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GEOMORPHOLOGICAL SURVEY OF CIVITA

CIVITA INSTITUTE 2023 “The Cultural Landscape of Civita di Bagnoregio” Fellowship

THE CIVITA INSTITUTE

INTRODUCTION

Civita di Bagnoregio and the surrounding “badlands valley” represent a “living landscape” of extraordinary beauty and particularity, one of the most fascinating, and problematic, sites in Italy and - maybe - in the world. For thousands of years, the main reasons that make Civita a unique and enchanting place have determined a rapid evolution of the slopes linked to complex interacting phenomena. The multiple types of landslides (in terms of movement mechanisms, speed, materials involved, evolution over time, etc.), have long had, and still have, a deeply negative effect on the life of the community in the town and on its urban and architectural assets.

The first and essential step of territorial analysis is an accurate geomorphological study carried out as much as possible not only in the present, but on a properly wide time scale. This is the basis on which the most suitable strategies for the conservation of the fragile town can be effectively developed. The peculiar dynamism of the territory and complexity of the instability processes constrain a special study methods and approach to the problems, specifically designed for the town’s situation, under a long-term-planning strategy.

At present the geomorphological maps available are dated, small-scale developed or do not differentiate in detail the various instability phenomena. It was therefore deemed necessary to carry out a new geomorphological survey campaign, integrated into this work with drone footage analysis (thanks to the Memo of Understanding “*Protocollo d'Intesa*” between The Civita Institute and the Municipality of Bagnoregio) and with the abundant documentation collected between 2012 and 2022 as Conservator and Curator of the Geological and Landslides Museum in Civita.

The contents of this paper has been submitted as an article to the “Italian journal of engineering geology and environment”, and it is expected to be published in 2025.

1. GEOLOGICAL SETTING

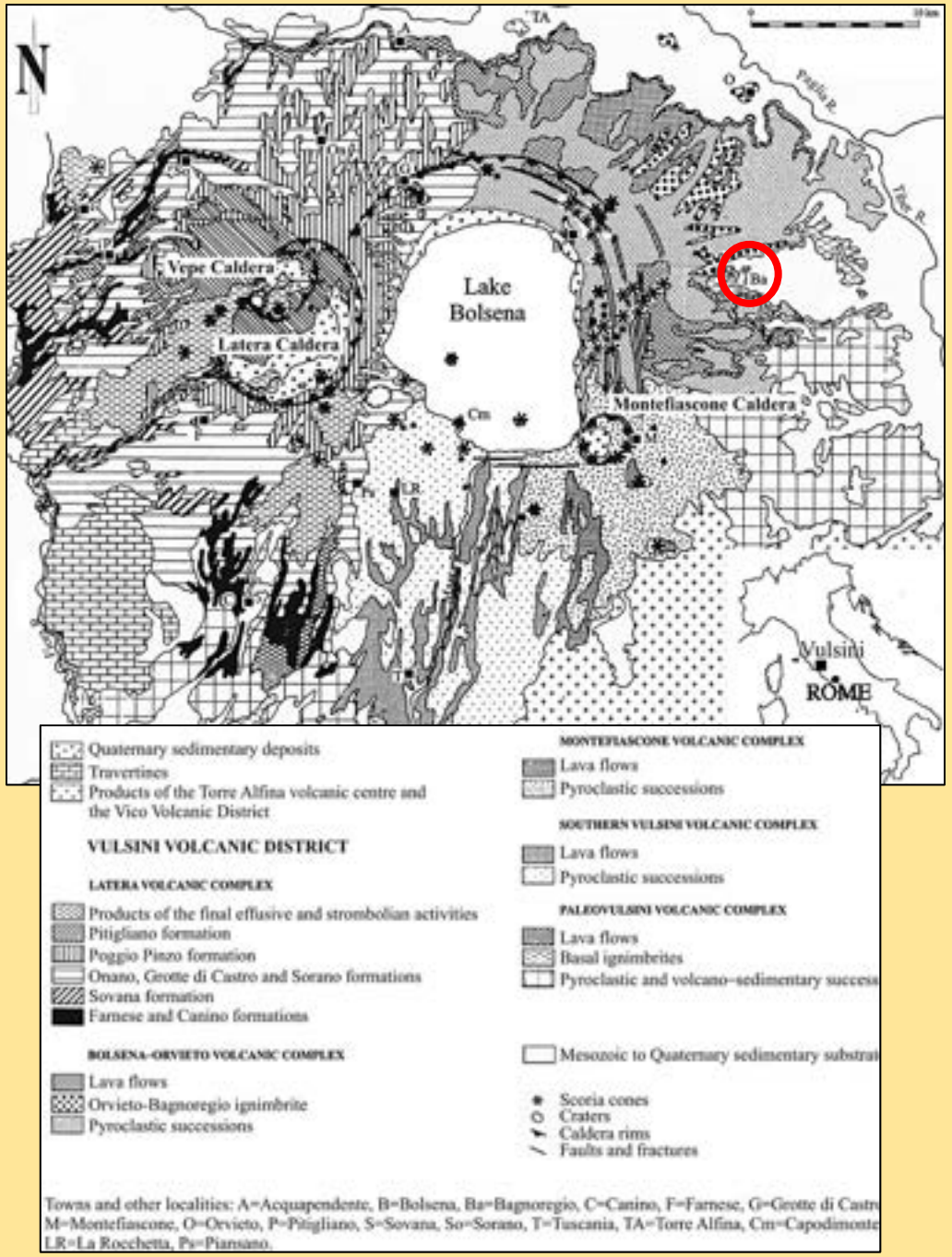
The area of Civita di Bagnoregio is characterized by a particular geomorphology due primarily to the geological features (various pyroclastic deposits overlaying silty clays of marine origin), and by the particular shape of the landscape, with very deep valleys and very inclined slopes. The clays were deposited on the seabed of the Tyrrhenian Sea between the Pliocene and the lower Pleistocene (Gelasian – Santernian – Emilian?) (Mancini et al., 2003-2004; Bizzarri & Baldanza, 2020).

After being raised several hundred meters for volcano-tectonic causes, the marine deposits were covered by pyroclastic deposits erupted from two of the five volcanoes of the "Vulsini Volcanic District" (VVD) during the middle Pleistocene. The volcanoes were active in the area of the present Bolsena Lake, whose depression originated from the collapse occurred in the late phase of volcanic activity (Acocella, 2012).

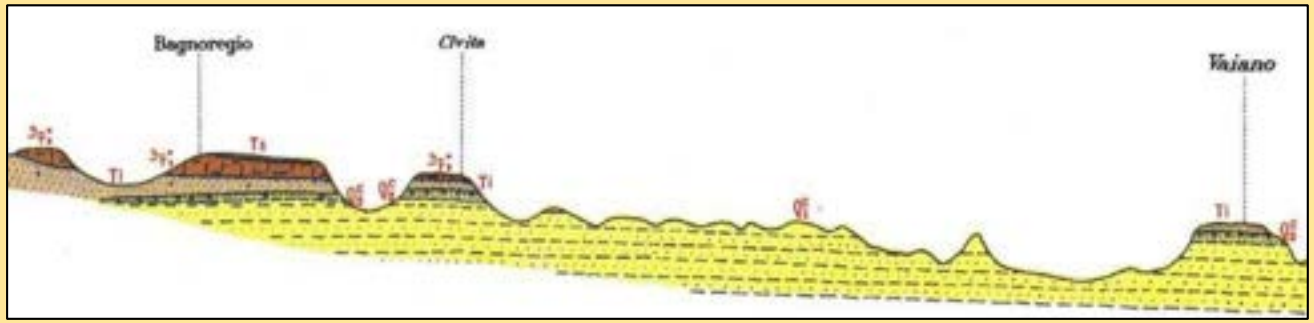
According to a wide geochronological and geo-volcanological data-set, the Vulsini volcanic activity spanned the ~590-111 ka (thousand years ago) time interval (Palladino et al., 2010 and reference therein; Marra et al., 2020a), with a broad spectrum of eruptive styles, intensities and magnitudes, ranging from small-scale explosive (Strombolian and hydromagmatic) and effusive eruptions from monogenetic centers up to Plinian and pyroclastic flow, caldera-forming, events (Sparks, 1975; Nappi et al., 1994, 1995, 1998, 2022; Palladino et al., 2010, 2016).

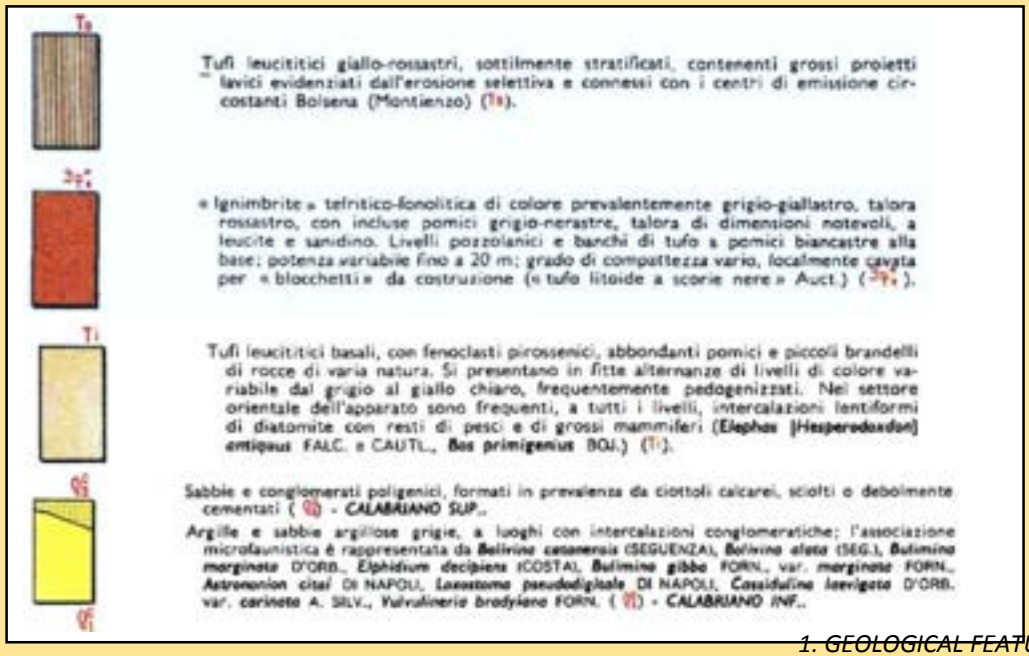
The cliff of Civita di Bagnoregio is made up of pyroclastic deposits of different origin and features, erupted by Paleovulsini and Bolsena-Orvieto volcanic complexes.

The following are the excerpts of the available geological maps of the Civita area.



Geological sketch map of the Vulsini Volcanic District (Palladino et al., 2010).





Tufi leucititici giallo-rossastri, sottilmente stratificati, contenenti grossi proietti lavici evidenziati dall'erosione selettiva e connessi con i centri di emissione circostanti Bolsena (Montienzo) (T_8).

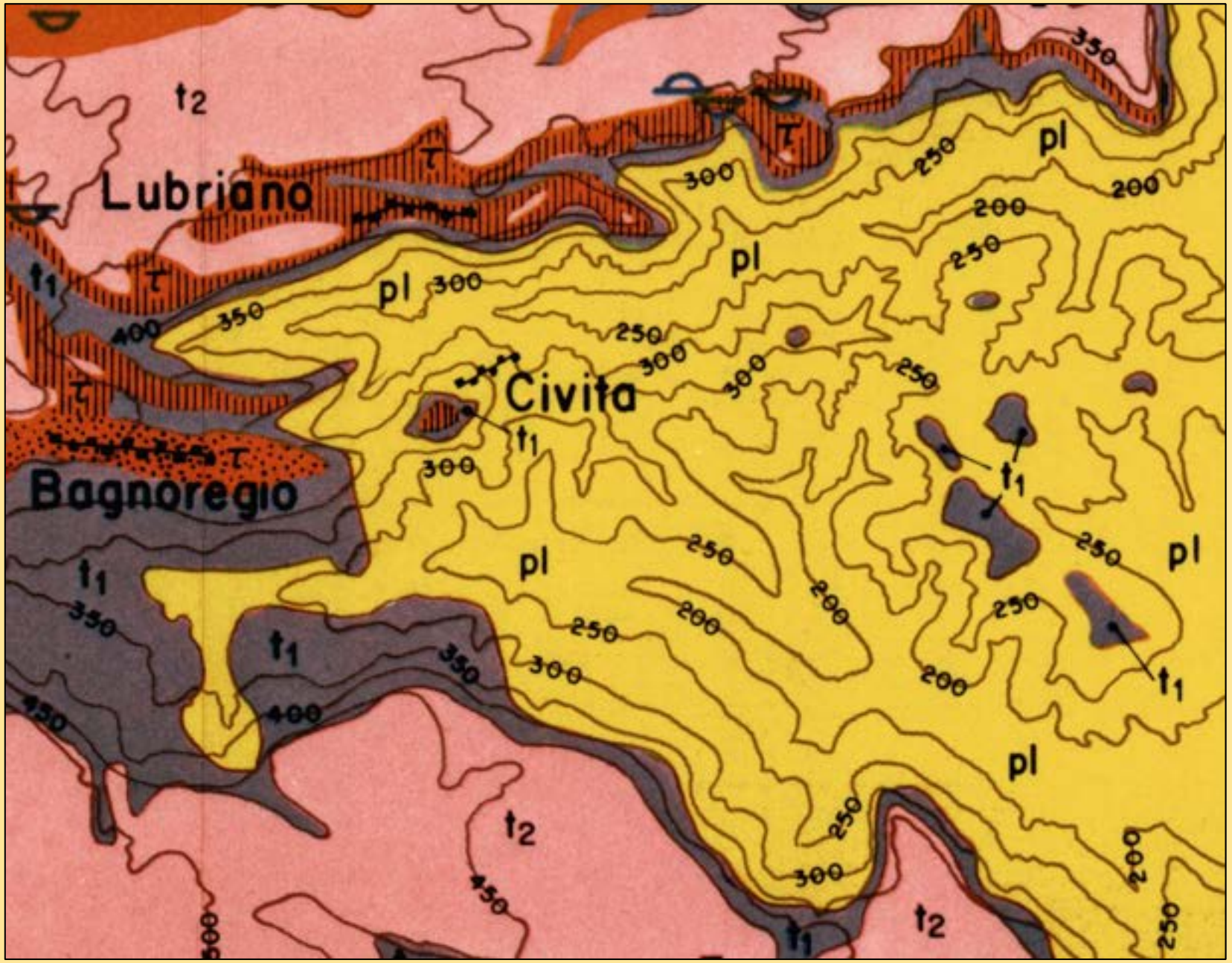
« Ignimbrite » tefritico-fonolitica di colore prevalentemente grigio-giallastro, talora rossastro, con incluse pomici grigio-nerastre, talora di dimensioni notevoli, a leucite e sanidino. Livelli pozzolanici e banchi di tufo a pomici biancastre alla base; potenza variabile fino a 20 m; grado di compattezza vario, localmente cavata per « blocchetti » da costruzione (« tufo litoide a scorie nere » Auct.) ($^3T_7$).

Tufi leucititici basali, con fenoclasti pirossenici, abbondanti pomici e piccoli brandelli di rocce di varia natura. Si presentano in fitte alternanze di livelli di colore variabile dal grigio al giallo chiaro, frequentemente pedogenizzati. Nel settore orientale dell'apparato sono frequenti, a tutti i livelli, intercalazioni lentiformi di diatomite con resti di pesci e di grossi mammiferi (**Elephas [Hesperodoxdon] antiquus** FALC. e CAUTL., **Bos primigenius** BOJ.) (T_1).

Sabbie e conglomerati poligenici, formati in prevalenza da ciottoli calcarei, sciolti o debolmente cementati (Q_3^2 - **CALABRIANO SUP.**.

Argille e sabbie argillose grigie, a luoghi con intercalazioni conglomeratiche; l'associazione microfaunistica è rappresentata da **Bolivina catanensis** (SEGUENZA), **Bolivina alata** (SEG.), **Bulimina marginata** D'ORB., **Elphidium decipiens** (COSTA), **Bulimina gibba** FORN., var. **marginata** FORN., **Astrononion citai** DI NAPOLI, **Lagenostoma pseudodigitale** DI NAPOLI, **Cassidulina laevigata** D'ORB. var. **carinata** A. SILV., **Vulvulineria bradyiana** FORN. (Q_3^1) - **CALABRIANO INF.**.

Geological map of Italy, scale 1:100.000, Sheet 137 "Viterbo", Geological Service of Italy, 1971. (On the right: author's original with different colors, ISPRA archive).
http://sgi.isprambiente.it/geologia100k/mostra_foglio.aspx?numero_foglio=137



LEGENDA

Alluvioni recenti ed attuali, detrito di falda ed epivulcaniti (a).

Prodotti post-ignimbritici: colate di lava di tipo da tefritico leucitico a leucititico; piroclastiti riferibili a "pyroclastic fall" e "pyroclastic surge" (t_2).

Ignimbrite trachitica "Tufo di Orvieto":

spessore affiorante superiore ai 20 metri (τ)

spessore affiorante compreso tra 10 e 20 metri (τ)

spessore affiorante inferiore ai 10 metri (τ).

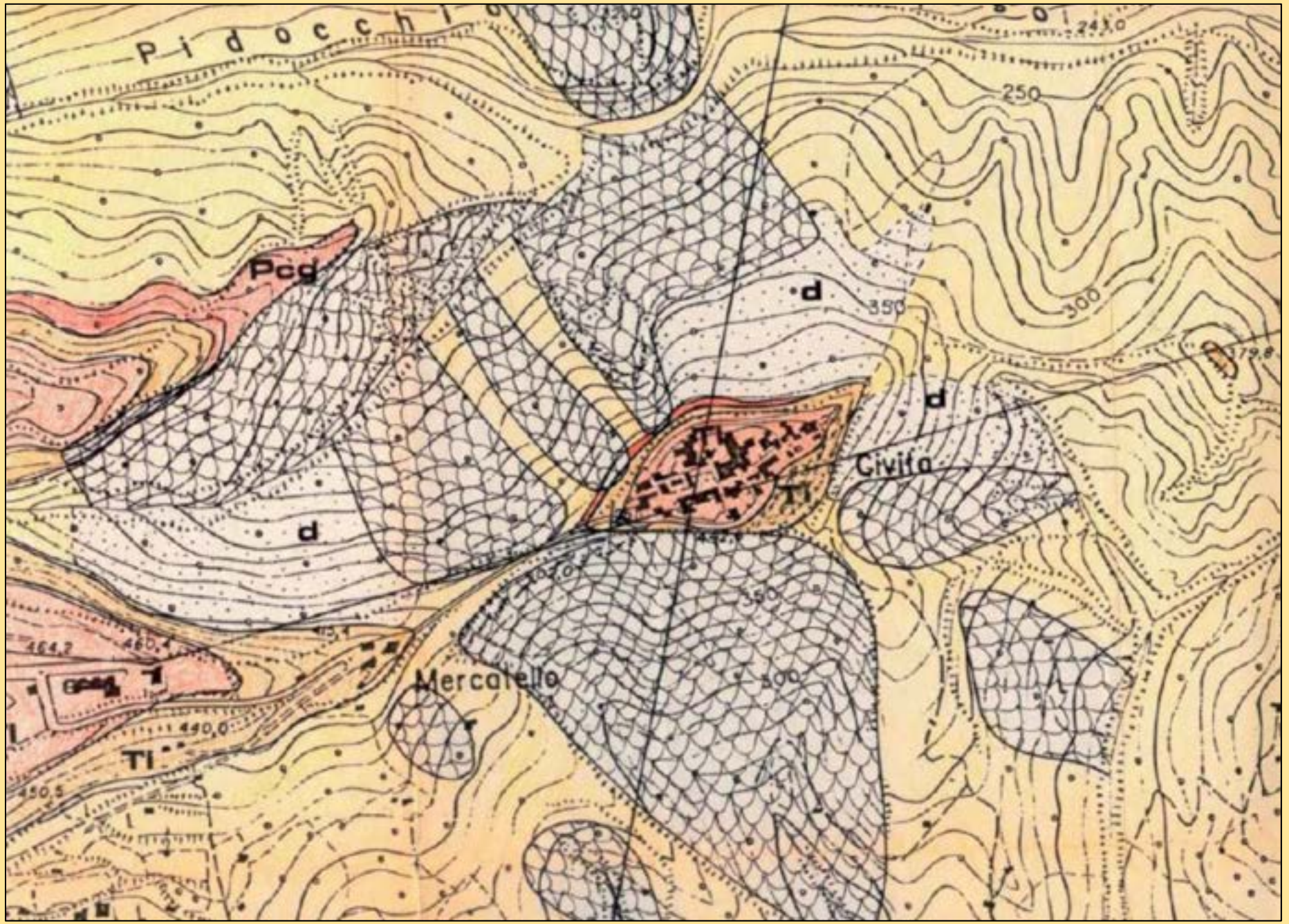
Prodotti pre-ignimbritici: colate di lava di vario tipo (da trachiandesitico a leucititico), prodotti piroclastici stratificati alternati a paleosuoli e depositi limnopalustri (t_1).

Argille, sabbie e ghiaie (Plio-Pleistocene) (pl).

Cave attive

Cave abbandonate

Geological map of the north-eastern Vulsini (Nappi et al., 1982).



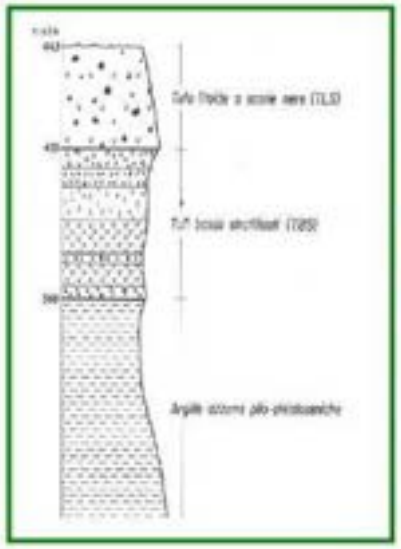
(Focardi, 1992).

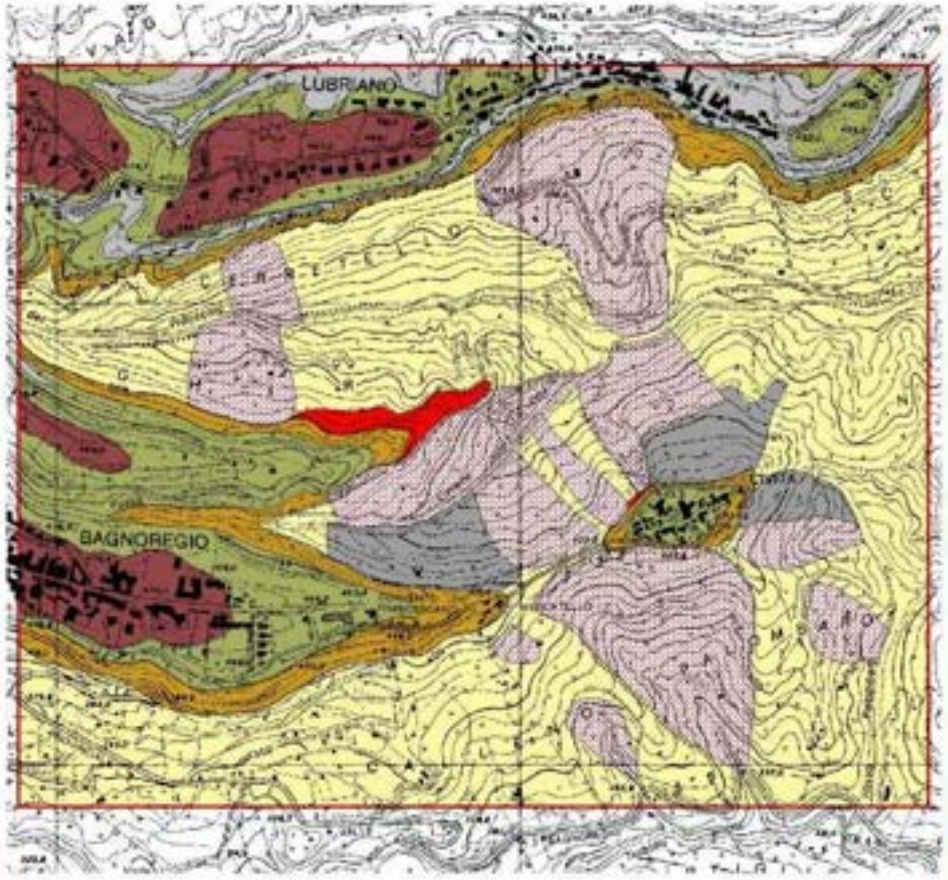
Progetto pilota del Ministero della ricerca scientifica

Allegato 1

Linee Guida per la salvaguardia dei beni culturali dai rischi naturali

Colonna Stratigrafica della rupe di Civita di Bagnoregio





Area di studio

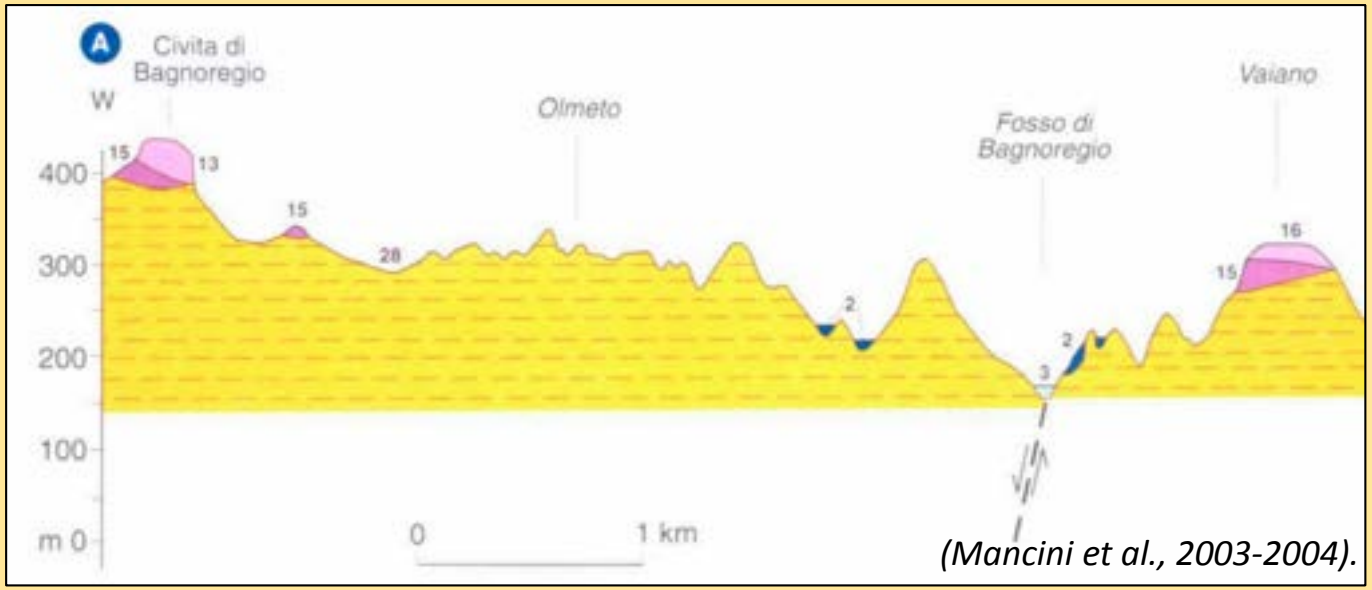
Carta Geologica

- **Frane Antiche e recenti**
- **Detrito**
  Blocchi e frammenti di tufo con matrice limoso-sabbiosa
- **Tufi Stratificati Superiori (TSs)**
  Tufi leucitico-tefritici costituiti da strati tufacei giallastri, sabbie vulcaniche grigiastre, pomici gialle o arancio, tufiti con pomicette chiare. (Pleistocene)
- **Livelli di Pozzolane (Pz)**
- **Tufo Litoide (TI)**
  "Tufo giallo a scorie nere". Ignimbrite tefritico fonolitica di colore giallo rossastro con inclusi pomici nere.
- **Tufi Stratificati Inferiori (TSi)**
  Tufi leucitico-tefritici con fenocristi piroxenici, abbondanti pomici.
  Presenza di livelli Pedogenizzati (Pleistocene)
- **Sabbie e Conglomerati (Pcg)**
  Formati in prevalenza da ciottoli calcarei debolmente cementati con matrice limoso - argillosa
- **Argille (Pag)**
  Argille limose con piccoli livelli di sabbie limose (Plio Pleistocene)

0.5 0 0.5 1 Kilometers

Scala 1:10.000

ENEA, 2001.



(Mancini et al., 2003-2004).

Detrito (1). *Olocene.*

Depositi colluviali argilloso-siltosi (2): sabbie, limi e argille derivati dall'alterazione dei depositi quaternari più antichi. *Olocene.*

"Unità di Sipicciano" (5): ghiaie con clasti di natura calcarea, arenacea, vulcanica e silicea, a stratificazione incrociata concava o tabulare; matrice sabbiosa abbondante e molto ricca in minerali femici. Lo spessore affiorante è di circa 15 m. Ambiente fluviale. ***Pleistocene superiore.***

"Tufo rosso a scorie nere vicano" Auct. (6): depositi piroclastici di colata, di natura tefritico-fonolitica, con grosse scorie nere o grigio scure, riferibili alla "Ignimbrite C" vicana. Età 151 ± 3 ka. Spessore massimo in affioramento: 30 m. ***Pleistocene medio terminale.***

"Unità di Fiano" (7): travertini stratificati in bancate tabulari dello spessore metrico. Prevalenza di facies fitoclastiche e sabbie calcaree; contengono resti vegetali incrostati e gasteropodi polmonati. Ambiente di piana alluvionale. Spessore massimo in affioramento: 20 m. ***Pleistocene medio terminale.***

"Unità di Fiano" (7): travertini stratificati in bancate tabulari dello spessore metrico. Prevalenza di facies fitoclastiche e sabbie calcaree; contengono resti vegetali incrostati e gasteropodi polmonati. Ambiente di piana alluvionale. Spessore massimo in affioramento: 20 m. ***Pleistocene medio terminale.***

Teverina, Agliano, Valle del Vezza). Frequenti intercalazioni di sabbie calcaree grossolane, molto ricche in minerali femici, e paleosuoli contenenti: *Pupilla musconum, Monacha cantiana, Cochlicella barbara, Chondrula tridens, Primatias elegans*. Resti di vertebrati (*Dama* sp.) sono stati trovati presso Castel Cellesi. Spessore massimo: 40 m. ***Pleistocene medio.***

Successioni vulcaniche e vulcano-sedimentarie vulsine (11-13) riferibili al **"Complesso Vulcanico di Bolsena"** (Nappi & Marini, 1986). Comprendono: lave leucititico-tefritiche (11), con spessori fino a 25 m, affioranti nelle zone settentrionali (Bagnoregio, S. Michele in Teverina) e intercalate ai depositi piroclastici (13); depositi vulcano-sedimentari (12) costituiti in prevalenza da epiclastiti, diatomiti e paleosuoli, localmente con spessori massimi di oltre 50 m; depositi piroclastici (13), in prevalenza ceneriti e pomici stratificate in bancate tabulari. Complessivamente presentano spessori variabili da oltre 100 m a pochi metri, da Ovest verso Est. ***Pleistocene medio.***

Successioni vulcaniche e vulcano-sedimentarie vulsine, riferibili al **"Complesso vulcanico del Paleobolsena"** (15-16). Sono costituiti da: depositi vulcano-sedimentari (15), diatomiti, epiclastiti, paleosuoli e travertini, stratificati e intercalati alle piroclastiti (16). Spessore di oltre 35 m. Depositi piroclastici (16), alternanze di bancate tabulari di pomici e ceneriti; comprendono, fra gli altri, i depositi della "Formazione di Civitella d'Agliano", costituita da ignimbriti di composizione trachi-fonolitica e datata 505.2 ± 6.7 ka. Spessore massimo: 50 m. ***Pleistocene medio.***

"Unità di Civita Castellana" (17): ghiaie e conglomerati a stratificazione piana orizzontale o incrociata. Clasti calcarei, arenacei e silicei; abbondante matrice sabbiosa, quasi esclusivamente costituita da quarzo e muscovite. Rare bancate sabbiose a stratificazione incrociata, dello spessore metrico, e localmente (Guadamello, San Vito) livelli calcareo-travertinosi. Spessore variabile da pochi metri, nelle zone più settentrionali (Castiglione), fino a circa 100 m a Guadamello. Ambiente fluviale di tipo *braid-plain*. ***Pleistocene inferiore terminale-Pleistocene medio iniziale.***

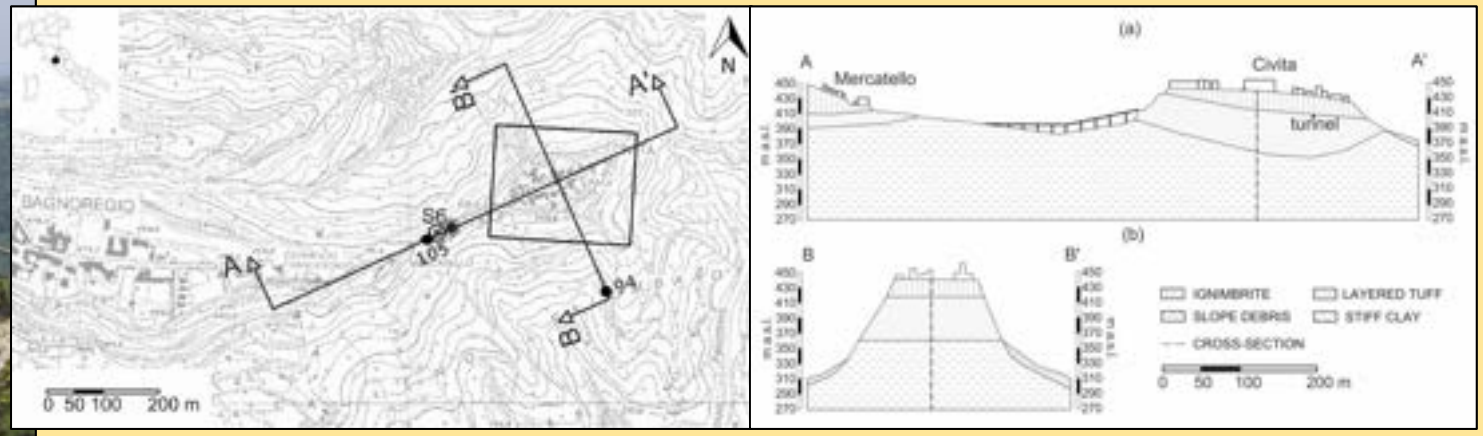
"Argille sabbiose di ambiente marino" (28): affiorano alla base della formazione per uno spessore massimo che localmente raggiunge i 200 m (Bagnoregio, Alviano). Si presentano mal stratificate oppure a stratificazione piana orizzontale. Si rinvengono talvolta livelli sabbiosi torbiditici e ad *hcs*. Contengono: *Ditrupa* sp., *Dentalium (Antalis) fossile, Corbula (Varicorbula) gibba, Natica tigrina, Archimedella spirata*. La microfauna è composta da *Bulimina marginata, B. elegans marginata, B. etnea* (specie nei livelli alti), *Cassidulina carinata, Bolivina alta, Uvigerina peregrina*; molto raramente nei livelli più bassi è stata trovata *Globorotalia inflata*. Ambiente di piattaforma, piano circalitorale e di transizione infra-circalitorale.

Strati orizzontali

Faglia normale:
a - osservata
b - presunta

Frana

North side of Civita cliff with stratigraphy.



Geological cross-sections (Cercato et al., 2020).

The top of the relief is made up of the lithoid tuff of the “Orvieto-Bagnoregio ignimbrite” (333±4 ka; Nappi et al., 1995) ("Bolsena-Orvieto" Volcanic Complex): it’s a massive ashy ignimbrite (deposited by a pyroclastic flow*) with variable thickness, mainly cemented by zeolites, bearing from scarce to abundant heterometric dark scoria, small pumices, small crystals of analcimized leucite and microliths. Volcanological and depositional features of the “Orvieto-Bagnoregio ignimbrite” are well studied (non-exhaustive list: Nappi et al., 1982, 1994, 1995; Capaccioni & Sarocchi, 1996; Peccerillo, 2012; Gentili et al., 2014; Palladino & Pettini, 2020), as well as its geotechnical and seismic ones (non-exhaustive list: Iacurto & Priori 1995; ENEA, 2001; Rotonda et al, 2002; Tommasi et al, 2013; Verrucci et al, 2015; Cercato et al, 2020).

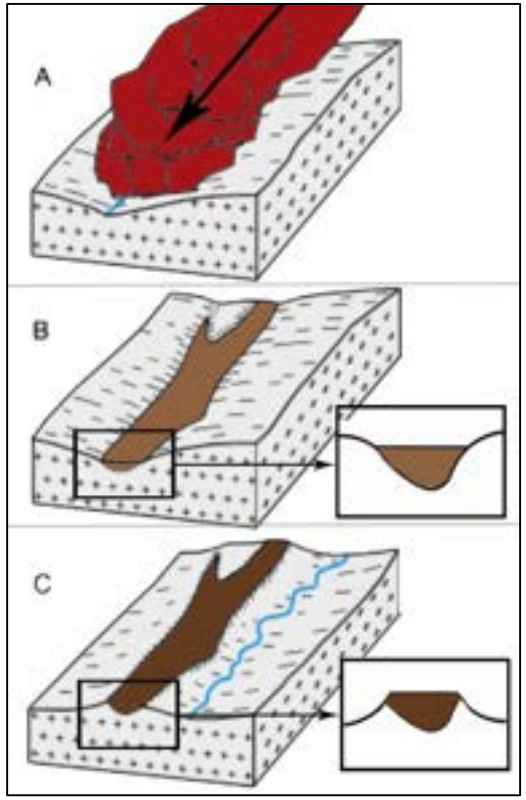
The top of the deposit is generally sub-horizontal, slightly inclined eastward and it is widely reshaped by the anthropic activity related to the urban settlement evolution; the base of the deposit is instead strictly dependent on the paleomorphology (top of the stratified pyroclastic deposits) that has conditioned the thickness of the deposit. In fact, the thickness is between about 3 meters (western sector, where the access door to Civita is) and about 24-25 meters (eastern sector; Napoleoni, 1991). At the base of the lithoid deposit there seem to be at least two other thin pyroclastic flow units (in Orvieto other facies than the lithoid one have been recognized and investigated: Nappi et al., 1982; Rotonda et al., 2002; Tommasi et al., 2013; Verrucci et al., 2015; Comodi et al., 2012).

Variable thickness of the ignimbrite at the top of the relief.

**PYROCLASTIC FLOW*

Very dense and often hot suspension (commonly between 100-200° and 600-700°C), made up by heterometric volcanic particles (often mostly ash) and gases that, following a particular eruption, rapidly descends along the flanks of a volcano at high-speed.

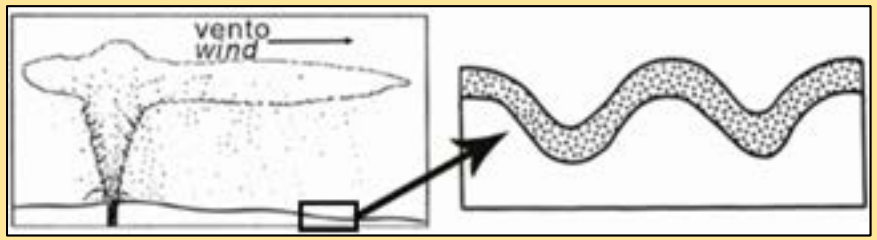
Pyroclastic flow races down the flanks of Mount Merapi, Indonesia, in 2006.
https://education.nationalgeographic.org/resource/hazards-pyroclastic-flows/



The pyroclastic flow moves quickly, along the flank of the volcano, tending to channel into the valleys.
Generally the warmer the flow, the more it will become lithoid (zeolitization process).
Over time erosion dismantles the more erodible surrounding deposits leading to the "relief inversion": so after more than 300 thousand years the morphologically depressed area where ignimbrite was deposited has became the Civita cliff.

"Relief inversion" made by an ignimbrite. From Peccerillo (2005), modified.

Underlying the ignimbrite there is a thick and highly stratified pyroclastic succession (“Gruppo di Civita di Bagnoregio” in Nappi et al., 2022) composed of mainly decimetric alternating layers of tephra and tufa: scoriae, pumices, lapilli, from fine to coarse variously compact ashes, and probably some re-worked horizons (Paleovulsini and Bolsena-Orvieto volcanic complexes). These deposits appear to have mainly an air-fall origin.



How air-fall piroclastic deposits form.

Some layers are separated by paleosols and erosive surfaces; others have loading deformations. Age ranges from 589±8 ka (Barberi et al., 1994) / 576±6 ka (Nappi et al., 1995) to 352±4 ka ("Ponticello" marker eruption; Nappi et al., 1995). In the lower part of the stratified pyroclastic succession, two successive paleosols constitutes a single brown layer of thickness greater than 2 meters (Di Buduo et al., 2024) and are interposed between the oldest banks of Paleovulsini pumices and the pyroclastic flow deposits known as "nenfri" (505±6 ka, Nappi et al., 1995).

Highly stratified pyroclastic succession in the western (above) and in the eastern (below) part of Civita.

In the western sector of the cliff the layers have an eastward dip with gradually decreasing inclination eastward from a maximum of about 25°-30° (bridge abutment, anti-dip slope) to become sub-horizontal in the central sector. In the eastern sector of the cliff, the lower part of the stratified pyroclastic succession has a light westward dip. This is consistent with the geological section of Cercato et al., 2020, and with the maximum thickness that such succession should reach just east of the tunnel (at least 50 meters) as found in the S3 borehole in Napoleoni, 1991. The thinner thickness (about 35 meters) is at the west end of Civita.

South-eastern side of Civita cliff.

South-western side of Civita cliff, from left (west) to right (east): variation in the inclination of the stratified pyroclastic deposits and in the thickness of the overlaying ignimbrite.

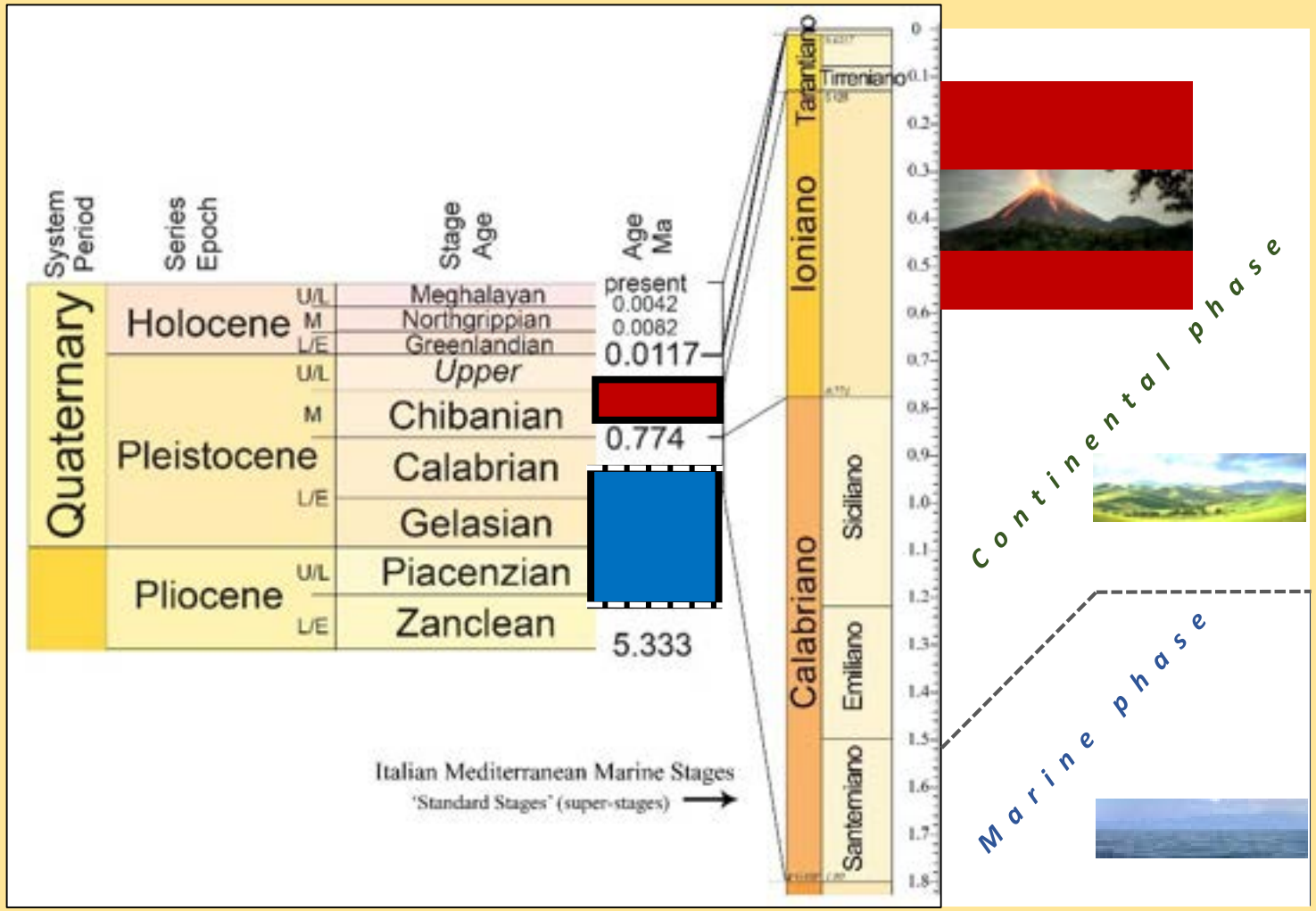
The volcanic deposits overlay silty clays and clayey silts of marine origin (lower Pleistocene), grey to light bluish colored, predominantly massive, locally poorly bedded and with intercalations of turbidite sands: these deposits are referred to the "Chiani-Tevere formation" (Chiani-Farfa Synthem), "sandy clays of marine environment" unit in Mancini et al., 2003-2004 and "Castello Ramici member" in Nappi et al., 2022. The Chiani-Farfa Synthem is representative of a sedimentary cycle between the Gelasian and the basal Emilian.

Studies in the left of the Paglia River valley (about 10 km NNE of Civita), in a paleogeographic context of proximity to the coasts, report for the stratigraphically higher clays a younger age (Emilian - early Sicilian) (Baldanza et al., 2011); at the present state of knowledge it is not possible to attribute this difference to lack of deposition or to erosion following emersion, or to both such factors.

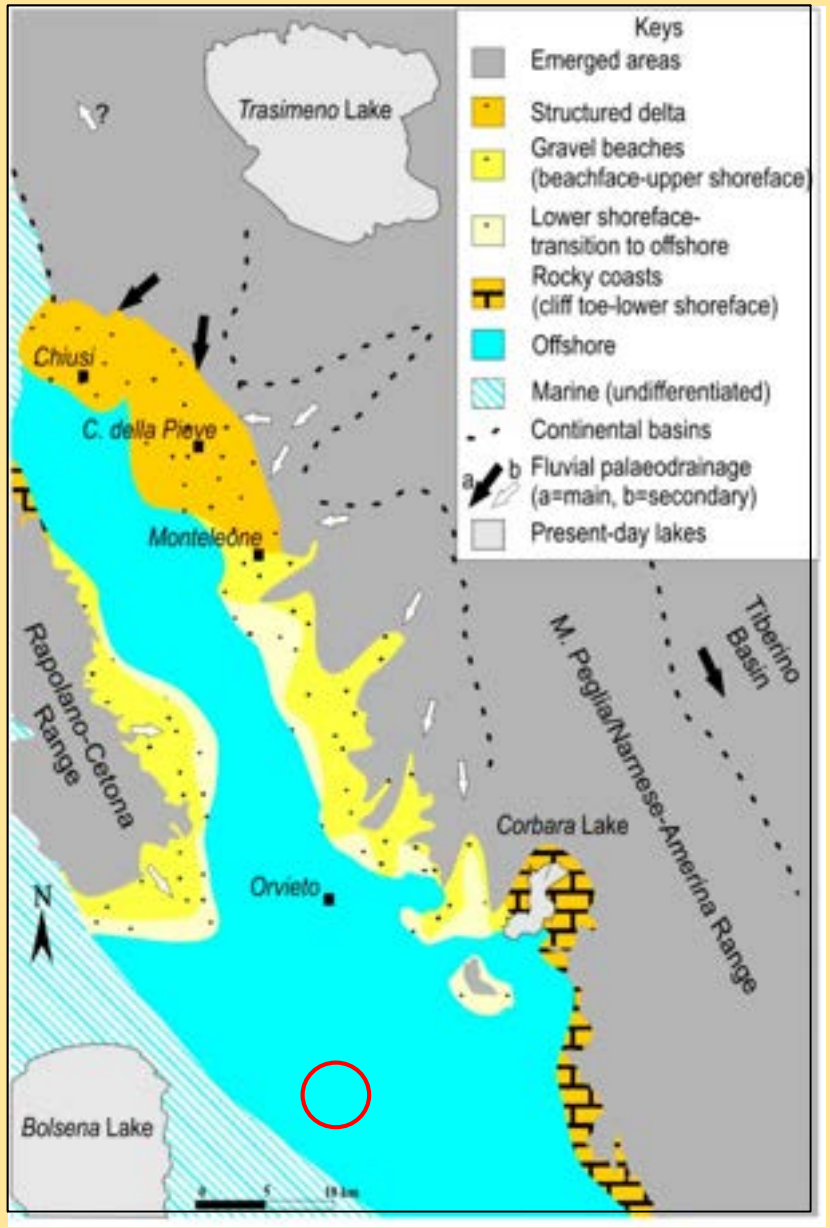
Deposits of marine origin in the Civita di Bagnoregio area have a maximum thickness in outcrop slightly lower than 200 meters, having a Santernian age and being referable to a depositional environment between the circalittoral and the transition to the infralittoral (Di Bella, 1995; Di Bella et al., 2000-2002; Frezza et al., 2005).

The structural context is that of the Paglia-Tiber Graben, a large extensional basin oriented approximately NNO-SSE, which developed from the Pliocene, in partial contiguity to the intrappenine basins of Rieti and Tiberino, the Roman basin to the south and the Val di Chiana and Radicofani basins to the north (Brandi et al., 1970; Baldi et al., 1974; Locardi et al., 1977; Conti et al., 1980; Funiciello et al., 1981; Sollevanti, 1983; Consiglio Nazionale delle Ricerche, 1987; Buonasorte et al., 1987; Barberi et al., 1994; Mancini et al., 2003-2004).

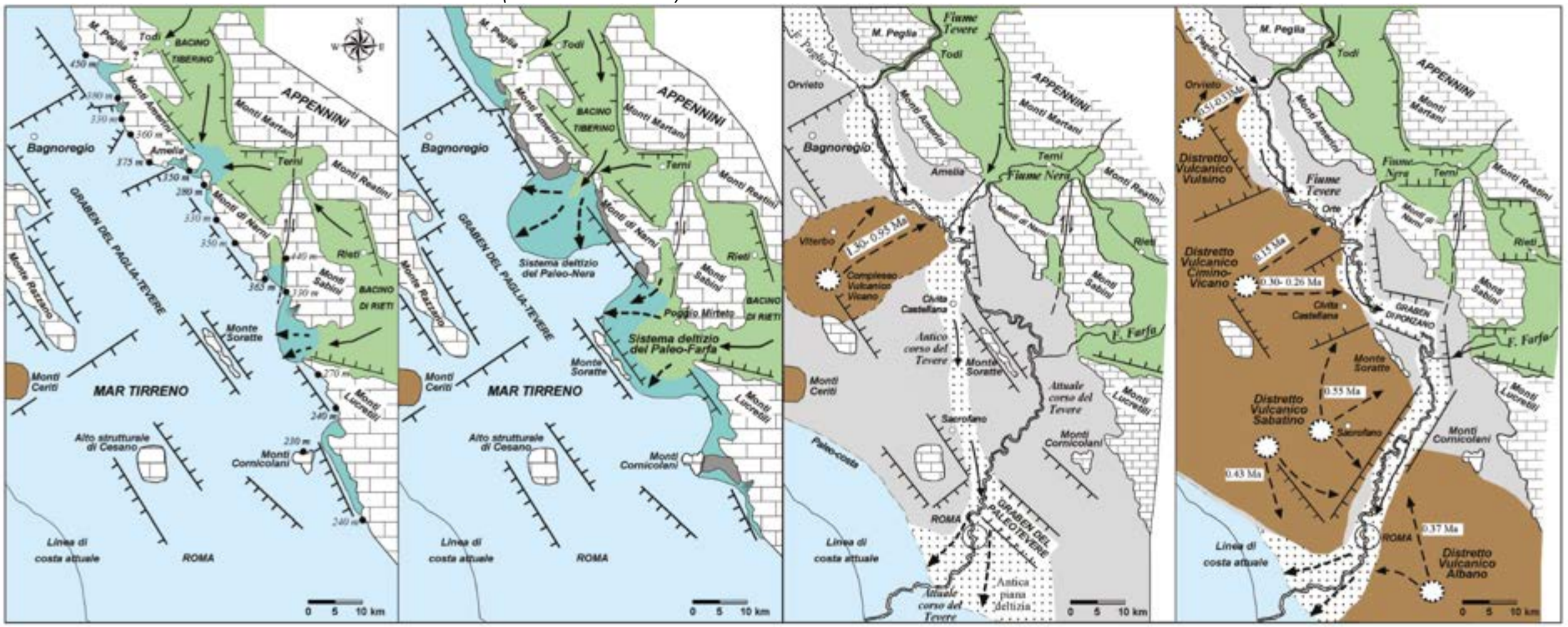
The stratigraphic, sedimentological and paleontological characteristics of the marine deposits of the Paglia-Tevere Graben have been extensively studied over time (non-exhaustive list: Bertini et al., 1971; Ambrosetti et al., 1987; Buonasorte et al., 1991; Carboni & Di Bella, 1996; Carboni & Palagi, 1998; Borzi et al., 1998; Mancini et al., 2003-2004; Bizzarri & Baldanza, 2020; all references within).



Geological time scale from Pliocene
(IUGS, International Union of Geological Sciences –
ICS, International Commission on Stratigraphy, 2022).
Ma: millions years.



Paleogeographic and paleoenvironmental reconstruction
during the early Pleistocene (Bizzarri & Baldanza, 2020).
Red circle: Civita di Bagnoregio area.



- Volcanic deposits
- Travertines
- Coastal and deltaic deposits
- Alluvial deposits
- Emerged marine deposits
- Meso-Cenozoic rocks
- Main dated pyroclastic and lava flows
- Volcanic center
- Paleostream directions
- Delta
- Delta progradation
- Alignment of lithophage organisms holes and their altitude
- Normal fault
- Transient fault

Paleogeographic evolution.
From Mancini et al., (2003-2004), modified.

2. INSTABILITY PROCESSES & LANDSLIDES

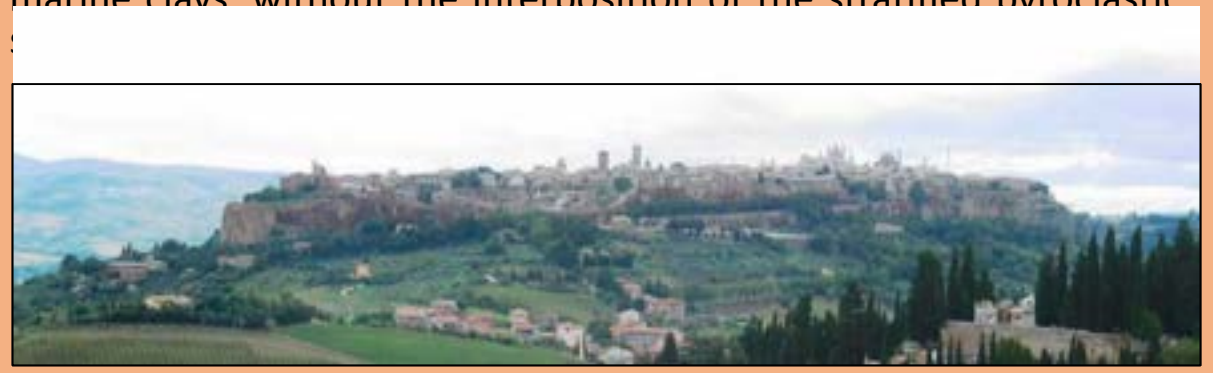
After the raising of the area with the consequent emersion of the marine deposits and the westward retreat of the sea, great climatic variations characterized the middle and upper Pleistocene; they intensely conditioned the geomorphological dynamics, with the alternation of erosion and alluvial phases that were chronologically and physically interposed to the volcanic and tectonic activities.

The rapid evolution of the slopes in the "valle dei calanchi", which is expressed by complex interacting phenomena, is in fact attributable to:

- ✓ the features of the geological deposits (which also influence the hydrogeological setting),
- ✓ the uplift and tectonic displacement of large areas that occurred particularly from about 330 ka (Marra et al., 2019),
- ✓ the intense deepening of the valleys that occurred during the last glacial period (last glacial maximum around 26-19ka; Clark, et al., 2009) ,
- ✓ the probable presence in this area of tectonic discontinuities of undefined kinematics with various orientations.

Since the end of 1980s, the area of Civita has been investigated in order to study the town evolution, to characterize geological deposits, to define the slope instability phenomena and geological hazards, and to carry out interventions to stabilize the riskiest areas (Lattanzi & Polci, 1988; Margottini & Serafini, 1990; Napoleoni, 1991; Iacurto & Priori 1995; Sciotti et al., 1997; ENEA, 2001; Delmonaco et al., 2004, 2008, 2009; Garbin et al, 2013; Margottini et al, 2017; Cercato et al, 2020; Donati et al., 2022; Scarascia Mugnozza et al., 2022).

Also, the literature on the Orvieto town is interesting for the Civita area, regarding geotechnical features and slope instabilities studies (Broili et al., 1978; Lunardi & Fornaro 1980; Manfredini et al., 1980; Lembo-Fazio et al., 1982, 1984; Cestelli Guidi et al., 1983; Cecere & Lembo Fazio 1986; Curli & Martini 1986; Conversini et al., 1995; Rotonda et al, 2002; Costanzo et al., 2004; Cafaro et al., 2005; Tommasi et al, 1996, 2005, 2006, 2010, 2013a, 2013b; Tommasi & Ribacchi 1998; Barbero et al. 2004; Bozzano et al., 2008; Verrucci et al, 2015) and monitoring and stabilization works (Lunardi & Fornaro, 1980; Cestelli Guidi et al., 1983; Curli & Martini, 1986; Tommasi et al., 1986; Soccodato et al., 2011, 2019). In the Orvieto relief, the Orvieto-Bagnoregio ignimbrite overlaying directly on the marine clays, without the interposition of the stratified pyroclastic



Orvieto (Bozzano et al., 2008).

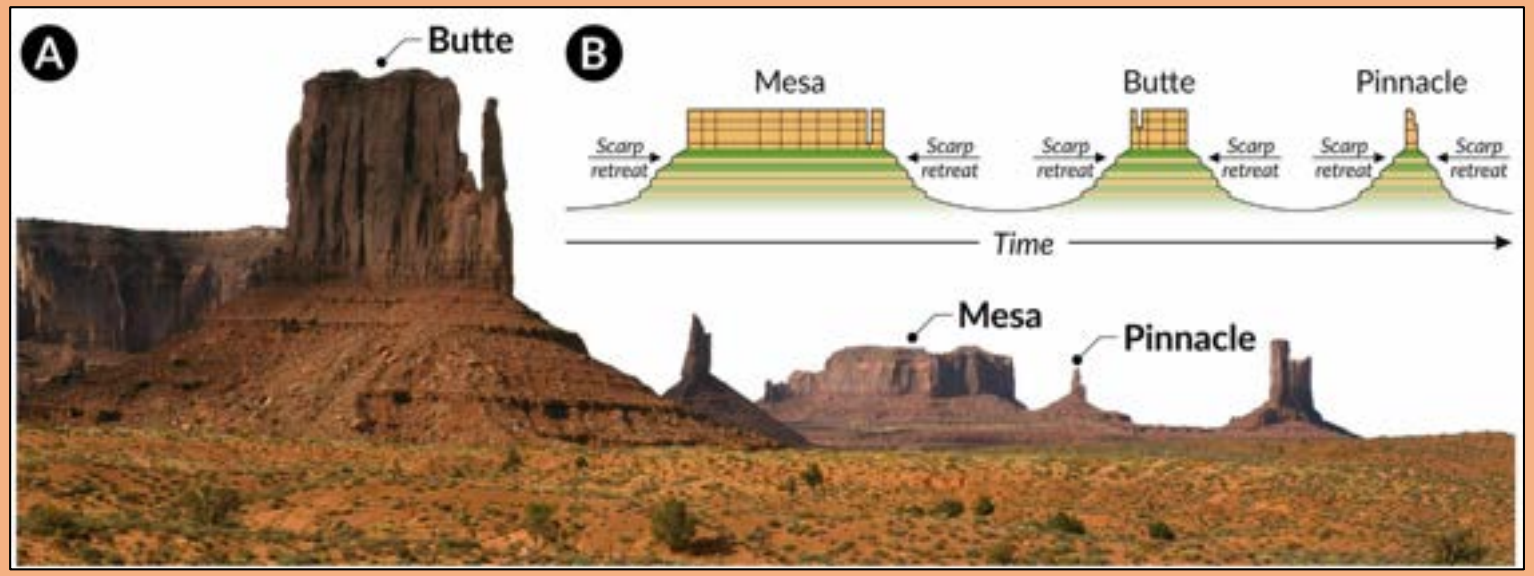
The geological setting of Civita di Bagnoregio consists of a stiff rock mass of volcanic origin, overlying a more deformable and erodible clay-silt mass of marine origin.

The action of gravity and rainfalls in a particular geomorphological setting (a “mesa”) results in the occurrence of complex instability phenomena, which over time have shaped the peculiar appearance of the cliff leading to its progressive narrowing.

A “mesa” is a flat-topped relief bounded by escarpments and steep slopes, generically with a width greater than the height.

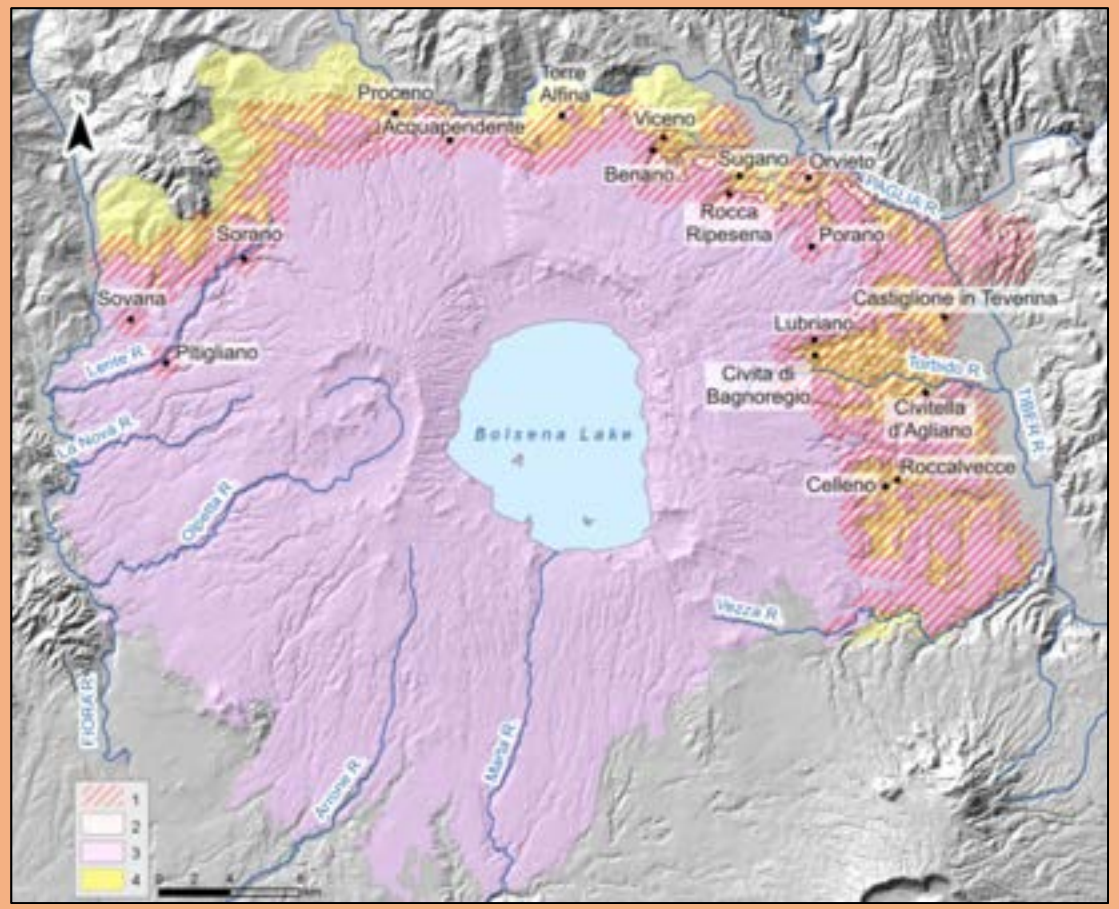
Along the north and east margins of the Vulsini Volcanic District, erosion has partially or totally isolated small reliefs on which man has settled even since the Bronze Age, witnessing a deep and constant connection between landforms (and their conservations over time) and human settlement, such as to lead to the use of “anthropogenic mesas” term (Margottini et al, 2017).

These small reliefs are in Tuscany, Umbria and Lazio, and many urban centers on them are known as the “tuff towns”, e.g. Pitigliano, Sovana, Sorano, Orvieto, Bagnoregio, etc.

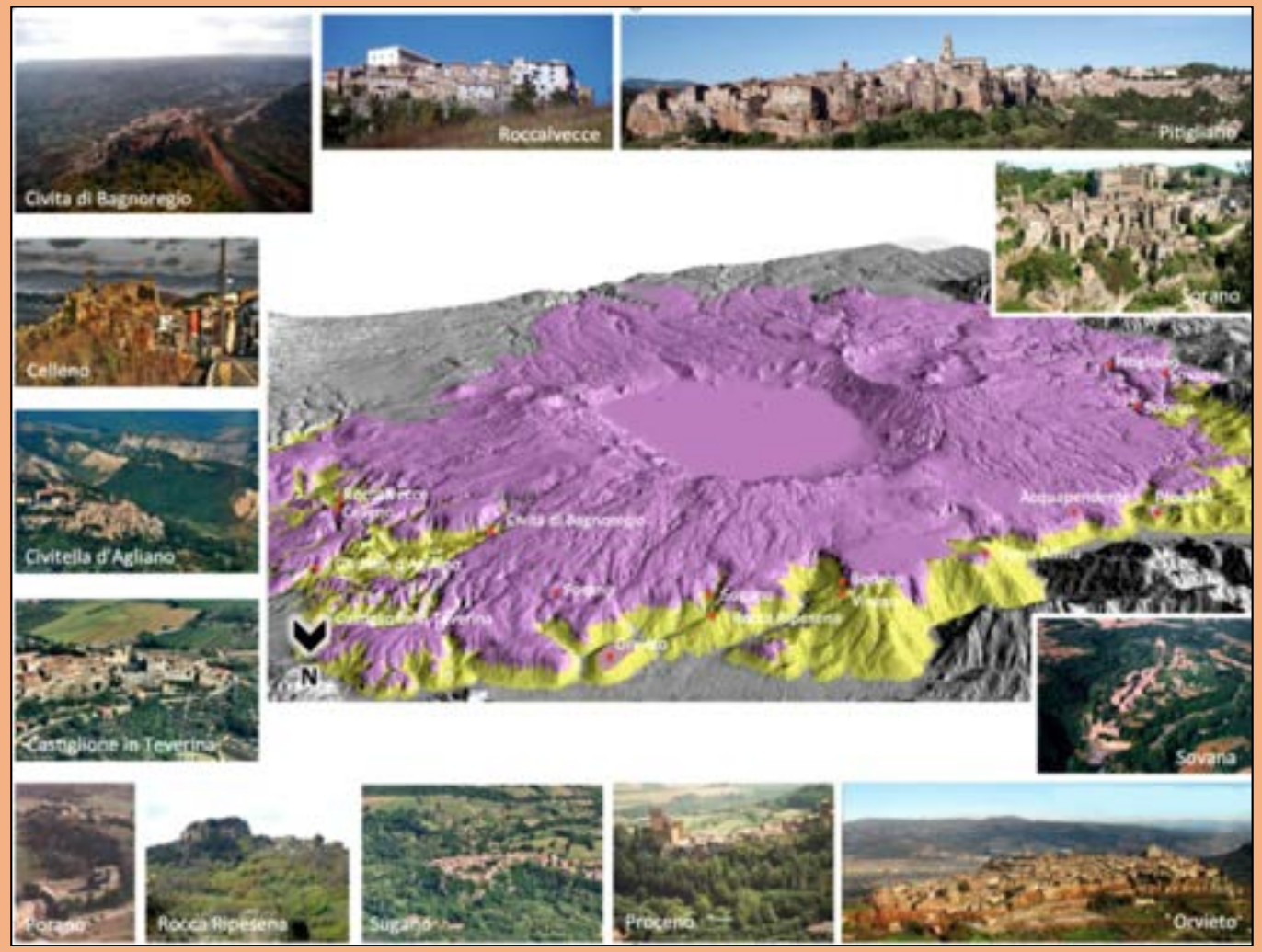


Evolution of residual hills in tablelands as usually presented. The background photo shows the classic locality of Monument Valley, USA (Migoń et al., 2020).

The Civita di Bagnoregio mesa.



Location map of "tuff towns" and geological sketch of the Vulsini area. 1 Geographical distribution of flat top areas, steep slopes and carved river valleys; 2 debris and colluvial deposits; 3 volcanic caprock; 4 marine clays (Margottini et al., 2017).



The Vulsini area on a 3D model with the most representative human settlements (view from north to south).
Purple: volcanic caprock ; yellow: marine clays.
(Margottini et al., 2017).

The marine clay-silt deposits underlying the volcanites are subject to an intense slope dynamic, although they are under a certain depth in overconsolidation conditions due to stress unloading following emergence and erosion (a reduction in thickness of about 150 meters has been estimated at Orvieto: Bozzano et al., 2008).

Along the surface these deposits are subject to swelling, resulting in alteration of the microstructure and degradation of the mechanical features of deformability and resistance.

From a rheological point of view towards the surface, the over-consolidated pelitic deposits (stiff clays) tend to acquire the behavior of normal consolidated deposits (softened clays) (Napoleoni, 1991; Delmonaco et al., 2004; Garbin et al., 2013; references within), with a situation similar to Orvieto, in which the layer of softened clays is thought to play a crucial role in the gravitational evolution of the cliff (Bozzano et al., 2008 and references within).

Marine silty clays.

Mudflows as a consequence of softening, and of the action of gravity and surface runoff.

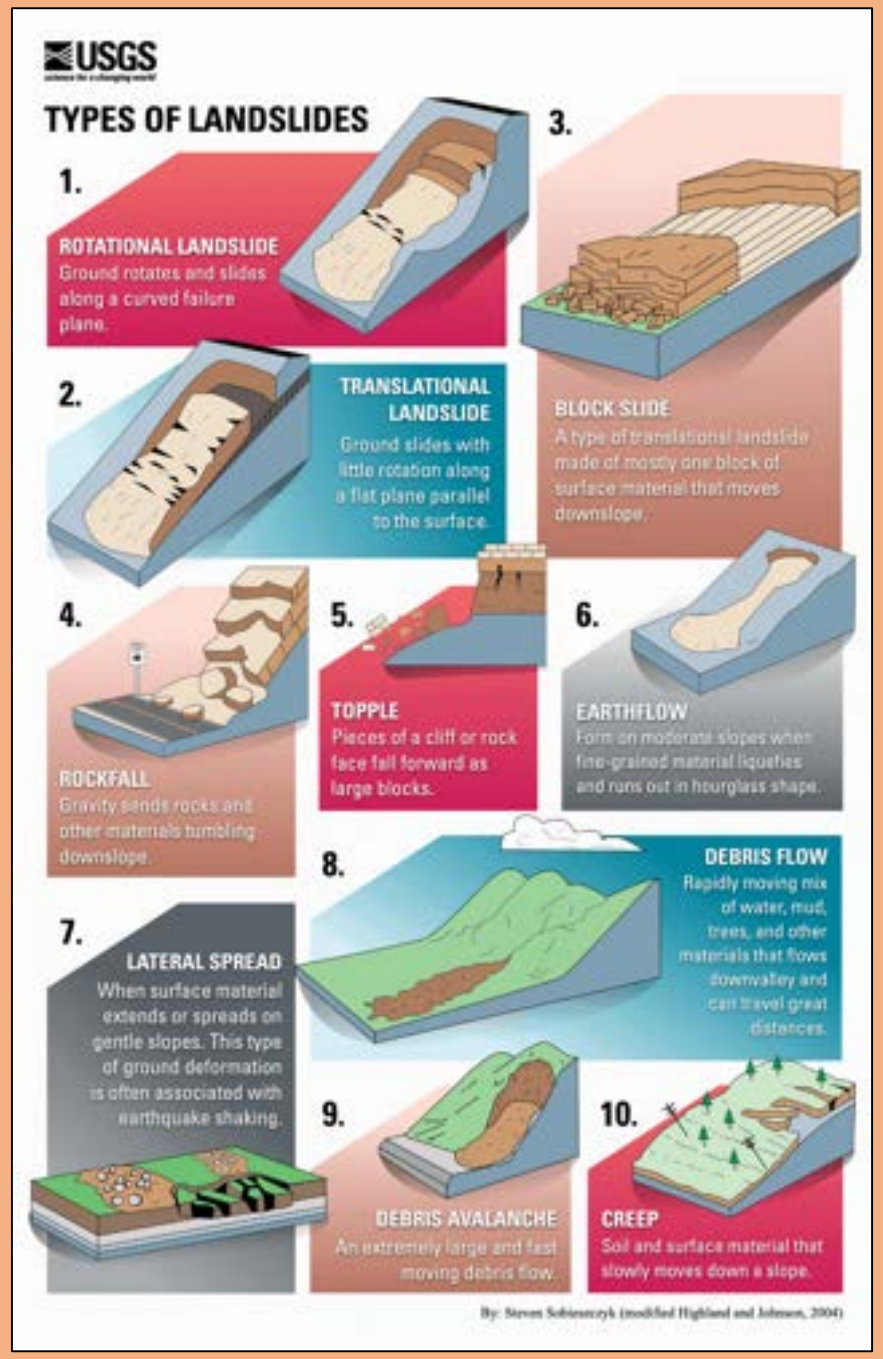
Fractures due to swelling in the marine silty clays, during the works on the northern slope of the bridge area in 1989 (by courtesy of Prof. Quintilio Napoleoni, Sapienza Università di Roma).

So the types of landslides occurring in the Civita area are the follows.

Rock falls, topples and detachment of rock fragments along the non-stabilized sectors of the cliff's edge.

On the clayey slopes:

- solifluction and soil creep;
- mudflows (very common and characterized by small thickness, frequent repetition and evolution in widening and retrogradation);
- debris avalanches, translational slides (less common);
- rotational slides of larger and deeper portions of the slope (infrequent);
- complex landslides, in which at least two types of movements occur in sequence (Varnes, 1978; Cruden & Varnes, 1996; Hungr et al., 2014; Cruden & Lan, 2015) (e.g. a rock fall that evolves in a debris avalanche) (less common);
- composite landslides that can be simultaneously classified in more than one category of kinematics, i.e. different types of movement occur in different areas of the displaced mass (Cruden & Varnes, 1996; Cruden & Lan, 2015) (e.g. a rotational-translational landslide) (less common).

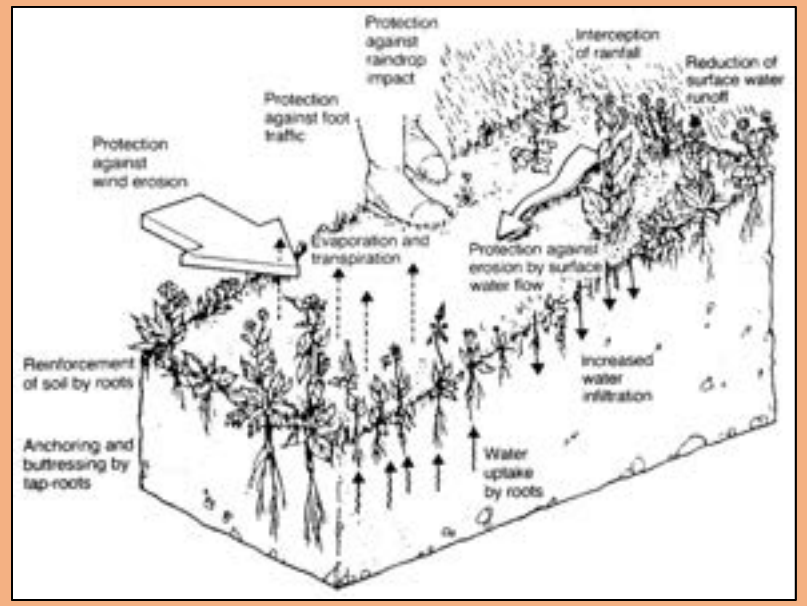


Types of Landslides, USGS, 2023
https://www.usgs.gov/media/images/types-landslides

On the clayey slopes spontaneous vegetation offers a good protection against surface erosion, making the surface part of clay-loam deposits less unstable. The type of vegetation varies mainly according to the slope inclination and secondly to its exposure: in the lower part of the slopes, where the inclination is less, trees are frequent, whereas in the upper part, with higher inclination, low-trunk vegetation (e.g. broom) and grass predominate.

When vegetation and soil are removed (naturally or artificially), the pelitic deposits are exposed to weathering and the softening and swelling processes go deeper, with a consequent decrease in shear strength.

For this reason, the first important step in preventing erosion on the clayey part of the slopes is to preserve soil integrity and vegetation cover.



Role of vegetation (from: Use of Vegetation in Civil Engineering ISBN: 9780860177111) http://observatoriaigua.uib.es/repositori/suds_ciria_5.pdf

Southern slope of the Civita bridge area.

The tuffaceous plate is affected by two types of stress, which together contribute to its morphological evolution over time, as occurs in other similar situations (Agnesi et al., 1978; Cecere & Lembo Fazio 1986; Canuti et al., 1990; Sciarra & Calista, 2001; Bozzano et al. 2005, 2013 and references within):

- ❖ stress release, that is lateral stress induced by erosion that leads to the progressive cutting of the scarps;
- ❖ stress relief, acting on the entire rock mass, induced by the deformation of the underlying silty clays deposits, more deformable (elasto-plastic behaviour) than the stiff volcanites.

So, the deformation of the marine silty clays amplifies the disarticulation of the overlying tuffaceous rock mass, that takes place gradually with the progressive opening of extensional fractures variously oriented.

The follow factors also act negatively, resulting in the widening and propagation of fractures:

- water infiltration (resulting in the chemical and physical alteration of the discontinuities with the consequent reduction of the shear strength of the mass),
- temperature variations (thermoclastism),
- freeze-thaw cycles (cryoclastism),
- the action of plant roots

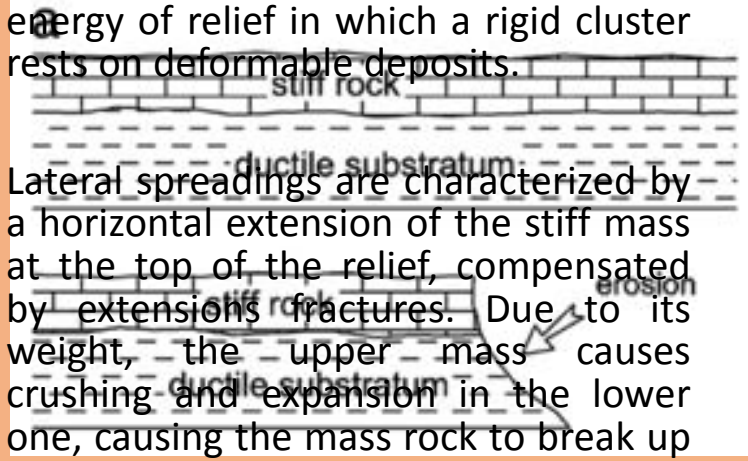
Moreover, the presence of poorly permeable intervals in the stratified pyroclastic deposits may result in the saturation of some sectors of the escarpment in unpredictable extent and time, with more or less local negative effects on stability.

In the Orvieto-Bagnoregio ignimbrite some fractures may have formed just after the deposition of the pyroclastic flow because of cooling contraction.

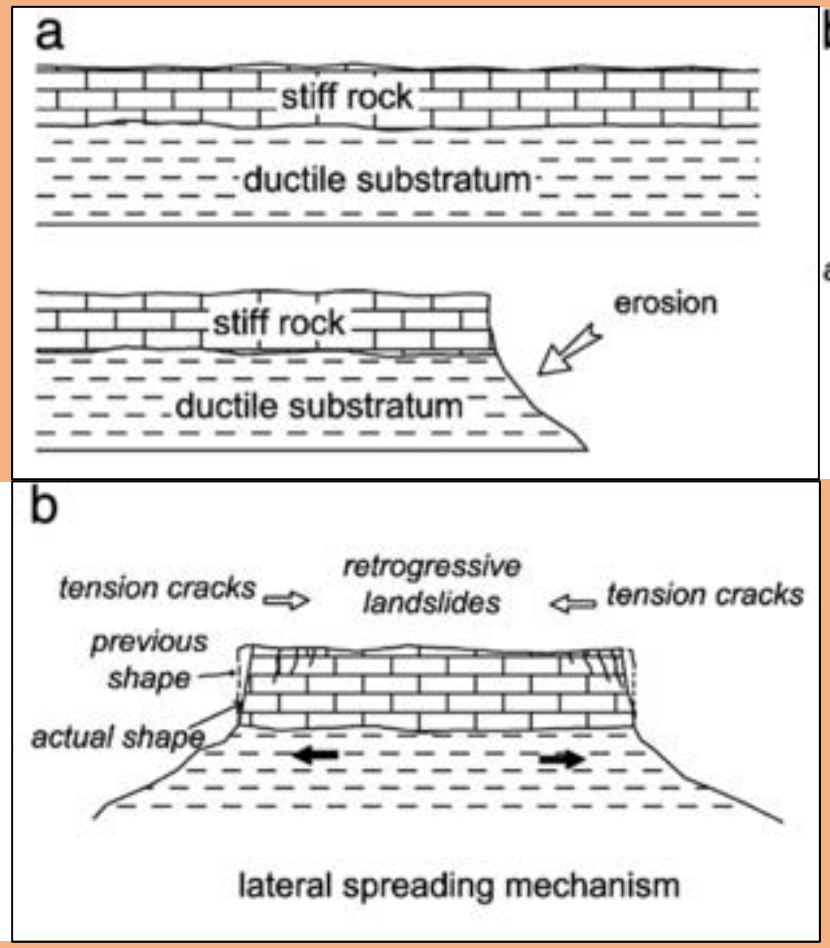
The instability processes in the volcanic mass rock are typically "retrogressive" and therefore, if not adequately mitigated, they can over time involve more internal portions of the cliff.

At the foot of the slopes there is also the erosive action made mainly by the streams in the north of Civita (Cireneo ditch and Lubriano/Rigo/Bagnoregio ditch).

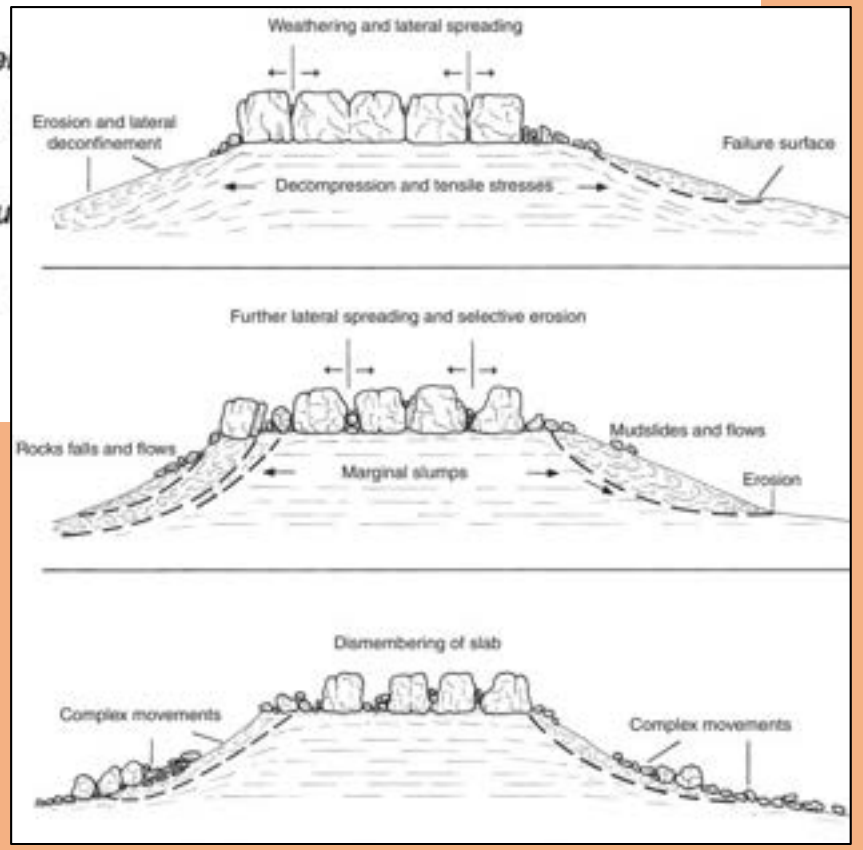
So, the peculiar geological and geomorphological setting, and the presence of persistent and open fractures in the mass rock along the central part of the cliff (visible in the hypogea), lead to hypothesize the possible occurrence of active global deformations of the cliff due to a mechanism of lateral spreading (Cruden & Varnes, 1996), typical of morphological situations with high energy of relief in which a rigid cluster rests on deformable deposits.



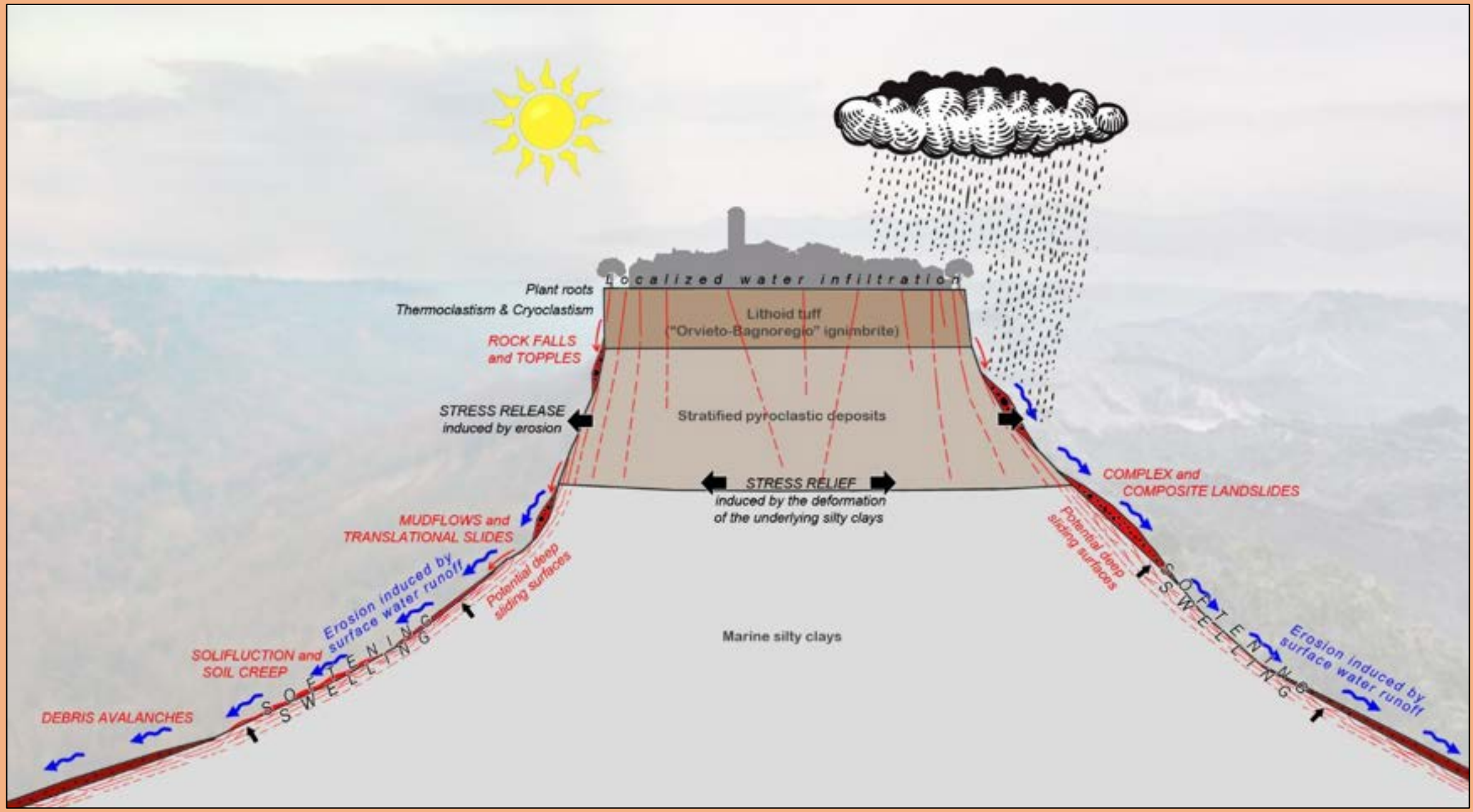
Lateral spreadings are characterized by a horizontal extension of the stiff mass at the top of the relief, compensated by extensions fractures. Due to its weight, the upper mass causes crushing and expansion in the lower one, causing the mass rock to break up into blocks delimited by gradually widening fractures.



a) Conditions necessary for a gravitational induced lateral spreading: lithological overlapping of a stiff lithology on a more ductile one; b) the horizontal deformation of the ductile substratum cause the jointing of external and not confined portion of the stiff lithology (Bozzano et al., 2013).



Evolutionary stages of rock spreading in brittle formations overlying ductile units (Pasuto & Soldati, 2013)



Schematic model of instability phenomena and landslide movements on the Civita di Bagnoregio relief (explanations in the text).

CALANCHI (BADLANDS)

A “calanco” (from “calans” Latin for “dropping” or “downhill”) is an erosive concave landform associated with clayey outcrops. As described by Alexander (1980), calanchi are systems of rills and gullies, connected in thick small drainage networks evolving headwards and separated by sharp and steep ridges (Delmonte, 2017).

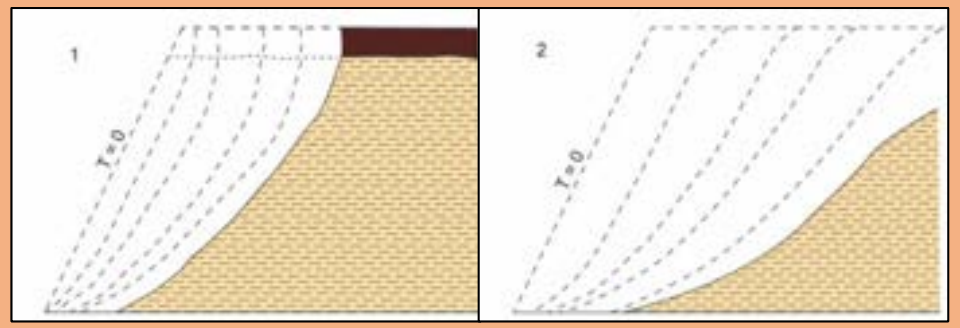
Calanchi morphology is favoured by the presence of a volcanic or sedimentary (sand and/or conglomerate) caprock (Scheidegger, 1961). Noticeable slope steepness favors diffuse mudflows, which strongly contribute to the removal of considerable volumes of sediment (Della Seta et al., 2009).

A copious international literature on the badlands has been produced over time. Several authors have investigated the main developing factors for the Italian calanchi (e.g. references within Moretti & Rodolfi, 2000). In the area of Civita di Bagnoregio geochemical and geomorphological inquiries have shown that the river drainage network of Rio Torbido is strongly influenced by regional neotectonic features, and the aspect of the basin areas have structural conditioning (Di Filippo et al., 1999; Ciotoli et al., 2003; Delmonte et al., 2013).

So, in short, the most significant factors for badlands in the area of Civita, besides physical, chemical and mineralogical properties of the marine clays, seem to be:

- strong river streams deepening in consequence of sea-level lowstands (i.e. during the last glacial maximum; Clark et al., 2009; Hanebuth et al., 2009) and volcano-tectonic uplift (Marra et al., 2019 and references within);
- the presence of a caprock inducing slopes steepness (Scheidegger, 1961); the caprock could have been thinner than in the surrounding volcanic plateaus, as occurred in the areas of “Pianale” and “Guadaiona” – “S. Antonio” along the watershed between Rio Torbido river (south) and Bagnoregio ditch (north);
- neotectonic lineaments (Barberi et al. 1994; Di Filippo et al., 1999; Ciotoli et al., 2003; Delmonte et al., 2013; Marra et al., 2019);
- south-facing slopes, where higher insolation restrains vegetation growth (Della Seta et al., 2009; Delmonte, 2017).

Greater calanchi development on south-facing slopes (to the left).



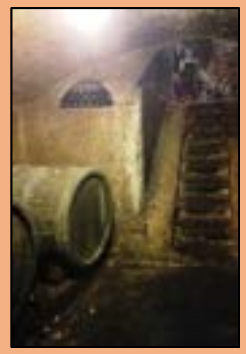
Scheidegger’s slope evolution starting from T = 0 (initial time): 1 clayey slope with caprock (Civita geological setting); 2 clayey slope without caprock (Delmonte, 2017).

HYPOGEA

The “Orvieto-Bagnoregio ignimbrite” besides being a good building material, is not so difficult to excavate to make stable underground cavities if dug with appropriate shape and size. Over time, hypogea of various shapes, sizes and functions have been made in Civita di Bagnoregio, to meet the needs of the community settled on the top of the cliff: canals and cisterns to collect rainwater, cellars for storing food, shelters for animals, cave dwellings, production sites for wheat, oil and wine, “butti” for garbage, and burial sites. The upper part of the Civita relief is therefore characterized by an extensive and complex network of hypogea on several levels, also expanded and/or modified over time, witnessing more than two thousand years of underground use of the tuff (Di Buduo et al., 2017).

Today most of the underground cavities belong to private homes, but some of them can be visited and are used for various purposes (restaurants, wine storage, exhibition purposes, worship, etc.). In the last decade many of these hypogea has been visited, allowing the writer to assess their good stability even where there are persistent discontinuities running through their entire section: instability phenomena have been found only where the underground cavities are near the escarpment, with a more intense state of fracturing that can predispose the detachment of rock prisms with heterogeneous volumes. In the nearby town of Orvieto, hypogea in the “Orvieto-Bagnoregio ignimbrite” have been studied, monitored and stabilized for years (Martini et al., 2018).

Hypogea of various sizes, at different heights in the fractured ignimbrite on the south-east side of Civita



3. GEOMORPHOLOGICAL SURVEY

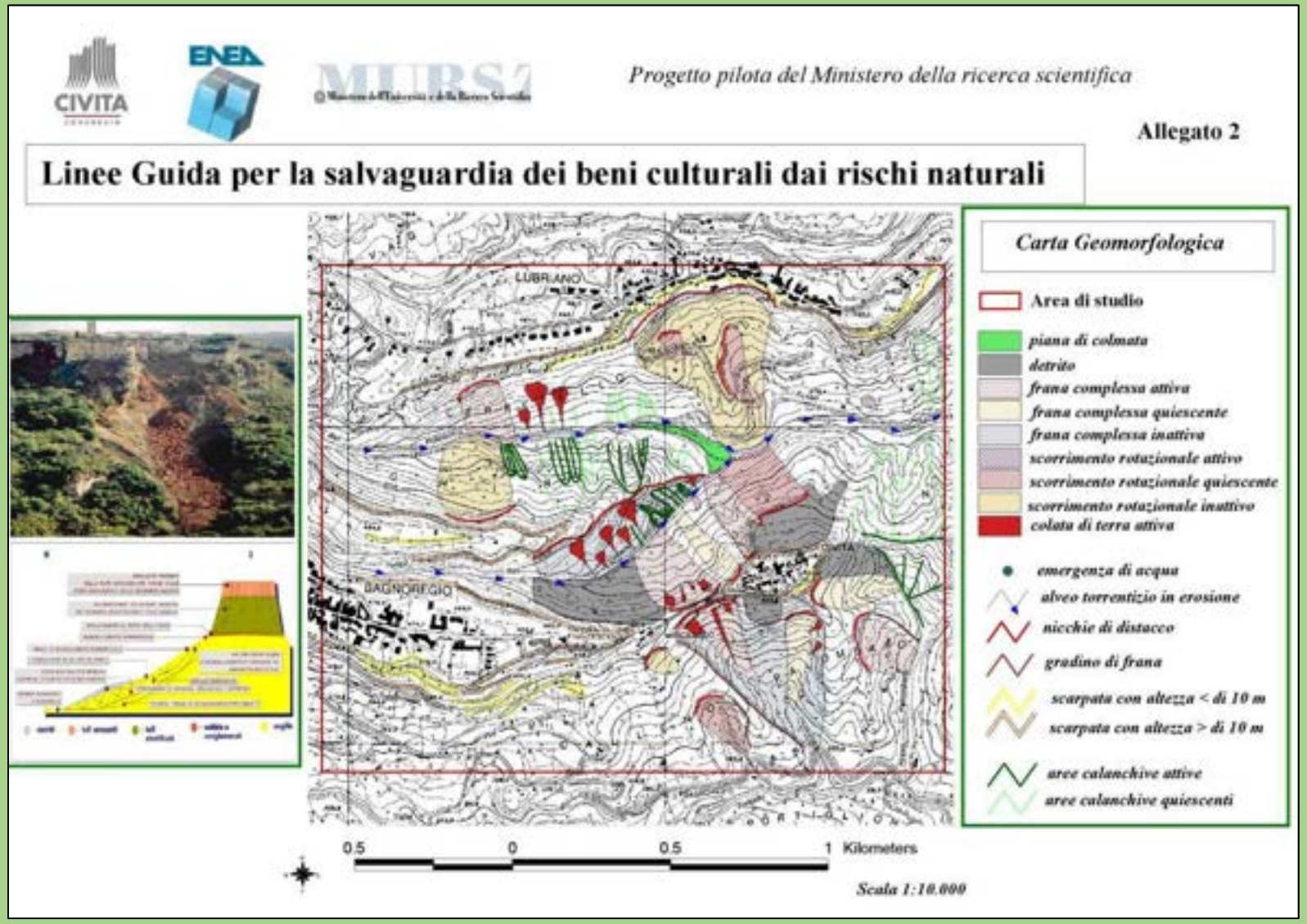
The geomorphological survey conducted between March and May 2024 has allowed me to identify the main and evident forms of the topographic surface. The analysis of the different sectors of Civita slopes has been also conducted with the abundant documentation collected between 2012 and 2022 as Conservator and Curator of the Geological and Landslides Museum in Civita: this has allowed me to verify the evolution of some phenomena over time.

The study also benefited from the analysis of drone footage made on 16 and 17 February by the dronists team of the Red Cross - Bagnoregio Local Committee, thanks to the Memo of Understanding (Protocollo d'Intesa) between The Civita Institute and the Municipality of Bagnoregio.

The following are:

- the excerpts of the available geomorphological maps of the Civita area;
- a description of the geomorphological characteristics and evolution in recent years of the various sectors of the Civita area.

The following are the excerpts of the available geomorphological maps of Civita.



ENEA, 2001.

I.F.F.I. PROJECT

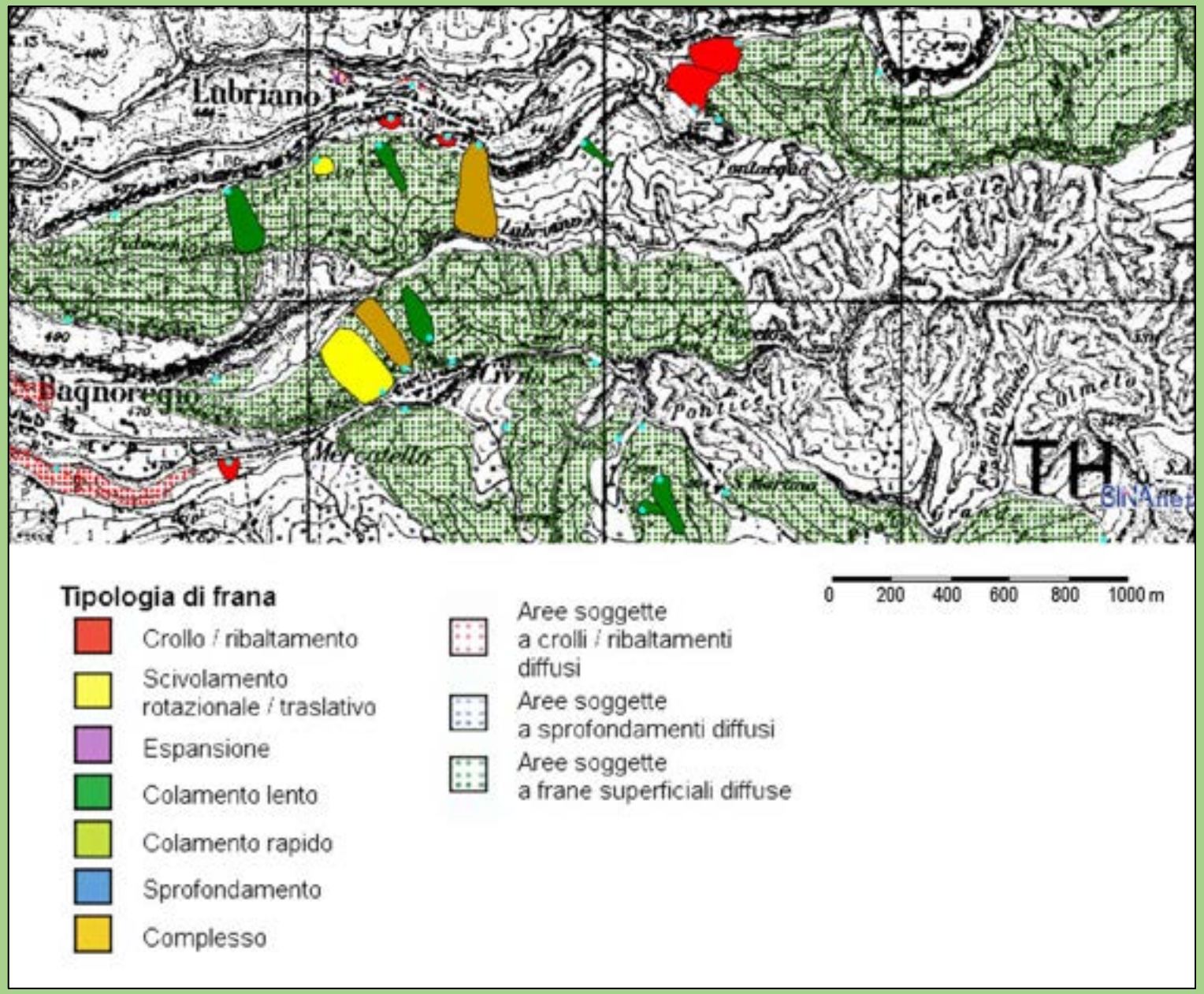
The I.F.F.I. project (Inventario dei Fenomeni Franosi in Italia - Inventory of Landslides Phenomena in Italy), carried out by ISPRA and the Autonomous Regions and Provinces, provides a information of the landslides distribution on Italian territory.

The inventory has recorded over 620,000 landslides on national territory.

The inventory is a basic knowledge tool for assessing the risk of landslides in Hydrogeological Setting Plans (P.A.I. - Piani di Assetto Idrogeologico) of the various Bacino Authorities (Autorità di Bacino), for the planning and preliminary design of interventions to protect the slopes and infrastructure networks and finally for the drafting of Emergency Plans for Civil Protection.

https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/suolo-e-territorio-1/iffi-inventario-dei-fenomeni-franosi-in-italia

Online mapping



P.A.I.
PIANI DI ASSETTO IDROGEOLOGICO
(Hydrogeological Setting Plans)

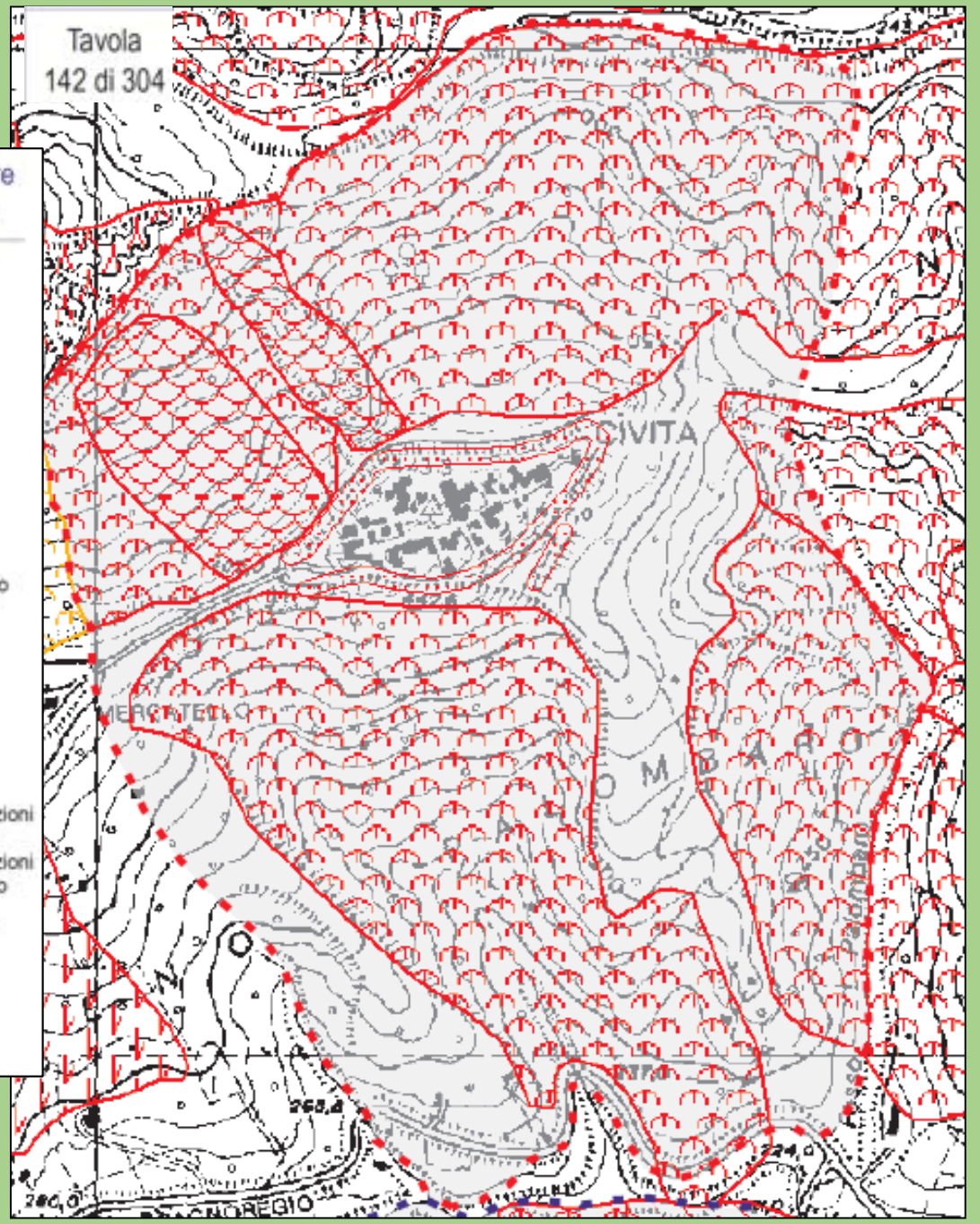
The area of Civita di Bagnoregio is under the competence of the District Basin Authority of the Central Apennines (Autorità di Bacino Distrettuale dell'Appennino Centrale).

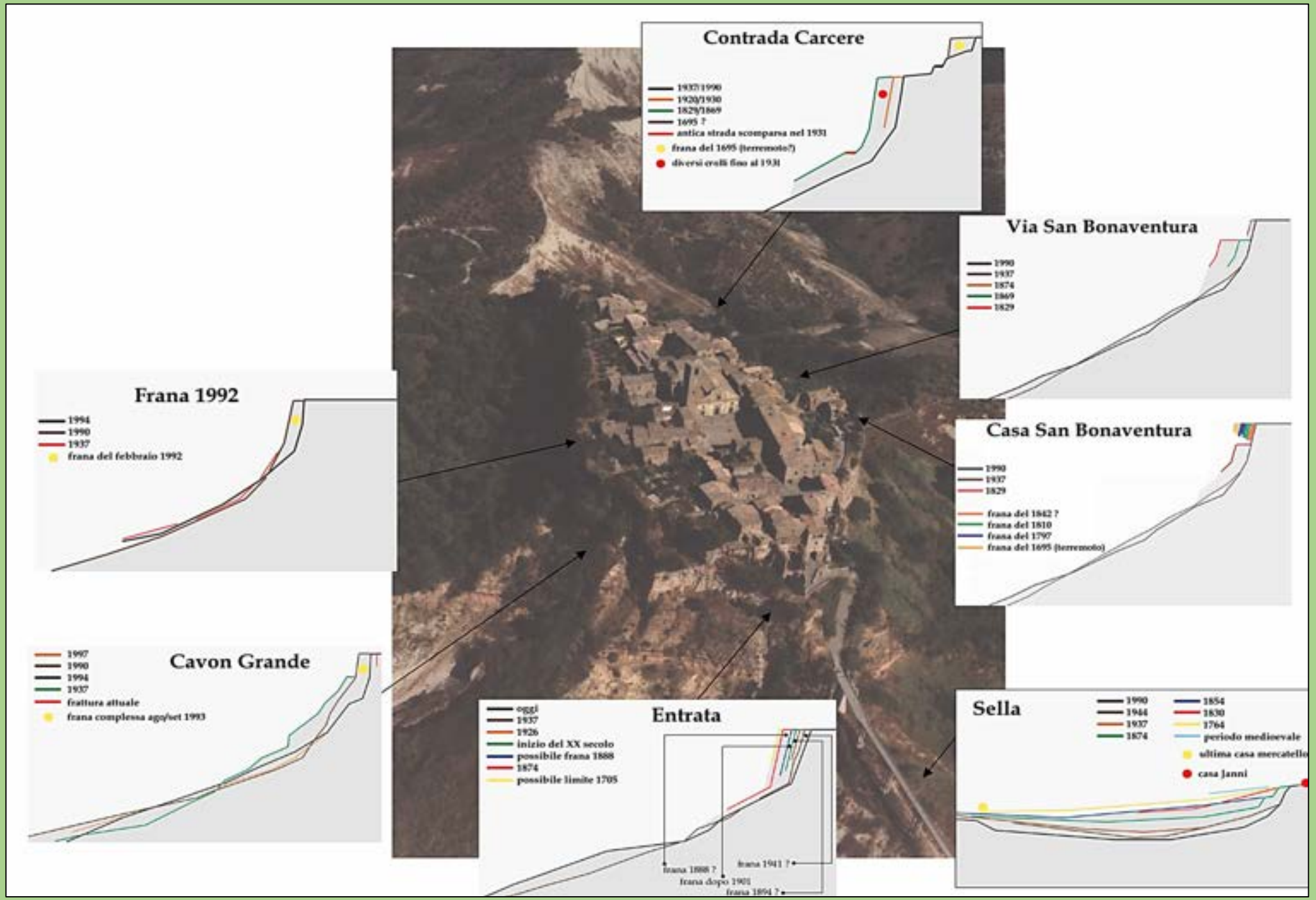
The available maps were drawn up by the former Tiber River Basin Authority (Autorità di Bacino del Fiume Tevere).

The Basin Authorities are responsible for planning and programming the unitary governance of the river basins through the Basin Plan tool.

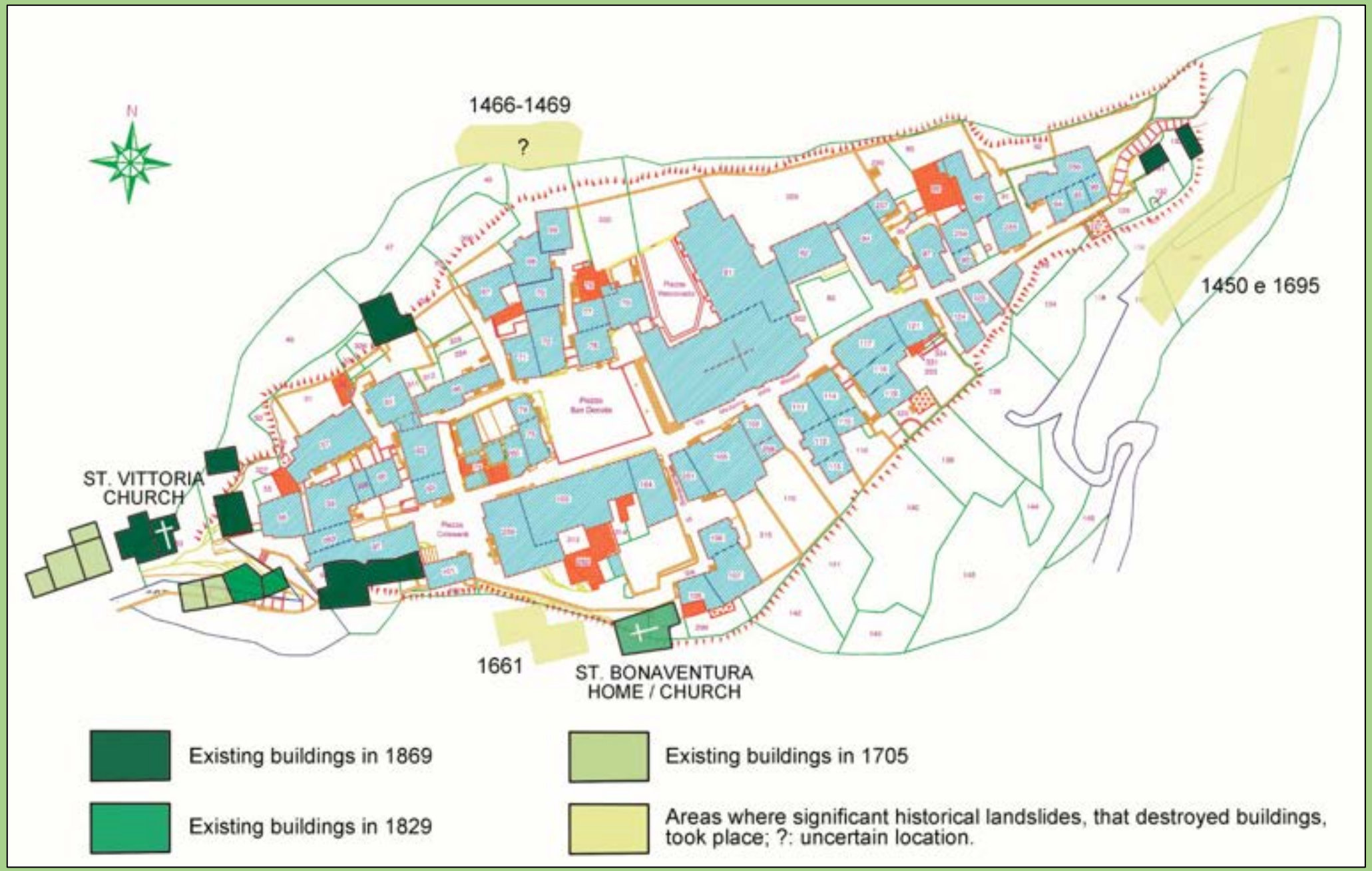
The Basin Plan is the knowledge, regulatory and technical-operational tool by which actions and use rules are planned and programmed for the conservation, defense and development of soil and the correct use of water (L. 183/1989).

The Basin Plan can be divided into plans for sub-basins or sub-plans (piani stralcio) for functional areas, such as hydrogeological setting.





Morphological evolution of Civita cliff over time (Margottini, 2017).



Evolution of Civita perimeter over time (Lattanzi & Polci, 1988: redrawned).

BRIDGE AREA

The fast erosion of the saddle between Bagnoregio Belvedere and Civita is clearly evident comparing the current ground surface with the reconstruction shown in the picture, where the colored lines represent the height of the old road from the medieval period until the 19th century: In the last 4 centuries this area has undergone a progressive dismantling up to 40 meters thick. The old pathway to Civita was replaced by the first bridge at the end of the 1920s. The current one replaced the first, following a remodeling of the area and it was inaugurated in 1965; its stability has been ensured for so long by the foundation poles (maybe 20 meters deep).

The rapid evolution of this area could be related to the thinner cover of volcanic deposits, as can be deduced from the dip of the stratified succession (whose top influenced the reduced thickness of the overlying ignimbrite at Bagnoregio Belvedere and in the Civita western sector). The erosive action of the Cireneo ditch at the base of the north slope may also have contributed to the geomorphological evolution of the saddle. Over time measures were taken to stabilize the water stream, which now have structural lesions or are partially covered by stream deposits.

Evolution of the bridge area from the medieval period until today (Margottini, 1990; redrawn).

The old path to Civita (on the left) and the first bridge (on the right).

** Technical-Numerical Regional Map (CTRN) scale 1:5.000, Lazio Region, 2014.*

BRIDGE NORTH SLOPE

Between the 80s and the 90s in the north side of the saddle between Bagnoregio Belvedere and Civita a wide stabilization project was realized consisting of: two rows of 11 contrasting concrete anchored structures, 16 meters long each; drainage channels and trenches.

On the upper part anti-erosive meshes were installed, but they did not resist to following rainfalls: so, in this area several mudflows are active and clearly in retrogradation as can be inferred from the photos of the last 10 years and from recent cracks in the parking lot above. On the upper part of the slope there is also locally visible evidence of soil creep.

Mudflows on the north side of the bridge.

North side of the bridge area: on top the stabilization works in progress (March 1990, by courtesy of prof. Quintilio Napoleoni), with the section of the wall-type (Napoleoni, 1991; redrawn).

BRIDGE SOUTH SLOPE

In this area several stabilization works were made between 2013 and 2014:

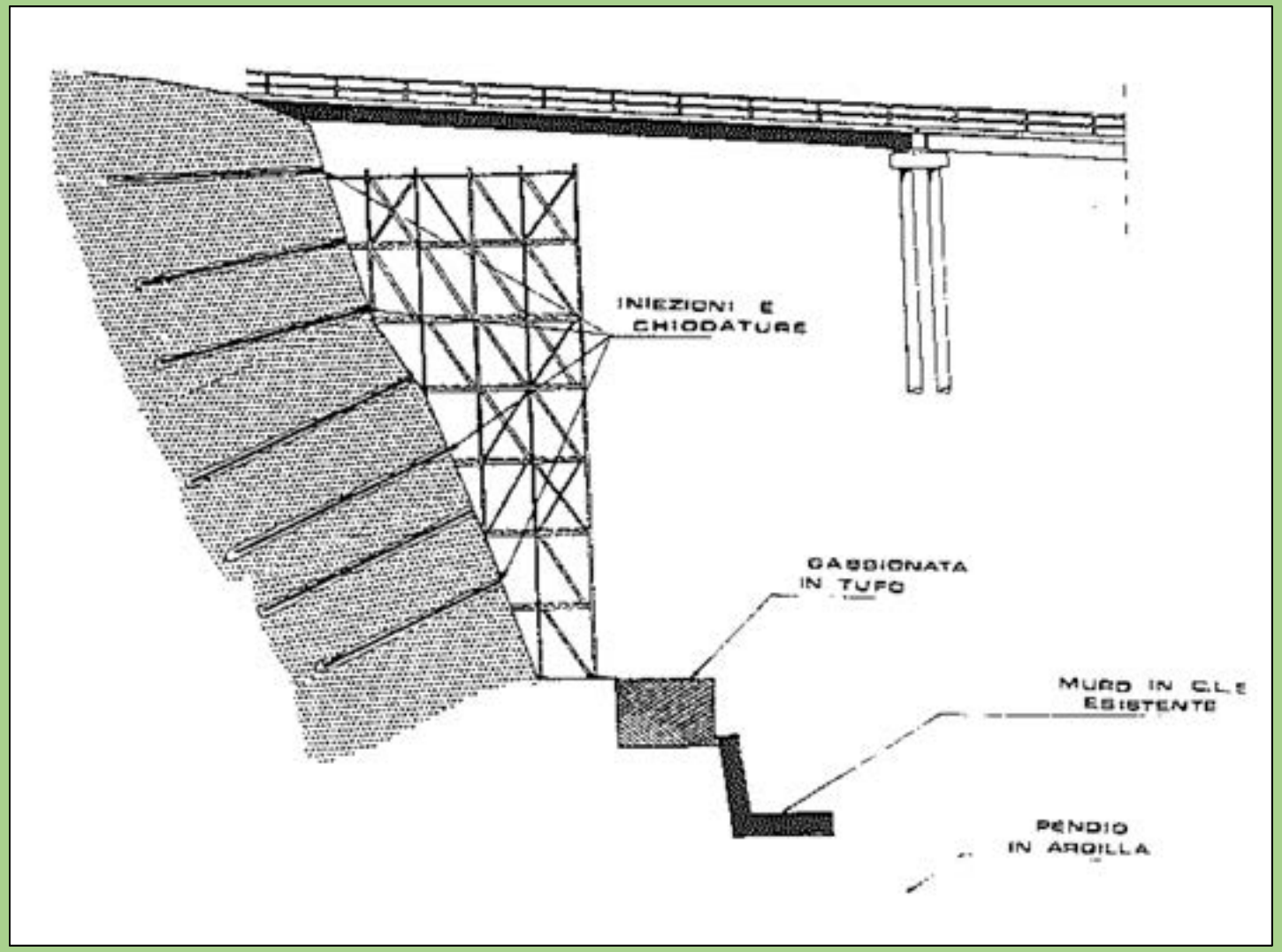
- in the lower part of the slope two bored pile walls to prevent deep movements (with overlying gabions against superficial movements),
- along the slope a drainage network with naturalistic engineering works, severely damaged by rainfalls just after installation;
- in the upper part a reinforced anti-erosion mat and quincunx bored piles (12 meters-deep?) connected by a concrete capping bean, on which the parking lot wall rests;

At present the slope ground surface is widely subject to deformation and erosion closely related to the rainfall regime: solifluction and mudflows (with crowns in retrogradation).

Evolution of the south side of the bridge area between 2012 and 2018 (Scarascia Mugnozza et al., 2022).

Drainage system severely damaged by rainfalls just after installation in 2015.
In the lower part: gabions against superficial movements based on two bored pile walls made to prevent deep movements.

Above: reinforced anti-erosion mat and quincunx bored piles (12 meters-deep?) connected by a concrete capping bean, on which the parking lot wall rests.
Below: mudflows with crowns in retrogradation under the mat.



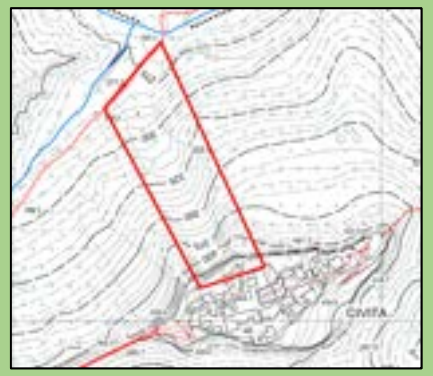
Stabilization works made on the southern side of the bridge abutment in 1990 (Napoleoni, 1991).
On the right: the intervention area.

NORTH-WEST SIDE

In this area it seems that wide instability movements are cyclically reactivated (several decades?), as evidenced by some photos dating back to the 50s and the presence of low-trunk vegetation until 2014. As a matter of fact, in November 2014 there were several rock falls from the escarpment, and in March 03, 2015 the rock debris was involved in a large debris avalanche, followed on its right side by a smaller translational slide.

The debris avalanche was probably induced by the weight of the rock debris and the heavy rains of the previous months. In the following years the instability phenomena have continued with sheet erosion on the surface of rupture and several small mudflows.

The deformation of the clays has led to the fractures propagation at the base of the escarpment with the dislocation of heterogeneous prisms: in this area has recently been installed a reinforced anti-erosion mat.

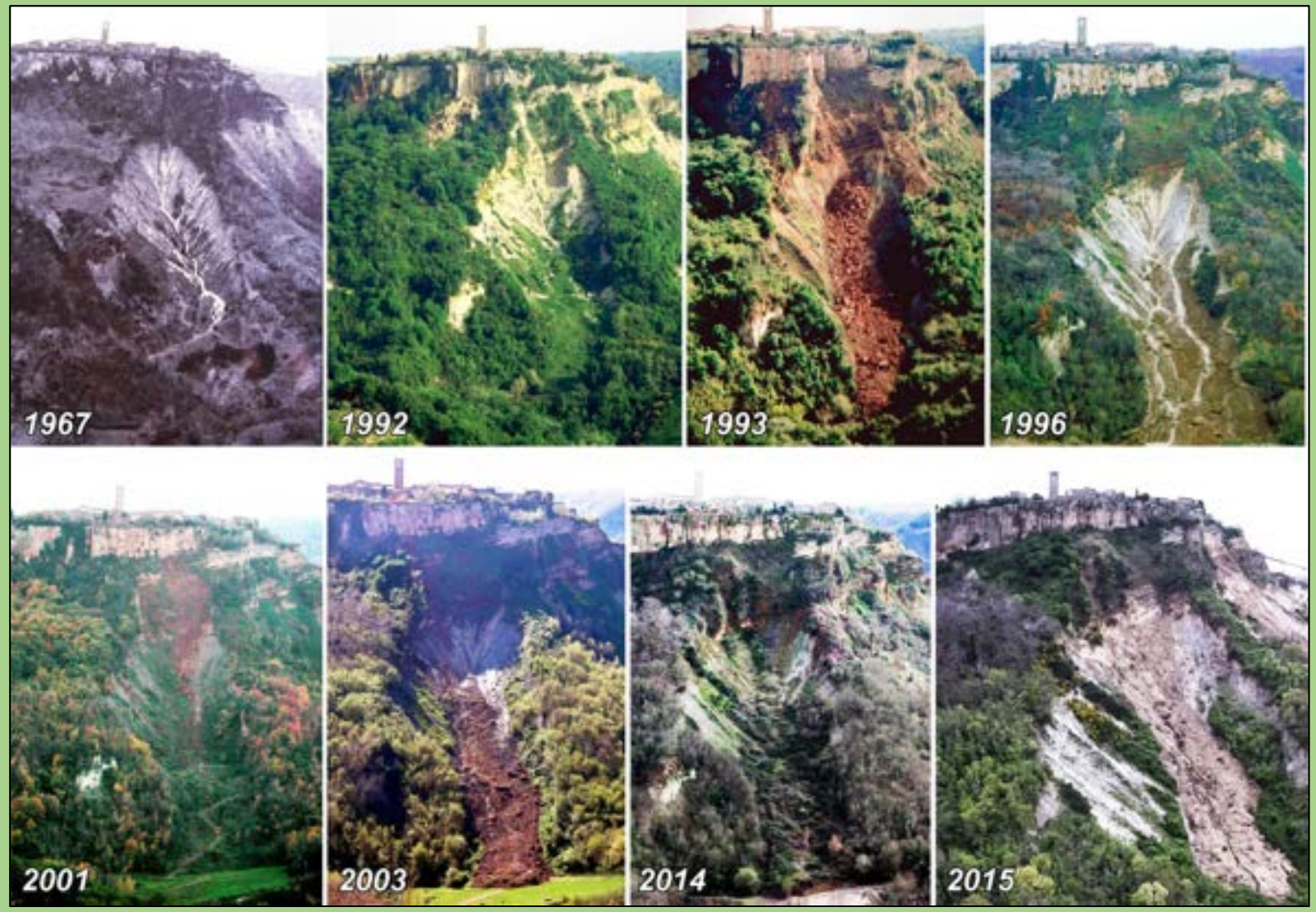


CAVON GRANDE

This area has undergone a quick evolution in the last decades, as evidenced by the succession of photos: in 1967 it looked like a calanco, but later the retrogradation of the slope movements in the silty clays led to the involvement of the cliff with several rock collapses between the 90s and 2000 and with following debris flows and avalanches.

Near the crown of the rockfalls area a stabilization system has made, consisting of passive and active anchors (nails and bolts) connected to 7 structural wells dug in the ignimbrite for a depth of about 16 meters, behind a long fracture in the cliff that in a few years led to the collapse of a part of Greco House.

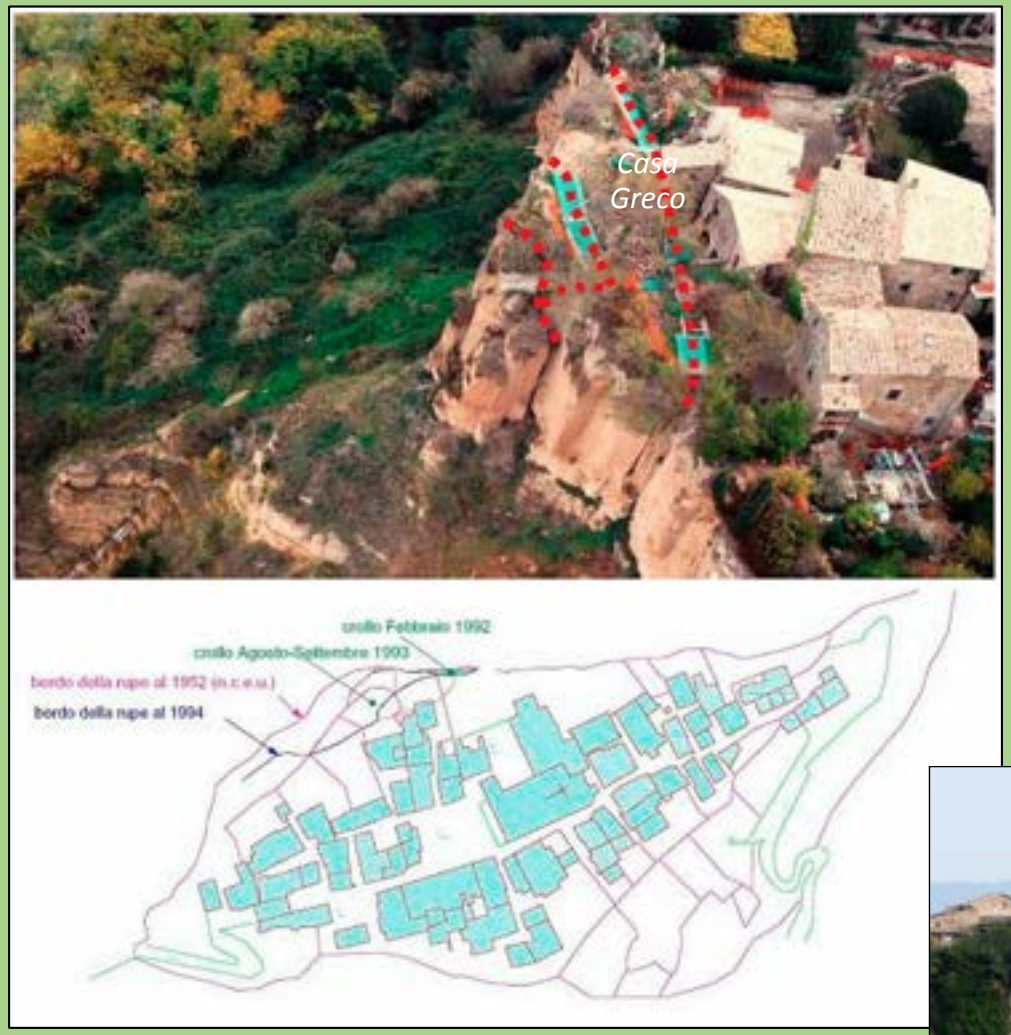
At present: rockfalls in the lower part of the scarp, mudflows and debris flows and avalanches.



Evolution of the "Cavon grande" since 1967 (Margottini & Di Buduo, 2017; modified).

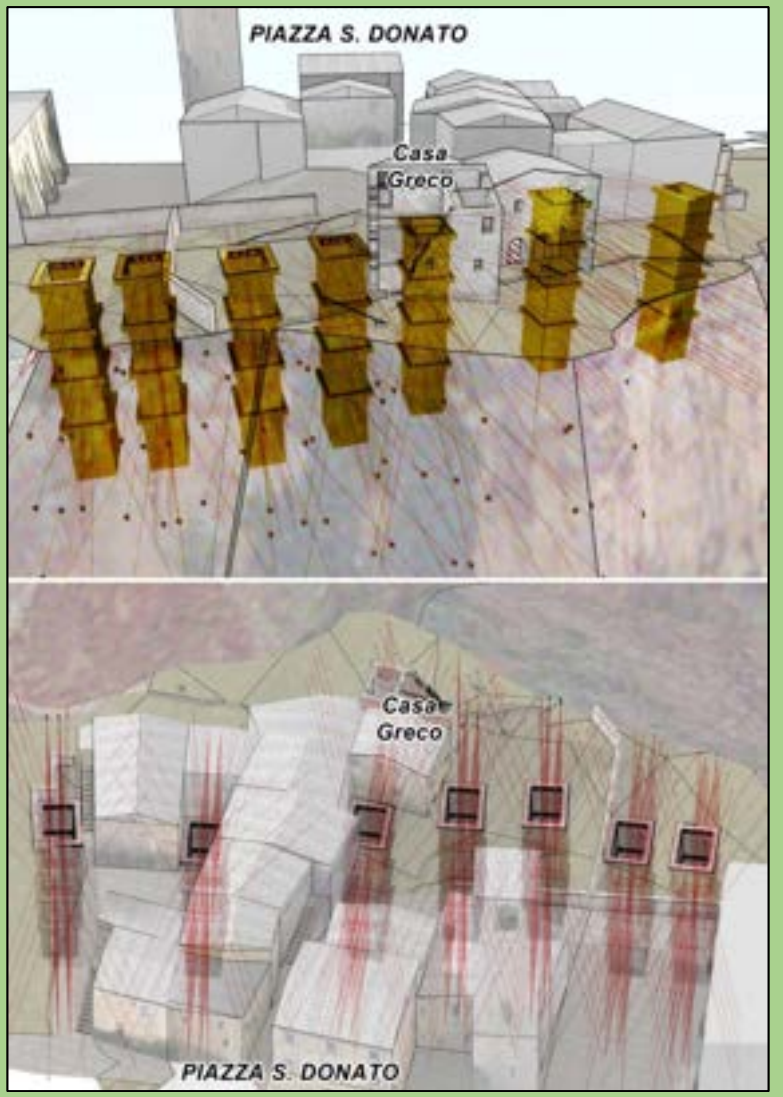
Recent rockfalls in the "Cavon grande".

The "Cavon grande" today. Vegetation in the lower part has grown on debris avalanche bodies.



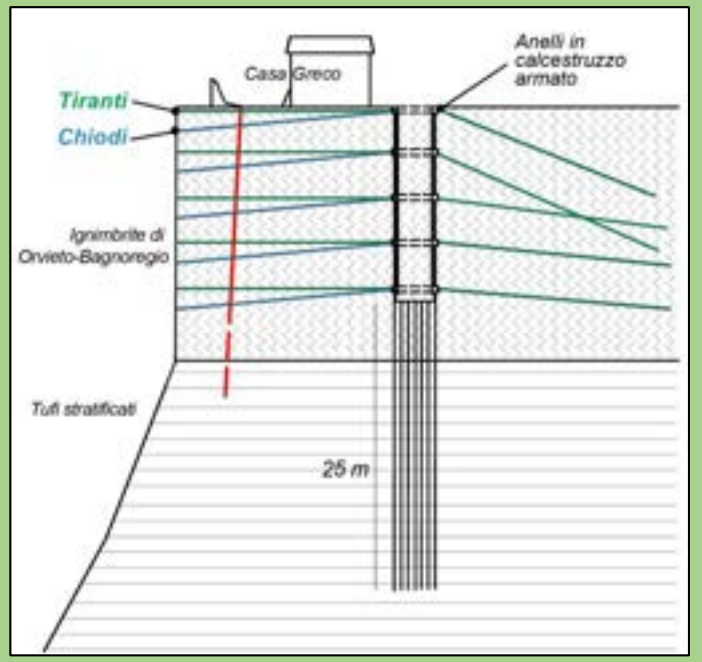
Recent landslides in the "Cavon Grande" crown area, a few years before the structural wells were built (Delmonaco et al., 2008).

The wells permit the creation of a series of semi-rigid structures inside the tuff rock, establishing a structural mesh linking various horizontal planes, both perpendicularly (tie-rods and anchors inside and outside the cavity-wells) and parallel to the front of the landslide (connections between wells)
(from Delmonaco et al., 2008).



Perspective view of the 7 structural wells on the north side of Civita (Museo Geologico e delle Frane, Civita di Bagnoregio).

The structural well of Casa Greco.



Schematic section of the structural well of Casa Greco (from Delmonaco et al., 2004; redrawn and modified).

Ignimbrite excavation for a structural well (picture: Museo Geologico e delle Frane, Civita di Bagnoregio).

NORTH-EAST SIDE

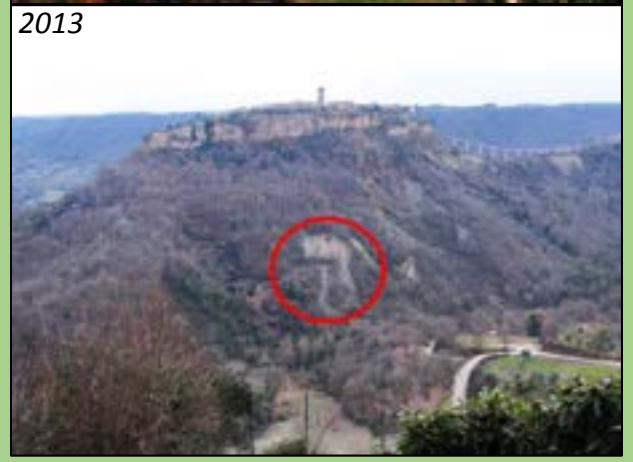
In the upper part of the north-east side of Civita a wide chestnut grove lay on a layer of debris at the base of the escarpment, ensuring better stability of this area than those neighboring. The tuff debris is highly heterometric, deriving from rockfalls, topples and detachment of blocks over time.

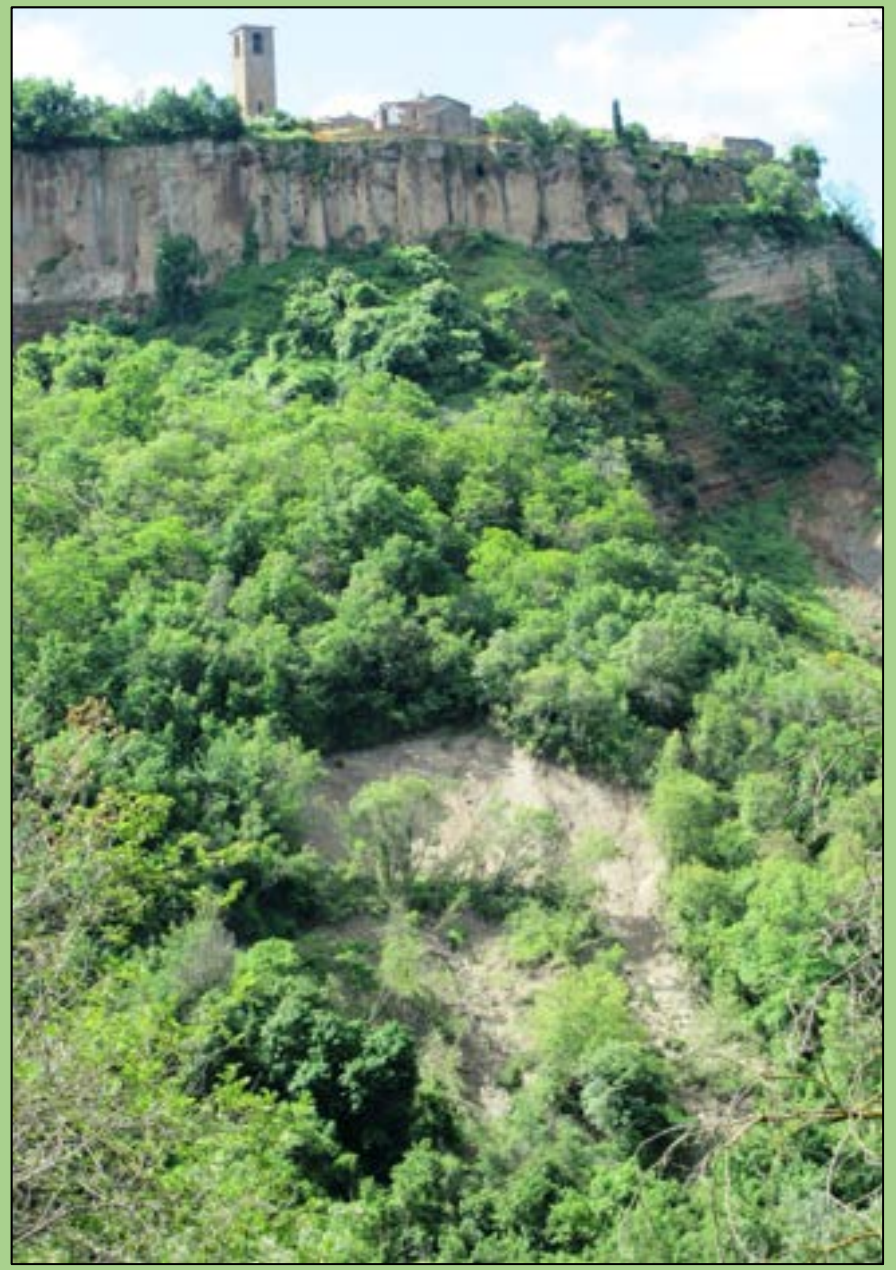
In the ignimbrite from the north end of the tunnel to the structural wells area of Greco house, rock anchorages were made a few years ago. The rest of the escarpment to the east is very fractured.

Recently, a restoration and extension of the path from the valley floor to the Civita tunnel has been carried out as follows:

- a rainwater drainage system has been made from the path side to the Lubriano ditch downstream of the ford;
- works of natural engineering have been performed in areas with active landslide, partly deformed or damaged by slope movements and water erosion.

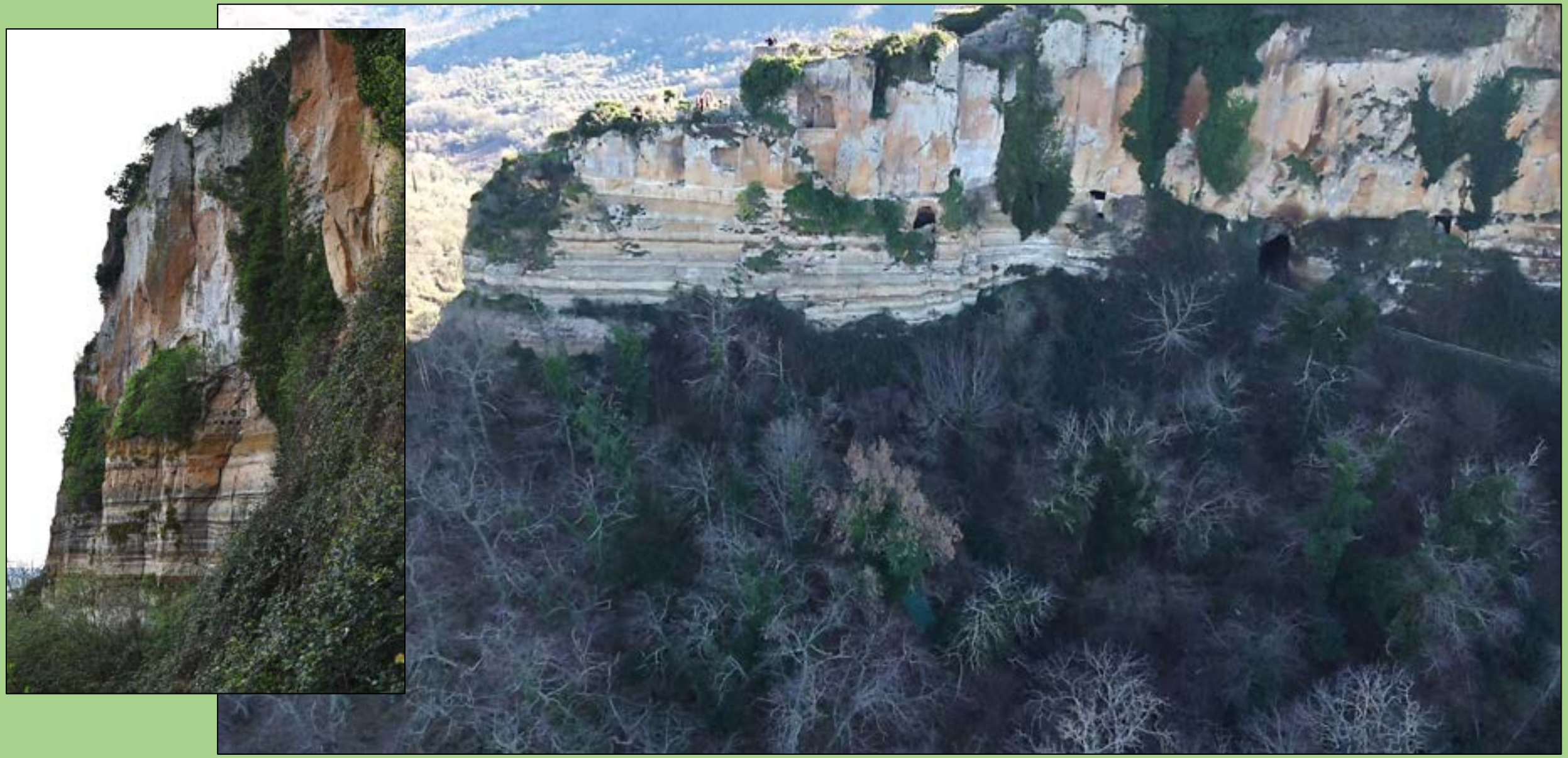
The most inclined part of the slope is the lower one (below the chestnut grove); here the active phenomena (soil creep, solifluction, mudflows) seem they could have an evolution in widening and retrogradation.





Landslide in 2013 on the north side of Civita (probably a translational slide). On the right: present situation.

North-east sector of Civita: rainwater drainage system partially obstructed by mud and debris.



North-east side of Civita cliff.

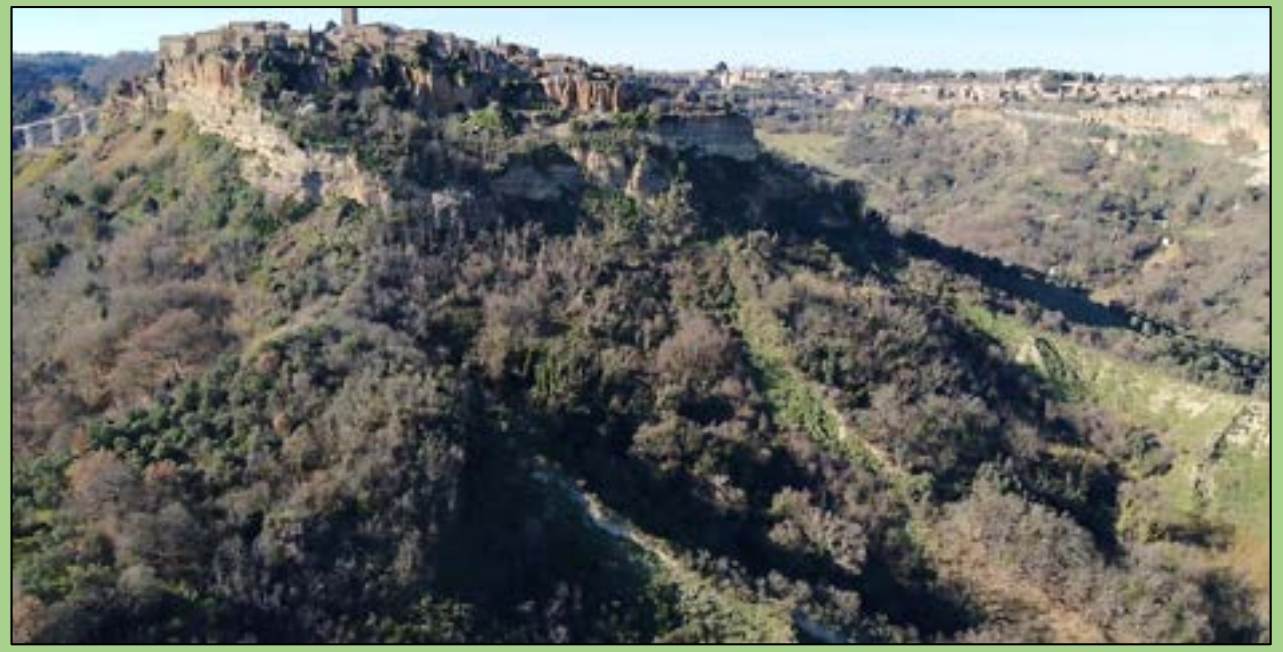
SOUTH-EAST SIDE

A large part of the southeastern sector of Civita (Contrada Carcere) collapsed during the strong earthquake of 1695. At present in the mass rock there are several families of discontinuities: the fractures are mainly vertical, very persistent and open, with a slight undulation, defining heterometric rock prisms potentially subject to falling/toppling and detachment of single blocks.

Such phenomena have also occurred recently, leading in 2012 and 2023 to the interruption of the pathway. The presence of hypogea at different heights in the scarp has probably a negative effect on the stability of mass rock.

The eastern end of the cliff is very thin and intensely fractured. At the southeastern base some mudflows and debris flows are active with frequency dependent on the rainfall regime.

South-eastern sector of Civita: discontinuities in the ignimbrite, detached blocks and a recent rockfall.



Mudflows in the south-eastern sector of Civita relief.

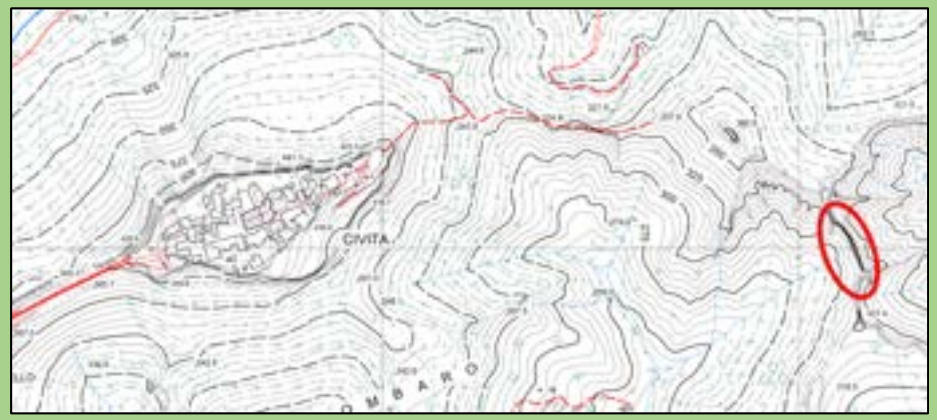
NATIVE HOUSE OF S. BONAVENTURA

St. Bonaventura is the most illustrious and famous person born in Civita (1217 – Lyons, France, 1274, 15 July): philosopher, theologian, minister of the Franciscan Order, bishop and the most important biographer of St. Francis of Assisi. Dante Alighieri meets St. Bonaventura in the 12th Canto of Paradiso among the wise spirits of the 4th Cielo.

About three hundred years after his birth, part of the house was transformed into a church dedicated to him, of which little is known.

Since the strong earthquake of 1695 the native house of St. Bonaventura was damaged several times by rockfalls until it was abandoned in ruins in 1826: currently there are few stones of the northeast corner of the building and a part of the basement.

Recently there's been a further small rockfall probably due to the action of tree roots.



PONTICELLI

“Ponticelli” is a very thin and unusual clay ridge, on which the Civita inhabitants used to walk on until the '60s, using it as a shortcut to reach some areas in the Rio Torbido valley, before erosion prevented definitively the passage.

This uncommon place shows in a enchanting and dramatic way the quick geomorphological dynamic of the Civita area and the badlands valley.

GUIDELINES FOR THE GEOMORPHOLOGICAL MAP OF ITALY

ISPRA - Istituto superiore per la protezione e la ricerca ambientale, SERVIZIO GEOLOGICO D'ITALIA

(HIGHER INSTITUTE FOR ENVIRONMENTAL PROTECTION AND RESEARCH, ITALIAN GEOLOGICAL SERVICE)

APAT - Agenzia per la protezione dell'ambiente e per i servizi tecnici, SERVIZIO GEOLOGICO D'ITALIA (1994)
Carta Geomorfologica d'Italia 1:50.000 - Guida al rilevamento. Linee guida per il rilevamento e la rappresentazione cartografica.
Periodici tecnici «I Quaderni», serie III, Volume 4/1994

APAT - Agenzia per la protezione dell'ambiente e per i servizi tecnici, SERVIZIO GEOLOGICO D'ITALIA (2007)
Carta Geomorfologica d'Italia 1:50.000 - Guida alla rappresentazione cartografica (primo aggiornamento).
Periodici tecnici «I Quaderni», serie III, Volume 10/2007

ISPRA - Istituto superiore per la protezione e la ricerca ambientale, SERVIZIO GEOLOGICO D'ITALIA (2021)
Carta Geomorfologica d'Italia alla scala 1:50.000 - Aggiornamento ed integrazioni delle linee guida della Carta Geomorfologica d'Italia alla scala 1:50.000 e Banca Dati geomorfologica (Fascicolo I, Versione 2.0).
Periodici tecnici «I Quaderni», serie III, Volume 13, Fascicolo I - Progetto CARG: modifiche ed integrazioni al Quaderno n. 4/1994

4. FINAL REMARKS

The study carried out has led to the definition of the current geomorphological situation of the area of Civita di Bagnoregio. The major problem that affected the study is the vegetation cover of many areas on the clay slopes, which while improving stability, on the other side is an impeding for landforms survey. It is therefore desirable that in the future a LIDAR survey can be carried out on the whole area in order to obtain a better identification of landforms in areas covered by vegetation.

In order to find long-term solutions to instability processes, the measures to be taken must be properly calibrated with the intense and complex dynamics of the slopes.

Basically it would be reasonable to program interventions considering the different situations on the whole slope and preventing landslides in addition to stabilize them.

This would only be possible with the constant and complete geomorphological analysis and instrumental monitoring of the area.

The instrumental monitoring should involve at the same time all the main elements of “slope-system”, each with different characteristics and stress-strain behavior:

- surface part of the clay slope subject to softening and faster deformation;
- clay deposits subject to swelling down to a certain depth;
- stratified pyroclastic deposits on the escarpments;
- human structures (buildings, roads, walls, etc.).

Taking preventive action gives great long-term benefits by optimizing the financial commitment: stabilizing a wide landslide after a long time has a considerably higher cost than the preventative intervention and often the work is technically complicate because of the considerable extension and complexity of the instability phenomena.

So, it would be essential to set up a committee of experts able to plan geotechnical investigations and monitoring, to analyze the instruments data, and to constantly update the geomorphological map, in order to identify and quantify the slopes dynamics for an appropriate program of technical actions to be taken over time.

It would be also very useful to create an accessible database with analyses, studies, surveys and monitoring carried out in the past.

In conclusion, the interventions that appear to be most important are:

- a proper regulation of rainwater (and wastewater) in order to avoid the infiltration in the mass rock and the flowing on the clay slope (the places in the rivers where water is channeled must be properly identified and stabilized);
- prevent as much as possible the deformation of the silty clay deposits at the base of the scarps.

5. ACKNOWLEDGEMENTS

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