular, was created by digitizing elevation data from the topographic maps "Carta Tecnica Regionale" at 1:5.000 scale, produced by Regione Lazio after aero-photogrammetric surveys carried out in 2002 (Procaccini et al., 2008). Elevation contours, elevation spots, and the hydrographic network were collected in a geographic database. All these data were used as input in the interpolation process to calculate the resulting DEM. The applied interpolation method is based on the ANUDEM algorithm (Hutchinson, 1989; Hutchinson and Dowling, 1991), specifically designed to produce hydrologically correct DEM from cartographic data. This algorithm consists of a discretized thin plate spline technique (Wahba, 1990) modified to allow the DEM to follow abrupt changes in terrain, such as streams and ridges, by using hydrographic data.

We then used four sets of aerial photographs and images (Figs. 2 and 4): one set from the 1943 RAF (Royal Air Force survey, July–November 1943; Fig. 4b), one set from the IGMI (1984–1985), and the two most

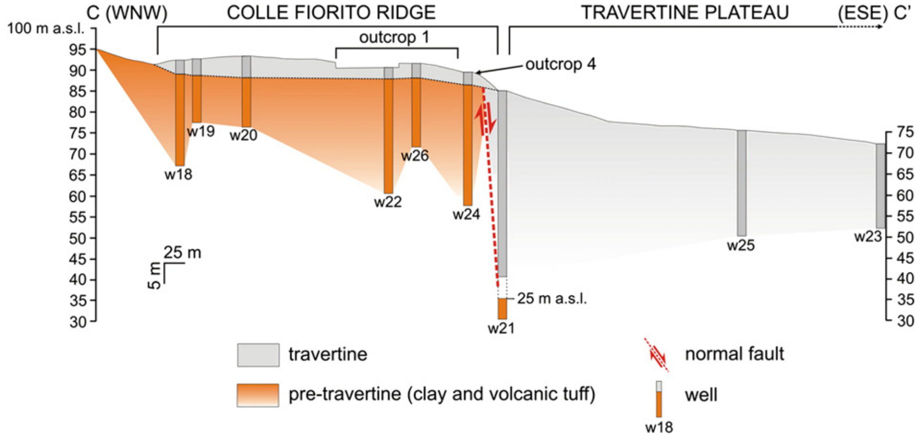


Fig. 6. Geological cross-section through the Colle Fiorito ridge (see the C-C′ track in Fig. 4a). The cross-section is based on stratigraphic well logs available from previous works (Ventriglia, 1990) and from the local industry of decorative and constructive stones (Supplemental Material 1). Note the difference between the deeply-radicated travertine plateau, to the east, and the shallow shield-like travertine structure of the Colle Fiorito ridge, to the west.

recent sets derived from satellite imagery of Google Maps and Bing Maps (Figs. 2 and 4a, respectively). The set from IGMI was, in particular, analyzed under stereoscopic view.

In the northwestern side of the Tivoli plateau, southwest of the Guidonia village, the Colle Fiorito elongate travertine ridge trending from N–S (southward) to NNE–SSW (northward) emerges from the adjacent plain of the Acque Albule basin (Fig. 3a). The ridge is characterized by a crestal flat area and by asymmetrical lateral flanks averagely striking N–S and dipping eastward and westward between 8 and 25° (Figs. 3c and 4a). At present, this prominent travertine structure is mostly covered by residencies of the Colle Fiorito village built during the 1970s–1980s years (Fig. 4a). Fig. 3(a) and (b) shows the topographic (elevation) contrast between the flat travertine plateau area (Acque Albule basin) and the prominent Colle Fiorito ridge, which is bounded by hill reliefs to the west, and by the mountain reliefs of the Apennines fold-and-thrust belt to the north. Moreover, Fig. 3(b) shows the linear topographic expression of the NNE-striking, ESE-dipping transtensional fault, which bounds the Colle Fiorito ridge toward the west. The morphological contrast between the Colle Fiorito ridge and the adjacent flat travertine plateau area is particularly evident in the perspective view of Fig. 3(c), which is characterized by a 10× vertical exaggeration.

The aerial photographs (Fig. 4b, c) taken by the RAF in 1943, when the ridge was totally uncovered by buildings and residencies, show fossil, probably-recent thermal springs, gas vents, and small cones

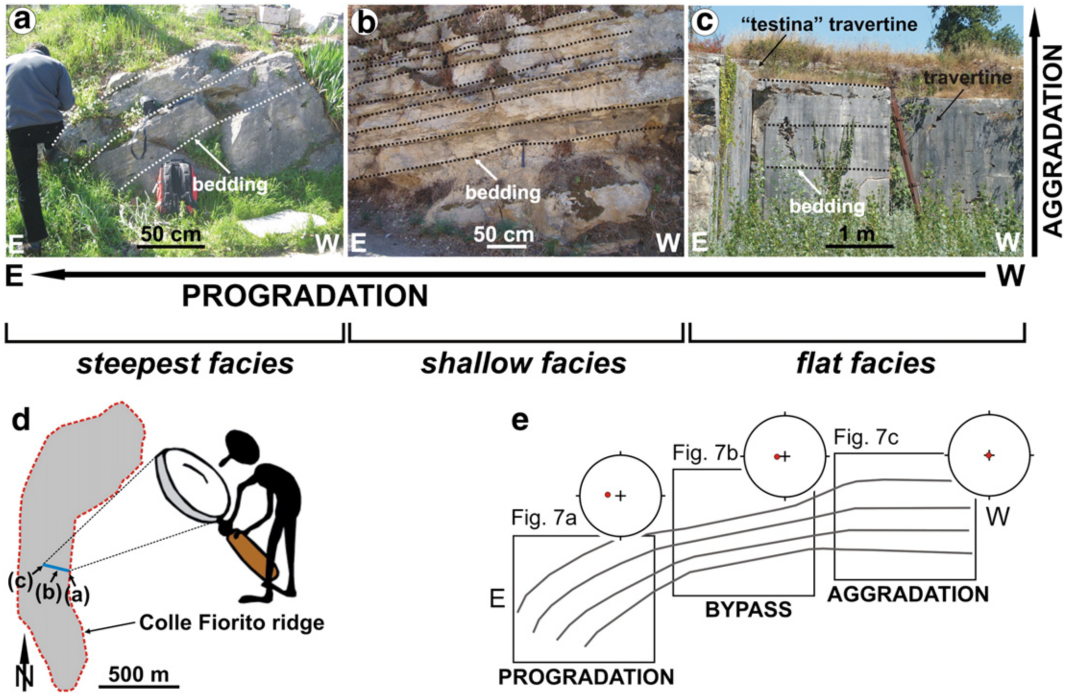


Fig. 7. (a) Photograph of inclined prograding travertine beds from Outcrop 4 (see location in Fig. 4a) along the eastern side of the Colle Fiorito ridge. (b) Photograph of gently-inclined thin travertine beds from Outcrop 1 (Fig. 4a) along the eastern side of the Colle Fiorito ridge. (c) Photograph of thick horizontal aggrading travertine beds from Outcrop 1 (Fig. 4a) along the crestal area of the Colle Fiorito ridge. (d) Point of view in the Colle Fiorito ridge for the three photographs shown in the preceding figures. (e) The three photographs shown in (a), (b), and (c) represent an ideal E–W cross-section through the central-eastern margin of the Colle Fiorito ridge, with horizontal and aggrading travertine beds in the central area, and inclined progressively-prograding travertine beds toward the eastern margin. Polar diagrams (obtained using the Daisy software, Salvini et al., 1999) are Schmidt nets (lower hemisphere) showing poles to bedding (red dots).

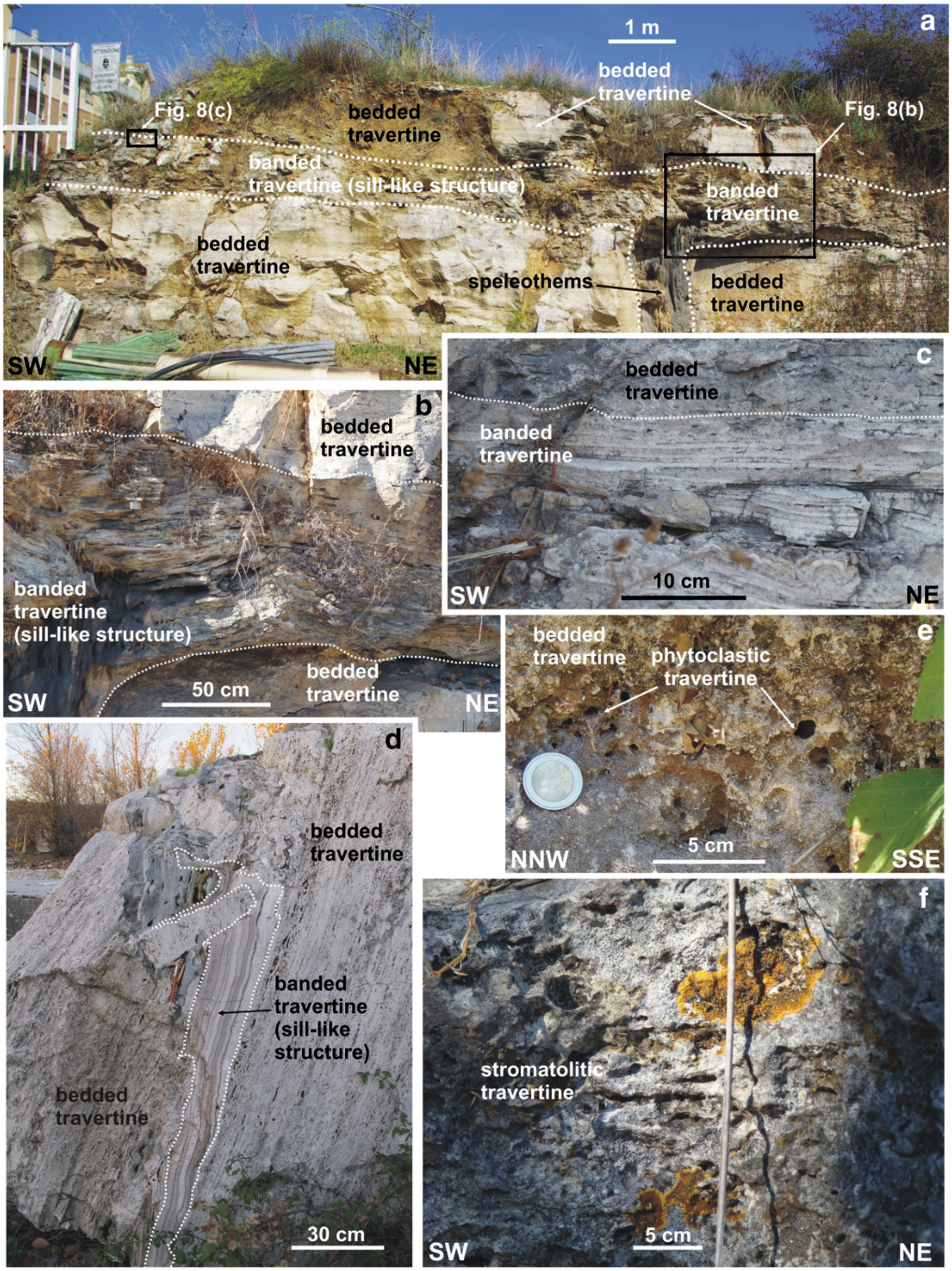


Fig. 8. (a) Exposed bedded and banded travertines in Outcrop 2. Note the T-like pattern of the banded travertine injected across (vertically) and along (horizontally, forming a sill-like structure) the strata of the bedded travertine. (b) and (c) Details from (a) of the banded travertine injected into the bedded one in Outcrop 2. (d) Banded travertine forming a sill-like travertine along strata of bedded travertine in Outcrop 3. (e) Exposed bedded travertine in Outcrop 5 with inclined phytoclastic deposits, which are characteristic of high-energy slope environments. (f) Exposed horizontal bedded travertine with stromatolitic facies (typical of horizontal low-energy environments) in Outcrop 6.

mainly distributed along the ridge crestal area. The presence of these geothermal structures was also confirmed by oral accounts provided by the eldest residents in the area, who were interviewed by us on this subject. Fig. 4(c), in particular, shows a sinuous crestal fissure along the central portion of the Colle Fiorito ridge. These crestal fissures are typical of all fissure ridge travertines and represent the surficial expression of the travertine-feeding conduits (e.g., Altunel and Hancock, 1996; Uysal et al., 2009; De Filippis and Billi, 2012; De Filippis et al., 2012). The external perimeter of the Colle Fiorito ridge has been identified using a stereographic analysis of the study area on aerial photographs from IGMI and then confirmed by field surveys and well logs (see Section 4.2 and Supplemental Material 1). On the modern photographs, the area of Colle Fiorito appears as extensively covered by modern residencies (Figs. 2 and 4a). Both vents and the axial fissure present in the 1943 RAF photographs are not visible in the modern sets of photographs. Only one vent is still slightly visible in Fig. 4(a). In the field, this latter vent appears as a small hill (3–4 m high) entirely covered by vegetation.

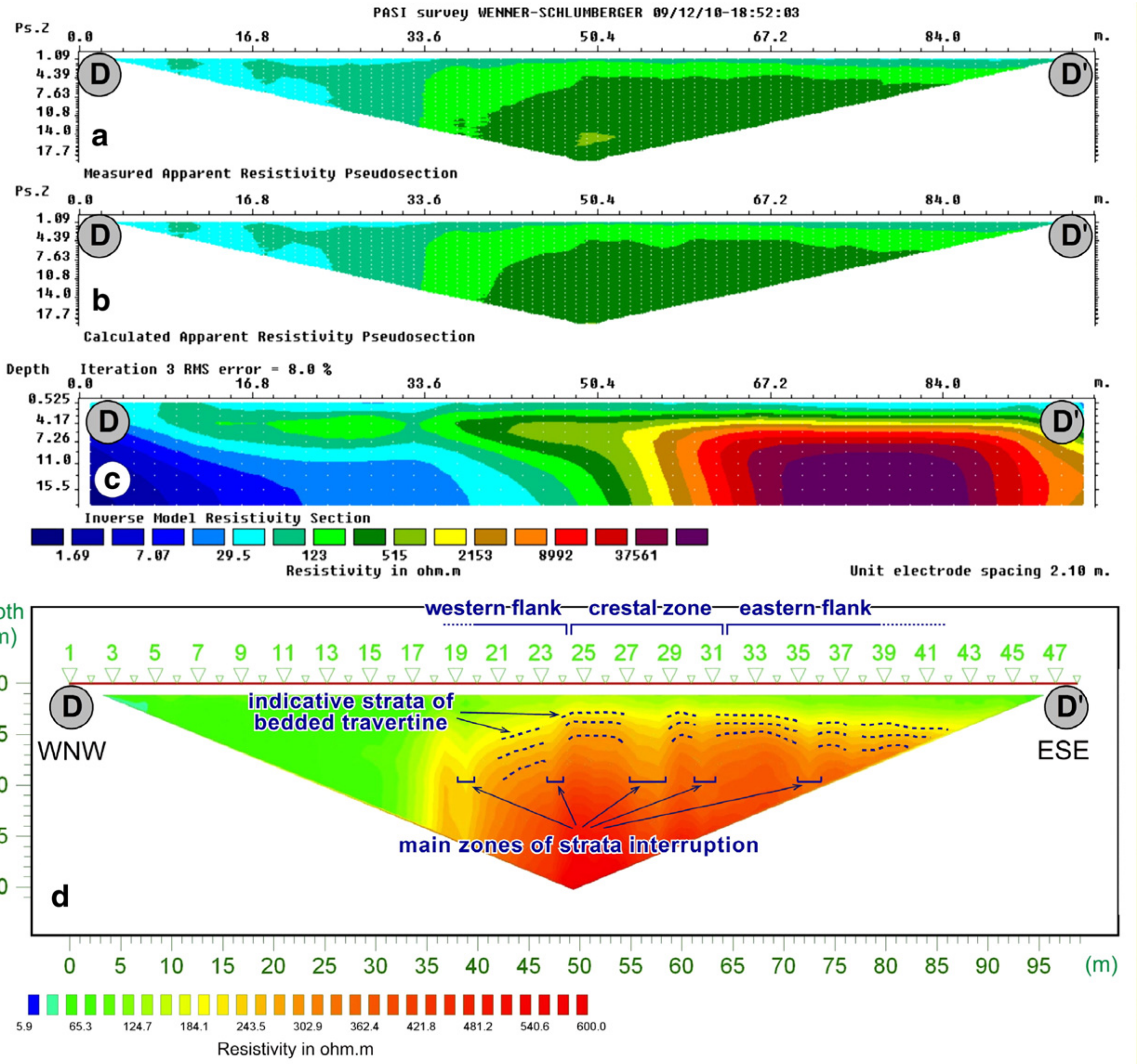


Fig. 9. Electrical Resistivity Tomography (ERT) cross-section (see cross-section track in Fig. 4a) showing the subsurface structure of the Colle Fiorito ridge. (a) Measured apparent resistivity pseudo-section. (b) Calculated apparent resistivity pseudo-section. (c) Inverse model resistivity section. (d) Calculated resistivity pseudo-section and, in blue, data interpretation.

In a previous paper, two of the authors examined the aspect ratios (length vs. width vs. height) of most known fissure ridge travertines in the world and found that these ratios follow roughly linear trends in bi-logarithmic diagrams (Fig. 5; De Filippis and Billi, 2012). The aspect ratios for the Colle Fiorito ridge are well consistent with these previous results. Fig. 5, in particular, shows that Colle Fiorito is one of the largest known travertine ridges in the world.

4.2. Geology

To understand the geological and sedimentological setting of the Colle Fiorito ridge, we analyzed a set of 32 well logs available from previous works (Ventriglia, 1990) and from the local industry of decorative stone (Fig. 6 and Supplemental Material 1). Through field surveys, we then studied the travertine outcrops over the Colle Fiorito area and collected a set of travertine samples to provide 14 thin-sections, which were magnified and analyzed under microscopic light to better understand the sedimentological features observed at the outcrop scale.

Well logs were used to better define the perimetral closure of the Colle Fiorito ridge (Fig. 4) and to construct a cross-section through the central portion of the ridge (Fig. 6). The cross-section shows that the Colle Fiorito ridge is a shield-like, thin-skinned structure less than 15 m high, lying over a shallow substratum consisting of pre-travertine clays and volcanic tuffs (Plio-Pleistocene). This geological setting contrasts markedly with the adjacent travertine plateau, which is constituted by a flat and thick (up to an average thickness of c. 45 m) travertine body (Figs. 1 and 6; Faccenna et al., 2008). Moving toward the northern portion of the ridge, the well log data (Supplemental Material 1) show that the ridge directly overlies the travertine deposits of the adjacent plateau. Collectively, the well log data prove that the Colle Fiorito ridge is a thin-skinned travertine deposit grown partly over the pre-travertine clays and volcanic tuffs (Fig. 6) and partly over the adjacent travertine plateau.

Below, we synthetically describe the six main outcrops studied during our field surveys (Figs. 7 and 8; see outcrop location in Fig. 4a and Supplemental Material 1). The number of significant outcrops is severely limited by the overbuilding in the study area and by the vegetation. The described sedimentological features derive from observations made at the centimetric–decimetric scale on outcrops and at the submillimetric scale in thin-sections. In the outcrops, two main types of travertine are recognized, which are common in most fissure ridge travertines: the bedded and banded travertines. The bedded travertine is a porous and stratified deposit that constitutes the bulk and flanks of fissure ridges, whereas the banded travertine is a sparry, non-porous, often subvertical, banded travertine (i.e., with growth bands of different colors) filling veins injected within the bedded travertine along the interior (axial) part of fissure ridges or sometimes forming sub-horizontal sill-like structures along pre-existing strata of bedded travertine (Bargar, 1978; Altunel and Hancock, 1996; Uysal et al., 2007; De Filippis et al., 2012; Gratier et al., 2012).

Outcrops 1 and 4: Outcrop 1 is a linear outcrop extended from the crestal portion of the ridge toward its eastern closure. In the crestal portion, a horizontal bedded travertine is exposed. This travertine is characterized by thick strata of stromatolitic facies (sensu D'Argenio and Ferreri 2004), which are typical of low-energy horizontal environments (Fig. 7c). The thickness of the strata suggests an aggradational pattern for these travertines. On top of this bedded travertine, the testina travertine is exposed (Fig. 7c). Moving toward the east, the bedded travertine is gently inclined (by about 10–15°) toward the east and characterized by thin strata with sedimentological facies (phytoclastic travertines with lensoid microhermal travertines and subordinate stromatolitic travertines) typical of a gentle slope environment (D'Argenio and Ferreri 2004; Fig. 7b). Moving further toward the east (Outcrop 4), an inclined (20–25°) bedded travertine (Fig. 7a) is exposed along the peripheral closure of the Colle Fiorito ridge. This inclined travertine is characterized by thick strata with features (phytoclastic travertine) typical of high-energy inclined slopes (D'Argenio and Ferreri 2004). This latter travertine (Fig. 7a) is symptomatic of a progradational system toward the distal portion of the ridge. Collectively, Outcrops 1 and 4 (Fig. 7d) constitute an ideal cross-section through the central-eastern portion of the ridge (Fig. 7e) and show a depositional system characterized by low-energy, horizontal, aggradational travertines in the crestal portion (Fig. 7c) and by progressively higher-energy, inclined, progradational travertines in the distal portion of the ridge (Fig. 7a, b). From these sedimentological observations, we infer that the inclined attitude of the travertine strata (Fig. 7a, b) should be substantially a clinostratification, perhaps only a little bit magnified (steepened) in the post-depositional time.

Outcrop 2: this outcrop shows subhorizontal bedded travertines (Fig. 8a) in the crestal portion of the Colle Fiorito ridge. The thickness of the strata in this outcrop, when compared with the thickness of the strata along the ridge flank (Fig. 7b), suggests an aggradational pattern. An interesting feature of Outcrop 2 is a banded travertine forming a sill-like structure lying along the interstratum surface of the bedded travertine (Fig. 8a to c). These features (sill-like structures) are very frequent in fissure ridge travertines from all over the world (De Filippis and Billi, 2012; De Filippis et al., 2012; Gratier et al., 2012). In Outcrop 2, the vertical fracture filled by banded travertine (partly covered by younger speleothems; Fig. 8a) is probably the vertical conduit from which the sub-horizontal sill-like structure was fed (e.g., Uysal et al., 2007, 2009; De Filippis et al., 2012).

Outcrop 3: In an old inactive quarry located at the top of the Colle Fiorito ridge, a quarried travertine block (i.e., left not in its original position over the bank of the old quarry) contains a banded travertine lying along the strata of the bedded travertine in a sill-like manner (Fig. 8d). The discovery of this structure suggests, together with the evidence from Outcrop 2, the action of mineralizing processes under pressure in a closed system so as to force fluid-driven mineralization along pre-existing bedding surfaces and to uplift the overlying rocks (Gratier et al., 2012). These processes may have contributed to form the ridge and to slightly tilt its flanks. The block shown in Fig. 8(d) has been recently removed and it is not, therefore, available for further analyses.

Outcrop 5: this outcrop is a tiny outcrop along the western flank of the Colle Fiorito ridge, showing a westward inclined (c. 15°) bedded travertine characterized by phytoclastic facies (Fig. 8e), which are typical of high energy slope environments.

Outcrop 6: this outcrop (Fig. 8f) is located in the crestal portion of the Colle Fiorito ridge and includes horizontal thick strata of bedded travertine mainly characterized by stromatolitic facies, which are typical of flat, low-energy environments. Also in this case, the thickness of the strata, when compared with the thickness of the strata along the ridge flank (Fig. 7b), suggests an aggradational pattern.

4.3. Geophysics

To understand the subsurface structure of the Colle Fiorito ridge, Electrical Resistivity Tomography (ERT) was completed across the ridge. In particular, we used a High-Resolution ERT (Wenner-Schlumberger method; e.g., Zohdy, 1989; Badmus and Ayolabi, 2005; Lundberg et al., 2012), which allowed us to define the subsurface stratal geometries up to c. 20 m depth. Results of the resistivity survey carried out along the D–D′ track (see the track in Fig. 4a) are shown in Fig. 9. The travertine has a characteristic high resistivity, whereas soil, alluvial, and lacustrine deposits are characterized by a lower resistivity. The interpretation of the ERT data is shown in Fig. 9(d), where the Colle Fiorito ridge appears as a gentle antiformal stratified structure affected by subvertical zones of strata discontinuity. These discontinuities may be subvertical fractures partly empty or partly filled by low resistivity material such as soil, alluvial, and lacustrine sediments. The discontinuities lie below the alignment (i.e., crestal zone in Fig. 9d) of thermal springs, gas vents, and

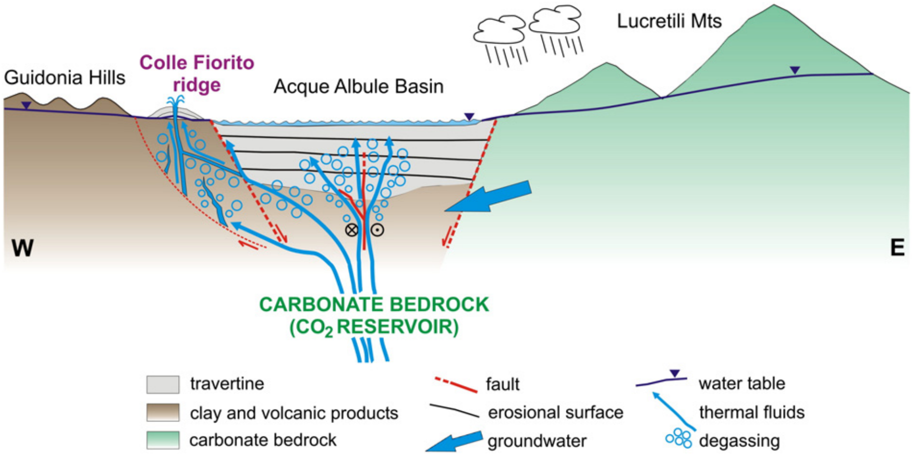


Fig. 10. Model for the formation of the Colle Fiorito ridge along the edge of the Tivoli travertine plateau in the Acque Albule basin. In late Pleistocene time, perhaps thanks to an abundant fluid discharge in the Acque Albule basin, part of these fluids laterally fed the growth of the Colle Fiorito ridge. The fluid discharge and related pressure were probably at the origin of fault (re)activation and opening of related fractures beneath Colle Fiorito, thus producing the necessary pathways for the ascension of geothermal bicarbonate-rich fluids. In the Colle Fiorito area, an amount of fluids generally lesser than that in the Acque Albule basin would have produced travertine (vertical) aggradation rather than travertine (lateral) progradation. The depth of the Meso-Cenozoic carbonate bedrock (CO_2 reservoir) below the Acque Albule basin is unknown.

small cones detected in Fig. 4(b) and could also be partly filled by banded travertine deposits forming subvertical veins or subhorizontal sill-like structures, as observed in Outcrops 2 and 3 (Fig. 8).

5. Discussion

5.1. Synthesis and interpretation

Our research started from the observation of the marked and apparently enigmatic morphological contrast between the flat travertine plateau of the Acque Albule basin and the prominent Colle Fiorito ridge along the northwestern margin of the plateau itself (Figs. 3 and 4). The geological and geophysical data presented in this paper reveal the surface and subsurface setting of the Colle Fiorito ridge and help to shed light on its origin. In particular:

(1) the geomorphological and geological evidence (Figs. 3–8) shows that the Colle Fiorito ridge is an elongate shield-like structure mainly formed by bedded travertine, which is horizontal in the crestal area and clinostratified along the flanks;
(2) the N–S to NNE–SSW trend of the Colle Fiorito ridge is roughly parallel to the main tectonic structures in the Acque Albule basin (Figs. 1 and 3a), thus suggesting a link between these structures and the development of the Colle Fiorito ridge;
(3) the aerial photographs taken by the RAF in 1943 show a crestal fissure segment on the summit of Colle Fiorito close to a set of small cones and other evidence of degassing structures (Fig. 4b, c);
(4) well logs show that, in the subsurface, the Colle Fiorito ridge is a thin-skinned structure (i.e., no deep roots) grown partly over the Plio-Pleistocene clays and volcanic products and partly over the pre-existing travertine plateau (Fig. 6 and Supplemental Material 1);
(5) the geophysical data show that the gentle antiformal travertine structure of Colle Fiorito is vertically disrupted by discontinuity zones below the crestal area of the ridge (Fig. 9). These zones are interpreted as fractures and disruption bands beneath the small cones detected on the ridge summit (Fig. 4b). This interpretation is supported by the exposure, in Outcrop 2, of a vertical fracture disrupting the bedded travertine (Fig. 8a, b);
(6) Colle Fiorito is located on the hanging wall of a seismic normal fault, as inferred by the NNE–SSW-trending tectonic lineament observed in Fig. 3(a) (to the west of Colle Fiorito) and by the earthquake hypocenters located right beneath Colle Fiorito (Fig. 2; Gasparini et al., 2002).

Collectively, our data indicate that the Colle Fiorito structure can be interpreted as a fissure ridge travertine very similar to other fissure ridge travertines studied, for instance, in Turkey (Uysal et al., 2007, 2009; De Filippis et al., 2012, in press), Italy (Guo and Riding, 1999), U.S.A. (Bargar, 1978; Chafetz and Folk, 1984; Hancock et al., 1999; Shipton et al., 2004, 2005; Dockrill and Shipton, 2010; De Filippis and Billi, 2012; Gratier et al., 2012), and elsewhere (De L'Apparent, 1966; Pentecost and Viles, 1994; Pentecost, 2005). The growth of these structures is known to be usually influenced by tectonics, fluid discharge, and paleoclimate oscillations (Hancock et al., 1999; Uysal et al., 2007, 2009; Brogi and Capezzuoli, 2009; De Filippis and Billi, 2012; De Filippis et al., 2012, in press; Gratier et al., 2012). The ridge growth usually occurs over tens of thousands of years through alternate phases of vertical growth of bedded travertine (aggradation) and inner injection of banded travertine across and along the pre-existing strata of bedded travertine (Uysal et al., 2007, 2009; De Filippis and Billi, 2012; De Filippis et al., 2012, in press). The main distinctive features of most fissure ridges hitherto studied are as follows: (1) elongate-mound morphology; (2) shield-like cross-sectional shape (i.e., lack of deep roots); (3) presence of a crestal fissure or a set of crestal fissures; (4) presence of horizontal travertine beds in the crestal area and of clinostratified ones along the flanks; (5) occurrence of banded travertine deposits injected, both sub-vertically and sub-horizontally, into the pre-existing bedded travertine forming the bulk of the ridge; (6) travertine growth contemporaneous with tectonic activity; and (7) in most cases, growth on top of a normal fault hanging wall. All the above-reported features are valid and true also for the Colle Fiorito ridge, and support our interpretation of this structure as a fissure ridge travertine deposit (Fig. 10). Moreover, the size and aspect ratio of the Colle Fiorito ridge is consistent with these same parameters for most known fissure ridges in the world (Fig. 5; De Filippis and Billi, 2012).

5.2. Age of the Colle Fiorito ridge

Active deposition of travertine on the Colle Fiorito ridge probably ceased during the late Pleistocene, as suggested by travertine dating from the summit of the ridge (i.e., 28 + 16 / −15 ka; Faccenna et al., 1994b). In our opinion, however, degassing from the Colle Fiorito ridge has been active until recent times, as suggested, primarily, by the presence of small cones on top of the ridge (Fig. 4b) and, secondarily, by the active seismicity beneath Colle Fiorito (Gasparini et al., 2002). This seismicity may have been, in fact, promoted by degassing phenomena and increased fluid pressure. Concerning the cones detected in Fig. 4b, it is known that travertines are readily erodible (between about 5 and 15 mm/a; Drysdale and Gillieson, 1997). The occurrence of these travertines on top of the Colle Fiorito ridge encourages us to think that these structures would have formed in recent, perhaps historical times; otherwise, they would have been completely eroded.

Given the age of the youngest travertine on Colle Fiorito (i.e., 28 + 16 / −15 ka), one viable hypothesis is that the Colle Fiorito ridge may have grown along the edge of the Tivoli plateau (Fig. 10) during the late stages of the plateau growth, when the climax of the travertine deposition rate was reached in the Acque Albule basin (i.e., between about 56 and 44 ka; Faccenna et al., 2008). This hypothesis is, however, still very speculative for the large uncertainty that applies to the above-reported travertine age (i.e., 28 + 16/−15 ka).

5.3. Fluid discharge and ridge growth

As hypothesized above, the increased fluid discharge and pore pressure would have activated the system of faults in the Acque Albule basin and opened new pathways for the fluids to ascend toward the nascent Colle Fiorito ridge (Fig. 10). Contrary to the Tivoli travertine plateau, which grew mainly by lateral progradation for the abundance of mineralizing fluids (Faccenna et al., 2008), our observations show that the Colle Fiorito ridge mainly grew by vertical aggradation of travertine beds (Figs. 8 and 9), thus originating the marked morphological contrast between the Colle Fiorito ridge and the adjacent travertine plateau (Fig. 4). The ‘aggradation’ versus ‘progradation’ styles of travertine growth imply also different fluid discharges. In travertine sedimentary systems, in fact, a larger fluid discharge is usually at the origin of lateral progradation (i.e., the travertine can precipitate also far away from the geothermal springs), whereas a lesser amount of fluids is usually at the origin of vertical aggradation owing to the fact that most travertine precipitate immediately close to the geothermal springs (e.g., De Filippis et al., in press).

In some outcrops from the Colle Fiorito ridge, there is also evidence of lateral progradation for the bedded travertine (Fig. 8a). This evidence testifies to the cyclic growth of this structure, as already pointed out for the adjacent Tivoli plateau (Faccenna et al., 2008) and for other fissure ridges elsewhere (e.g., De Filippis et al., 2012). The evidence of a lateral progradation of travertine beds (in the distal part of the Colle Fiorito ridge; Fig. 8a) involves, in fact, periods of large fluid discharge such that the travertine precipitation occurred, at least in part, through lateral progradation far away from the crestal springs. On the contrary, periods of lesser fluid discharge must have involved the vertical aggradation of travertine owing to its preferential precipitation close to the crestal springs. A partial progradational pattern of travertine beds has also been observed in the Akköy fissure ridge (Turkey; De Filippis et al., 2012), whose dimensions are very similar to the ones of the Colle Fiorito ridge. These two fissure ridges are among the largest structures of this type ever found on the Earth (De Filippis et al., 2012).

5.4. Possible implications

Previous studies on fissure ridge travertines help us to understand the significance and possible implications and applications of our discovery in the Colle Fiorito area.

(1) Several studies have established a causal link between the growth of fissure ridge travertines and active tectonics (Altunel and Hancock, 1993a, b; Çakır, 1999; Hancock et al., 1999; Altunel and Karabacak, 2005; Mesci et al., 2008; Brogi and Capezzuoli, 2009, 2012). In particular, Altunel and Hancock (1993a, b), studying some fissure ridges from the Denizli basin (western Turkey), have significantly corroborated the general idea of Barnes et al. (1978), who found that thermogene travertines are commonly associated with seismically active faults. Uysal et al. (2007, 2009) have explained the formation of veins filled by banded travertine within fissure ridges (Turkey) as being caused by rapid coseismic precipitation of $CaCO_3$ (see also Kele et al., 2008, 2011). These same vein deposits and their radiometric ages have been used to infer paleostress directions and associated deformation rates (Hancock et al., 1999; Altunel and Karabacak, 2005; Uysal et al., 2007; Mesci et al., 2008). Some authors, through mapping of fissure ridge travertines, have noted their preferential distribution in the hanging wall blocks of active or recently-active normal faults, particularly in the releasing step-over zones of normal faults. This latter evidence suggests a significant enhancement of geothermal circulation caused by fault-related dilation fracturing, which is particularly intense in releasing step-over zones (e.g., Çakır, 1999; Hancock et al., 1999; Mesci et al., 2008; Brogi and Capezzuoli, 2009).

(2) Our discovery of the Colle Fiorito fissure ridge travertine has the potential to be used in the future for paleoclimate studies. The deposition of travertine in fissure ridges has been, in fact, demonstrated to be influenced also by paleoclimate oscillations (Hancock et al., 1999; Uysal et al., 2009; De Filippis et al., 2012, in press). It has been noted, for instance, that veins of banded travertine in fissure ridges formed preferentially during cold/dry climate events when the water table beneath fissure ridges was depressed, whereas the bulk of fissure ridges (bedded travertine) formed preferentially during warm/wet events when the water table rose (Uysal et al., 2009; De Filippis et al., 2012, in press; Kampman et al., 2012). This evidence points out the importance of groundwater hydrology modulated by paleoclimate oscillations in the growth of fissure ridges. Paleoclimate oscillations have been demonstrated to be influential also in travertine deposits different from fissure ridges (e.g., Rihs et al., 2000; Faccenna et al., 2008; De Filippis et al., in press).

(3) Regarding the role of fluids, in particular CO_2, in the growth of fissure ridges, these latter structures are now considered a valid analog of long-term (tens of thousands of years) CO_2 degassing from artificial subsurface reservoirs and also a valid record of long-term geothermal circulation (e.g., Frery, 2012; Gratier et al., 2012; Khoury, 2012). For instance, Kampman et al. (2012), exploring some travertine mounds from central Utah (USA), have concluded that also geological repositories of CO_2 located far from active structures can experience CO_2 leakage (see also De Filippis and Billi, 2012), thus claiming that in situ stress characterization is needed for the prediction of secure long-term storage. Frery (2012), analyzing travertine deposits from Utah, estimated the long-term average CO_2 degassing rate (about 1000 kg per year), which may find important applications in the modern CO_2 sequestration industry. To better understand the potential implications of our results on the CO_2 subsurface storage, we here briefly report what is known from previous papers about the Tivoli travertine feeding circuit (Manfra et al., 1976; Minissale et al., 2002; De Filippis et al., in press). Geochemical studies of the Tivoli travertine demonstrated that this deposit substantially derived from meteoric waters that were, at depth, heated and CO_2 enriched probably for the effect of the nearby active Colli Albani volcano. The CO_2 enrichment must have counteracted and exceeded the effect of temperature rise, thus leading the CO_2-rich meteoric waters to chemically weather the bedrock of Meso-Cenozoic carbonates. Afterward, while ascending toward the surface, the carbonate-rich warm waters were cooled in intercepting the shallow and colder aquifers. Eventually, when the fluid reached the surface, the decrease of pressure led to CO_2 degassing and therefore to travertine precipitation (Fig. 10).

(4) Eventually, it is interesting to know that the banded travertine typical of the inner portion of most fissure ridges has been often considered a precious decorative stone (e.g., Pamukkale in Turkey and Bridgeport in California). For instance, the banded travertine from the Bridgeport fissure ridges (De Filippis and Billi, 2012) has been used to decorate important buildings such as the rotunda of the City Hall in San Francisco, California.

6. Conclusions

Starting from a marked morphological contrast between adjacent deposits of travertine in the Acque Albule basin, we have discovered a hitherto unknown fissure ridge travertine deposit in the Colle Fiorito area. The contrasting morphology between the travertine deposits forming the Tivoli plateau and the adjacent Colle Fiorito ridge hides different subsurface architectures: basin-filling deeply-rooted versus surficial shallow deposits, respectively. We explain these different morphologies with different deposition mechanisms and styles, namely, aggradation in the Colle Fiorito ridge versus progradation in the Tivoli plateau. With this study, we point out the importance of thermogene travertines and their morphology in constraining and understanding present and past geothermal systems, in terms of the location of the feeding conduits for hydrothermal fluid flow, age of faulting, fluid discharge, and also surface hazardous processes (e.g., Brogi et al., 2012; Nishikawa et al., 2012).

Acknowledgments

We warmly thank A.J. Plater and two anonymous reviewers for their constructive suggestions and editorial work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geomorph.2013.04.019. These data include Google maps of the most important areas described in this article.

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