Geological Field Trips and Maps

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Travertine depositional systems of Central Italy: Rapolano Terme and the Acque Albule Basin. An overview of geometries and lithofacies associations of the depositional setting

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Cover page Figure: Panoramic view of the quarried walls in Rapolano Terme (A) and in the Acque Albule Basin (B) showing the geometries of the travertine depositional units (Photos courtesy of Alessandro Mancini).

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ABSTRACT

Central western Italy is famous for the occurrence of several Quaternary travertine depositional systems. Travertine deposition in this area is controlled by the degassing of CO_2-charged groundwater, circulating in deep carbonate-evaporitic reservoirs and associated to recent magmatic and tectonic activity. This guide provides the opportunity to recognise the different geometries and the lithofacies associations of travertine depositional system of central Italy. In order to provide a complete view of travertine depositional environment-lithofacies associations and the dimension of the depositional system, the Rapolano Terme area and the Acque Albule Basin field examples were selected and described in different field stops. The field trip could be performed in two days. The guide is organised into five different parts: an overview of continental carbonate deposits and a general geological setting of the Northern-Central Apennines, followed by the geological setting of the two selected areas. The chapter dedicated to the stop is organised in a brief overview of the depositional systems, followed by the location of the field stops. The conclusion chapter provides, finally, a brief explanation and the position of the stops respect to the travertine depositional system observed.

Keywords: Rapolano Terme, Acque Albule Basin, *Lapis Tiburtinus* travertines, lithofacies associations, depositional environments, central Italy.

PROGRAM SUMMARY

The field trip is organised in six stops located in the Rapolano Terme (Siena, Tuscany) and the Acque Albule Basin (Tivoli, Latium) (Fig. 1). The entire field trip can be performed in two days.
The outcrops-stops selected are easy to reach with the car and walking in the field. However, some stops (i.e., stop 1.2 – Rapolano Terme, stop 2, 2.1, 2.2, 2.3 – Acque Albule Basin) are inside quarries area and in this case, it is mandatory to follow the safety rules adopted by the quarry owners.
The stops can be visited in all seasons, but due to the vegetation and also the high temperature within the quarries, the recommended period is the autumn-winter. The stops offer the possibility to observe the entire travertine depositional environment, as well as the lithofacies associations and the geometries of the architectural element composing the travertine system.

SAFETY

The stops and the related outcrops can be reached by car and with easy walking with no difficulties. However, mountain walking boots, sun protection, hats or headscarves, and sunglasses are recommended.

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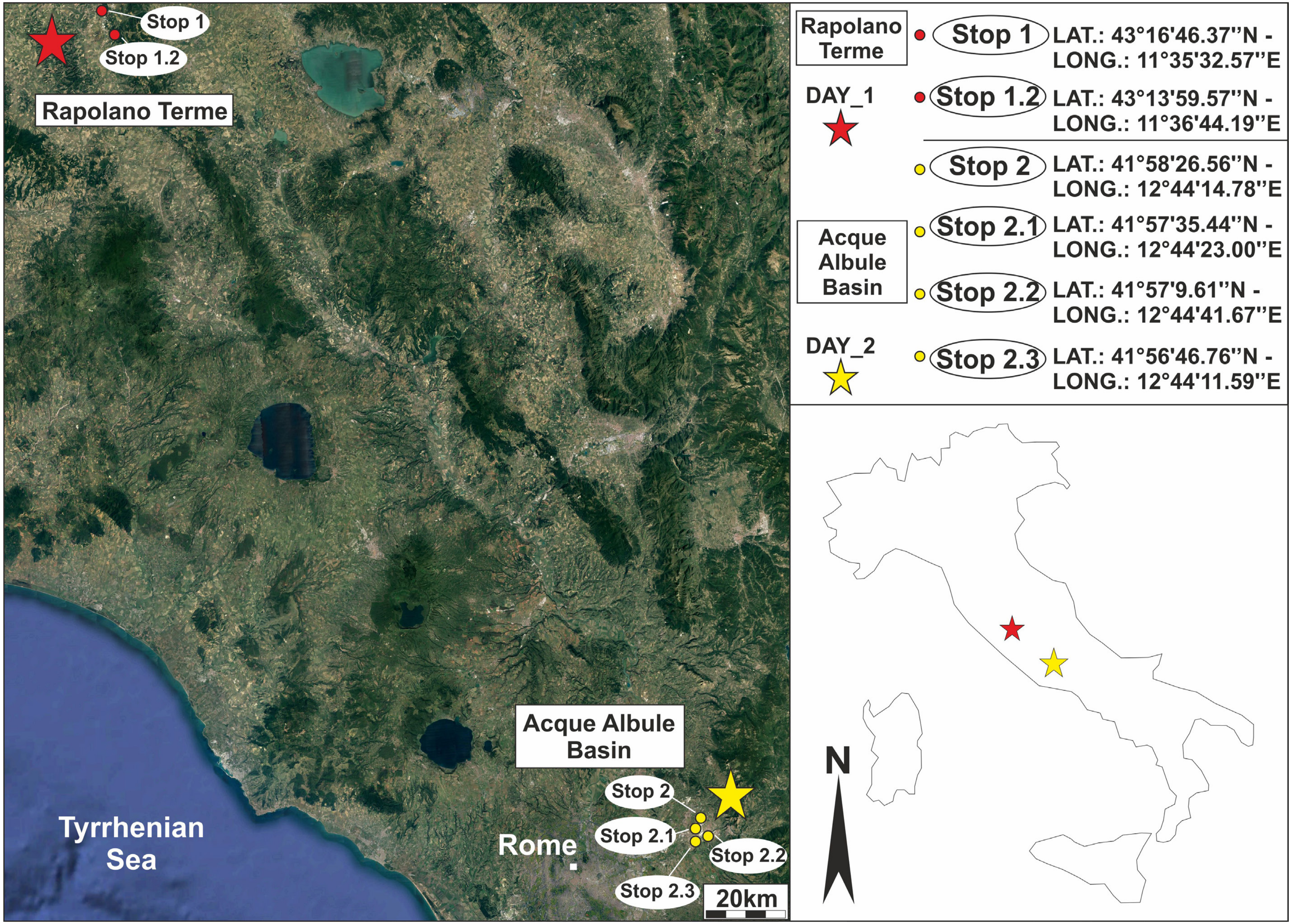

Fig. 1 - Location of the stops in the Rapolano Terme area (Terme San Giovanni - Stop 1; Cava Oliviera - Stop 1.2) and in the Acque Albule Basin (Querciolaie 1 - Stop 2; Pacifici 1 - Stop 2.1; Poggi S – Stop 2.2; Pacifici 2 – Stop 2.3) (modified from Google Earth-Digital Globe, 2018).

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HOSPITALS

- General Emergency and Fire Brigade – Emergenze generiche e Pompieri. Tel: 112
- Local first aid: Presidio Socio Sanitario, Via Pietro Nenni, 1, 53040, Rapolano Terme (Siena). Tel: +390577 536552
- Hospital San Giovanni Evangelista, Via A. Parrozzani, 3, Tivoli (Rome). Tel: +39 0774 3161

ACCOMODATIONS

There are several hotels and B&B around the proposed field trip. Based on the self-organization it is recommended to book an accommodation in Rapolano Terme and in Tivoli village if the field trip is divided in two days.

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Travertine: two thousand years of History

The travertine deposits of Rapolano Terme and Acque Albule Basin have accompanied the History of civilization during a period longer than two thousand years. This connection is also represented by the presence of Roman building as *Villa Adriana*, built around 120 AD by Roman Emperor Hadrian near the Acque Albule Basin (Tivoli) and now UNESCO World Heritage Site. Exploited as ornamental stone, both in Rapolano Terme and in the Acque Albule Basin the travertine was used for the construction of several buildings as the Colosseum in Rome (70-80 AD), the *Torre* (tower) *del Mangia* in *Piazza del Campo* and the seat of *Monte dei Paschi*, founded in 1472, in Siena. Moreover, the occurrence of travertine deposits is also strictly linked with the presence of thermal and freshwater aquifers. Also in this case, the thermal water provided the possibility to build thermal spas or spectacular fountains, especially during the Italian Renaissance period. One of the most spectacular examples is represented by *Villa d'Este* (UNESCO World Heritage Site), built during the 16th century, close to Tivoli village and famous for its several fountains. The use of travertine as ornamental stone continued also over the 18th century and one of the most important buildings of this period which are decorated with travertine is represented by the University Campus of Sapienza in Rome, built during the 1930s under the guidance of the architect Marcello Piacentini.

Despite the fact that travertine used for the building construction and also the quarried areas offer the opportunity to observe directly lithofacies and geometries of the depositional units, the exploiting activity performed in more than two thousand years has strongly modified the landscape. For this reason, future exploitation will have to be probably more focused on the environmental impact (Rinalduzzi et al., 2017) in order to find a sustainable use of the ornamental stones not only in Italy but also abroad.

Continental carbonate deposits: an overview

Tufa, speleothem, calcrete, and travertine characterise the large range of deposits related to the continental carbonates (Fig. 2A) (e.g., Chafetz and Folk, 1984; Pedley, 2009; Jones and Renaut, 2010; Capezzuoli et al., 2014; Mancini et al., 2021). The definition regarding travertine deposits is still a matter of debate (Chafetz and Folk, 1984; Ford and Pedley, 1996; Pentecost, 2005; Capezzuoli et al., 2014; Della Porta, 2015). Based on Capezzuoli et al. (2014), travertine is a continental calcium carbonate deposit, related to the circulation of non-marine hydrothermal waters (Fig. 2B). Famous in the world as heritage sites (i.e., Yellowstone National Park, USA, Fouke, 2011- Pamukkale, Turkey, Kele et al. 2011) and as ornamental stone (i.e., *Lapis Tiburtinus* travertines, Faccenna et al., 2008), travertine deposits are able to influence the landscape evolution and to form morphological reliefs in a fast way, with an accumulation rate reaching 1000 mm/year (mean value: 200 mm/year; Pentecost, 2005). Thermal springs, controlled by faults and fractures affecting the travertine substratum, allow the arising of the hydrothermal fluids, leading to the creation of step-side constructional morphologies (Brogi et al., 2016; Mancini et al., 2019a). Travertine deposits are influenced by the physical, chemical, and biological processes of the environment where they develop (Capezzuoli et al., 2014;

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Luo et al., 2022a). The influence of these factors is then reflected by the complex facies distribution, mainly composed by biotically (i.e., biological processes, CO_2-degassing and water cooling) and abiotically (i.e., high temperature, turbulence and water composition) driven systems (Jones and Renaut, 1995; Guo and Riding, 1994; Rainey and Jones, 2009; Fouke, 2011; Gandin and Capezzuoli 2014; Della Porta, 2015; Mancini et al., 2019a, b, c). According to Capezzuoli et al. (2014) and Mancini et al. (2019a) a travertine depositional system can be divided in three different depositional zones respectively known as proximal, intermediate, and distal (Fig. 2C). The proximal zone is the area where thermal water flows out from a spring, starts the deposition of calcium carbonate deposits, forming fissure-ridge, mound, pinnacle and mud pot macro-morphologies (Curewitz and Karson, 1997; Brogi et al., 2021; Luo et al., 2022b). The intermediate zone is the area where thermal water, flowing towards lower depositional areas, forms different inclined geometries as slope and channel (Mancini et al., 2019a). The distal zone is instead the marginal part of the system, mainly characterised by low relief topography, associated with marshes, shallow lakes, rivers, and alluvial plains with variable dimensions and influenced by the local morphology (Guo and Riding, 1998; Sant'Anna et al., 2004; Brogi et al., 2012). Furthermore, the proximal zone is the area where travertine rapidly forms mostly by the abiotic process associated with the rapid CO_2-degassing, with lithofacies mainly characterised by abiotic crust in subaerial setting (i.e., fissure ridge and mound) and by biotic crust in the subaqueous depositional environment (i.e., mud pot, pinnacle, mound). Lithofacies association of the intermediate zone reveals instead the local existence of more favourable life conditions, highlighted by the alternation of abiotic and biotic crusts, with the last one becoming predominant in the distal zone due to the mixing of thermal and freshwater (Guo and Riding, 1998; Rainey and Jones, 2009) attesting for a completely favourable life condition.

General geological setting

Travertine deposits are principally located in the western side of the Northern-Central Apennines range (Fig. 3A) (Mancini et al., 2019b, c). This range represents a collisional belt related to the progressive convergence – collision of the European continental margin and the African Plate (Adria; Patacca et al., 1992; Carmignani et al., 1994; Molli, 2008; Carminati and Doglioni, 2012; Rossetti et al., 2015). Several tectonic phases, mainly during the Cretaceous-Early Miocene, led to the formation of a tectonic pile made up of superimposed units related to different palaeogeographic settings associated to oceanic and continental domains of the African palaeomargin (Bianco et al., 2015 with references therein). In particular, the tectonic units are divided into: a) Ligurian units mainly composed of slices made up of Jurassic fragments of oceanic crust overlain by Cretaceous-Palaeogene sedimentary succession, b) Sub-Ligurian and Tuscan units, characterised by evaporite, carbonate and terrigenous deposits, non-to very low-grade metamorphic successions and metamorphic units spanning from Palaeozoic to Early Miocene, c) Umbria-Marche and Sabina units, principally composed by an evaporite succession overlain by platform and pelagic carbonate deposits, developed on top of the thinning and subsiding Adria continental crust from the Triassic to the early Cenozoic (Barchi, 2010; Cosentino et al., 2010;

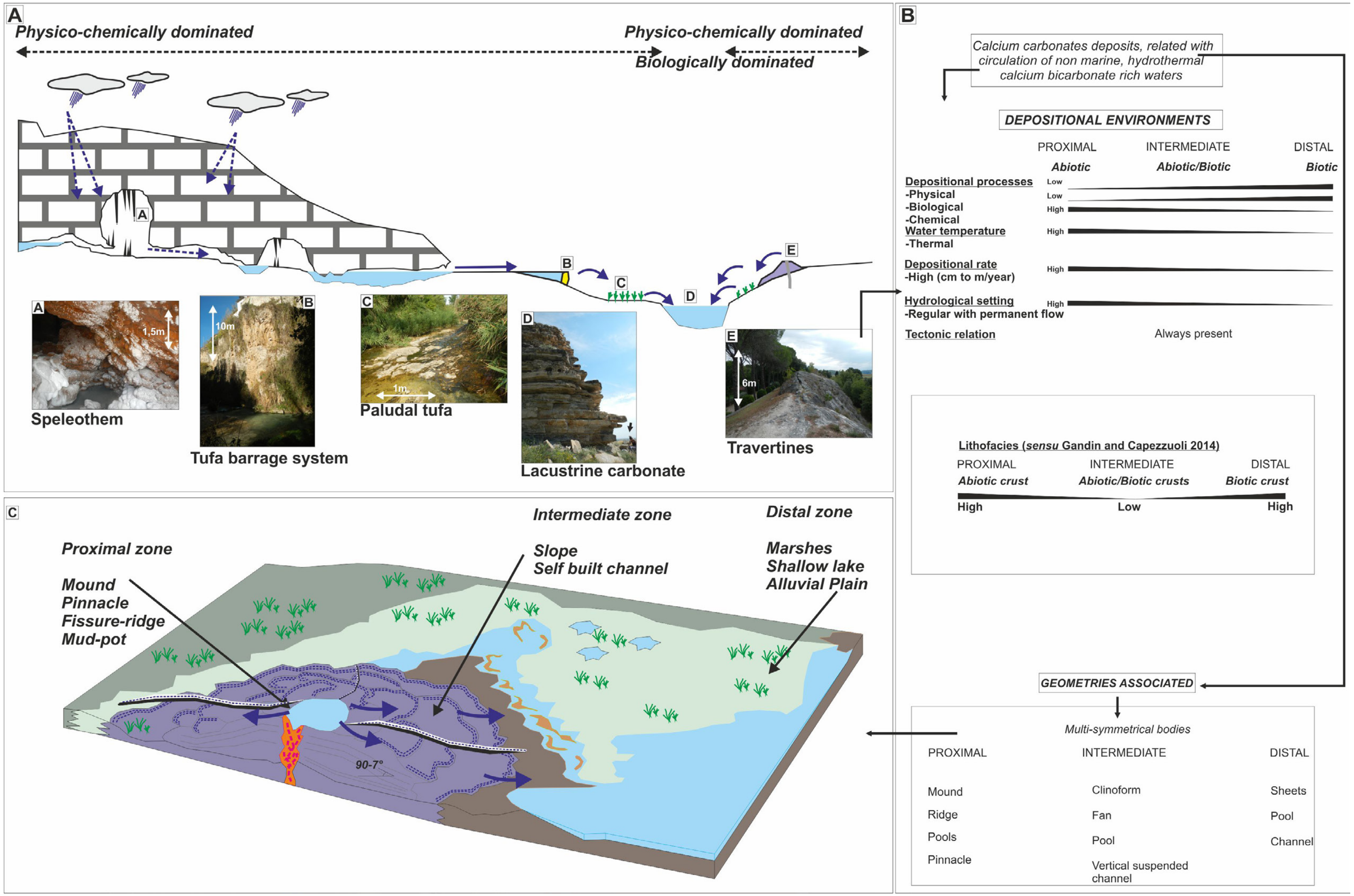

Fig. 2 - A) Continental carbonates are represented by a large type of deposits (speleothem, tufa, lacustrine carbonate and travertine) that, according to Pedley and Rogerson (2010), can be considered as a part of the same depositional environment (A: Tivoli, Italy; B: Triponzo, Italy; C: Acqua Borra, Italy; D: Torrente de Cinca, Spain; E: Terme San Giovanni, Italy). B) Travertine can be defined as continental carbonate composed by calcium carbonate associated to circulation of hydrothermal waters. Travertine lithofacies (abiotic *vs* biotic sensu Gandin and Capezzuoli et al., 2014) and geometries are related to the different depositional environments, controlled by physical, biological and chemical processes as well as water temperature, while local geological features influence the depositional rate, the hydrological and tectonic setting. C) Scheme showing travertine depositional system (modified from Guido and Campbell, 2009). Travertine depositional system can be divided in proximal, intermediate and distal zones. Springs, generally associated to mound or fissure ridge elements are typical in the proximal zone, while the intermediate zone, in function of its topographical inclination, is characterised by slope, self-built channels, active-inactive fans and pools. The distal zone represents instead the marginal part of the travertine depositional system with channels, shallow lakes, sheets and alluvial plain (modified from Mancini et al., 2019a).

Brogi and Giorgetti, 2012; Bianco et al., 2015). The Neogene-Quaternary tectonic evolution of the inner Northern-Central Apennines was instead characterised by the eastward migration of compressional tectonics in the outer zone and by extensional tectonics in the inner zone since Early-Middle Miocene (Patacca et al., 1992; Carmignani et al., 1995; Barchi, 2010). The accretion of the Apennine orogen is still active today in the eastern outer zone of the belt, while pre-existing compressional structures are partly disrupted by extensional tectonic activity in the western sector (Malinverno and Ryan, 1986; Ricchi Lucci, 1986; Brogi and Liotta, 2008; Barchi, 2010). NW-striking normal faults and NE-striking transfer fault systems characterise the extensional process, producing several Neogene-Quaternary basins, mainly filled by marine to continental deposits and successively accompanied by widespread magmatism (Neogene-Quaternary; Liotta, 1991; Martini and Sagri, 1993; Liotta et al., 1998, 2015; Peccerillo, 2003, 2005; Dini et al., 2005, 2008; Acocella and Funiciello, 2006; Brogi and Liotta, 2008; Mancini et al., 2014; Milli et al., 2017; Brogi et al., 2014, 2020). Thinned lithosphere, positive regional Bouger anomaly, high heat flow, localised to regional uplift and geothermal fluids circulation characterise at present the western side of the Northern-Central Apennines area as well as the presence of travertine deposits (Della Vedova et al., 2001; Batini et al., 2003; Minissale, 2004; Chiodini et al., 2007, 2013; Liotta et al., 2010; Zucchi et al., 2017). Travertine deposits in the area, investigated by several authors to reconstruct the tectonic activity, are generally associated to hydrothermal activity and deep CO_2 degassing phenomena (Chiodini et al., 1999, 2000; Capezzuoli et al., 2009, 2010; Brogi and Capezzuoli, 2009, 2014; Brogi et al., 2010, 2012, 2016, 2017, 2018). The numerous thermal springs and the CO_2 degassing areas are controlled by tectonic activity, while the hydrothermal circulation is favoured by the fluid flow concentrated at the intersection of near orthogonal fault systems (Chiodini et al., 1991, 2004, 2013; Minissale, 2004; Brogi, 2004; Frondini, 2008; Frondini et al., 2004, 2012; Brogi and Capezzuoli, 2009; Brogi et al., 2012; Luo et al., 2021).

Geological setting of the Rapolano Terme area

Rapolano Terme area (Fig. 3B) is part of the Siena-Radicofani Basin, a NNW-SSE structural depression of 90 km, developed during Neogene extensional activity. The basin is filled by Pliocene marine deposits, overlain by Quaternary continental succession mainly composed by gravel, sand, clay and travertine deposits (Bertini et al., 1991; Bossio et al., 1993; Martini and Sagri, 1993; Carmignani et al., 1994; Liotta et al., 1998; Costantini et al., 2009; Lazzarotto et al., 2010; Ghinassi et al., 2021; Martini et al., 2021). The travertine deposits (Pleistocene-Holocene) develop on an area of 14 km^2 with a thickness of approximatively 50 m (Brogi, 2004). Travertine deposits are related to hydrothermal fluids associated to thermal springs characterised by temperatures up to 38°C, high salinity, $CaSO_4$ composition, and a total discharge rate of about 40 l/s (Minissale, 2004; Frondini, 2008; Frondini et al., 2008). The average flow rate per unit area of similar spring systems is considered to be 7 ± 3 l/km^2 (Celati et al., 1990). The recharge area of the aquifer, related to the Mesozoic carbonate rocks crops out in the Rapolano-Trequanda Ridge (Brogi et al., 2007), can be estimated in 5.7 ± 2.5 km^2. Travertine deposits are intensely quarried as ornamental stone. The fossil system, as well as the active springs, are aligned along the intersection with the transversal and normal- NNW-SSE striking Rapolano fault, bounding the eastern margin of the Siena-Radicofani Basin and separating the Neogene sediments from the pre-Neogene

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units exposed in the Rapolano-Trequanda Ridge (pre-Neogene marine carbonate and turbidite deposits of the non-metamorphic Tuscan Succession; Lazzarotto et al., 2003; Brogi, 2004; Costantini et al., 2009).

Geological setting of the Acque Albule Basin (The *Lapis Tiburtinus* travertine)

The Acque Albule Basin (Fig. 3C) is located 30 km east of Rome (Faccenna et al., 2008; Mancini et al., 2017, 2021; Scalera et al., 2021; Cardello et al., 2022). The basin is bounded by the Neogene Appenine fold and thrust belt to the north and to the east (i.e., Cornicolani-Lucretili and Tiburtini Mts.), by the quiescent Colli Albani volcanic complex and by the Aniene River to the south (Pleistocene; Karner et al., 2001) and by the Tiber valley to the west, originated during the Pliocene-Quaternary period and associated to the Tyrrhenian extensional domain (De Filippis et al., 2013; Milli et al., 2017). Despite the fact that according to Mancini et al. (2021), the geometry of the travertine deposits is influenced by base-level fluctuations of the Aniene River, De Filippis et al. (2013) suggest that the Acque Albule Basin could be considered as a pull-apart basin, controlled by NW-striking and extensional faults, accompanied by transverse or oblique (N-NE-striking) strike-slip faults acting as accommodation structures between the different extensional sectors (Alfonsi et al., 1991; Faccenna et al., 2008). The travertine deposits quarried from the Roman architects until now is worldwide know as *Lapis Tiburtinus* (meaning the stone of *Tibur* by the ancient name of Tivoli; Faccenna et al., 2008). This deposit (maximum thickness: 90 m; Faccenna et al., 2008), occurring after or concurrently with the last volcanic phase activity of the Region (Late Pleistocene; Faccenna et al., 2008; Mancini et al., 2020), covers an area of approximatively 28 km^2 and overlies Pleistocene alluvial, lacustrine, and epivolcanic deposits developed on top of the Meso-Cenozoic marine carbonate succession (La Vigna et al., 2013; Mancini et al., 2021). The H_2S-$CaSO_4$ thermal waters are enriched by large quantity of CO_2 mainly derived from the decarbonisation of Meso-Cenozoic limestone and mantle degassing (Pentecost and Tortora, 1989; Chiodini et al., 2000; Minissale et al., 2002; Minissale, 2004; Carucci et al., 2012; La Vigna et al., 2013; Di Salvo et al., 2013). Water temperature of the springs (Regina Lake; ~1850 l/s and Colonnelle Lake; ~250 l/s; La Vigna et al., 2013), located in the central part of the Acque Albule Basin, range between 23 and 24 °C with a pH of 6.0-6.2 (Pentecost and Tortora, 1989; Chiodini & Frondini, 2001; Minissale et al., 2002; Minissale, 2004; Carucci et al., 2012; La Vigna et al., 2013; Di Salvo et al., 2013). The recharge area of the springs (220 Km^2; Boni et al., 1986; Chiodini et al., 2000; Mancini et al., 2019b) is represented by the Meso-Cenozoic limestones of the Apennine range cropping out in the north, northeast and east of the basin and represented by the Lucretili-Tiburtini and Cornicolani Mts. (La Vigna et al., 2013; Carucci et al., 2012), while the total natural discharge of the system is about 4000 l/s.

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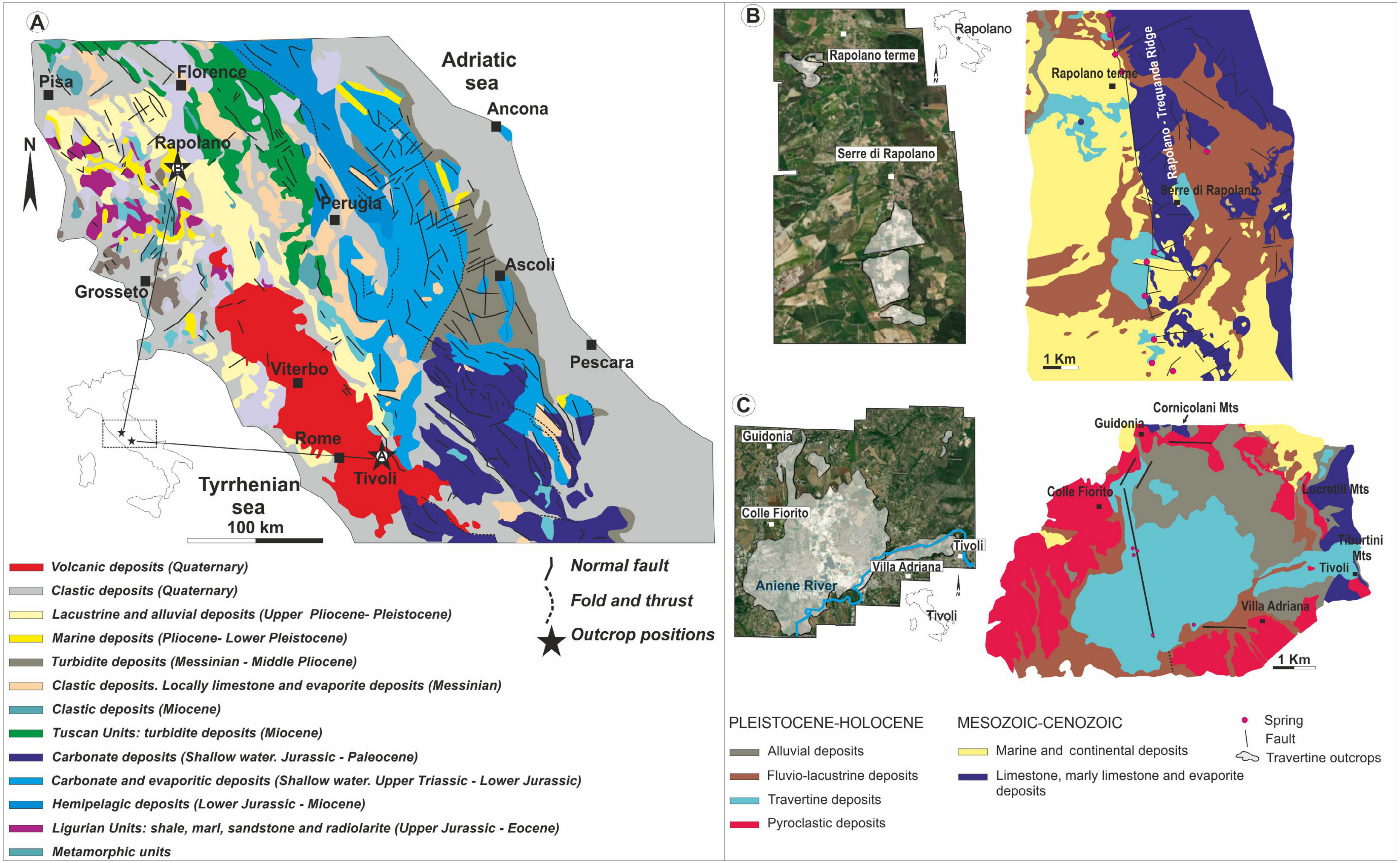

Fig. 3 - A) Geological map of Central-Northern Apennines. B) Geological setting of the Rapolano Terme area. C) Geological setting of the Acque Albule Basin (modified from Mancini et al., 2019b).

DAY 1

The Rapolano Terme area: general overview

Together with Tivoli, near Rome (Italy), and Angel Terrace in Yellowstone National Park (USA), the Rapolano area hosts one of the most well-studied travertine deposits around the world (Cipriani et al., 1972; Guo et al., 1996; Carrara et al., 1998; Guo and Riding, 1998, 1999; Minissale et al., 2002a; Minissale and Sturchio, 2004; Brogi, 2004; Brogi et al., 2007, 2018; Brogi and Capezzuoli, 2009). The hills around Rapolano mainly consist of Meso-Cenozoic rocks belonging to the Tuscan Nappe and Pliocene deposits (*Crete senesi*) which are buried by banks of travertine and gravel. It was the abundance of travertine, together with the presence of the hydrothermal springs, which dictated Rapolano's fortunes. Quarrying activity from the Etruscan period is documented up to the XVI century, as witnessed by a document of 1597 concerning Noceto quarry, which provided the church of S. Maria in Provenzano in Siena with much of its constructional material. Mainly linked to commissions concerning the building of single mansion, the extraction of the travertine peaked between the last years of the XIX century and the first years of the XX century. In particular, the twenty years of fascism saw the erection of much architecture inspired by the monuments of the Roman empire and these were often built with travertine. The Rapolano Terme travertines consist of isolated masses up to 40 m thick. The travertines, deposited during the Pleistocene and Holocene (Carrara et al., 1998; Brogi et al., 2010b; Mancini et al., 2019c) by hot water issuing from thermal springs, are developed in-paludal environments and on slopes bathed in thin sheets of flowing water. Varying depositional geometries and morphologies characterise these carbonate rocks: tabular and fan-slope bodies, fissure ridge, terraced mound, cone, and waterfall deposits (Guo and Riding, 1992, 1994, 1998, 1999). The travertine bodies were controlled by resurgent hydrothermal circulation along fracture zones located at the intersection points between two generations of faults of different ages which developed as part of the Neogene-Quaternary tectonic evolution of the Northern Apennines. Several CO_2-rich thermal spring emergences are also present in the Rapolano area, as well as some CO_2 mofettes (Minissale et al., 2002a). Nowadays, the spring has been tapped by a well drilled by the local spa, and the original ridge from which travertine used to precipitate is largely inactive. Position of the stops is reported in Figure 4.

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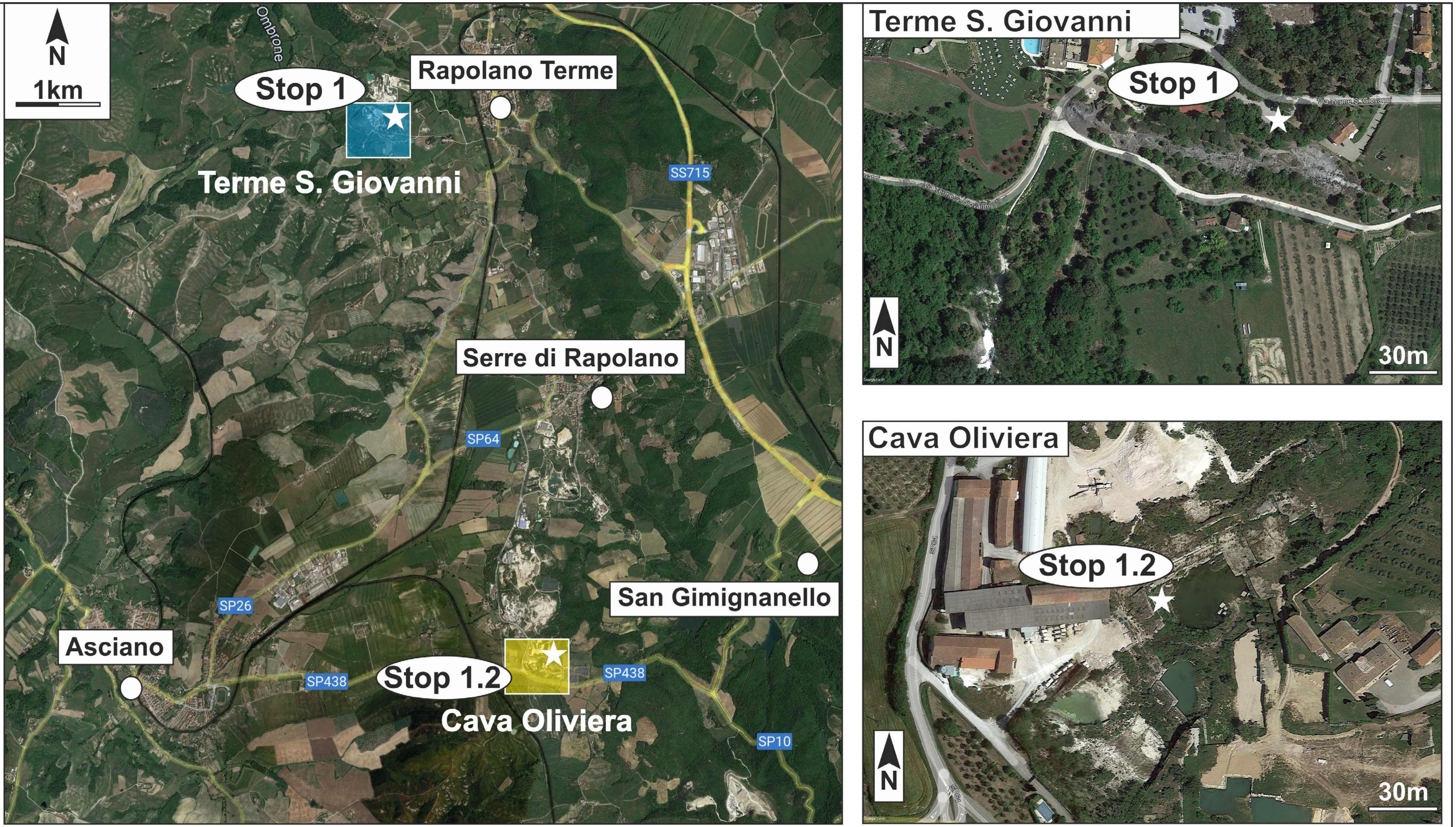

Stop 1 LAT.: 43°16'46.37''N - LONG.: 11°35'32.57''E

Stop 1.2 LAT.: 43°13'59.57''N - LONG.: 11°36'44.19''E

Fig. 4 - Position of the stops in the Rapolano Terme area: Terme San Giovanni - Stop 1; Cava Oliviera - Stop 1.2; (modified from Google Earth-Digital Globe 2018).

Stop 1 - Terme San Giovanni

Coordinates: Lat. 43°16'46.37''N, – Long. 11°35'32.57''E

Terme San Giovanni is currently the most active travertine-depositing site in the area, even though most of the water is diverted for use in thermal baths at the hotel health spa adjacent to the fissure ridge. Water is piped off and circulated through the baths before being returned along artificial surface channels, whose courses are changed from time to time, to natural streams in adjacent valleys. The travertine fissure-ridge located at the Terme San Giovanni area (1 km SW of Rapolano) represents a travertine body along the Rapolano Fault trace. This morphotectonic feature, about 250 m long, 30 m wide, and a maximum of 10 m high, has been described by Brogi and Capezzuoli (2009) (Fig. 5A, B, C). It is located on a fluvial terrace linked to the morphological evolution of the Ombrone River, running about 1 km to the west. The base of this fissure-ridge has been drilled to increase the hot water inflow in the nearby thermal resort. Travertine fissure-ridge overlies Pleistocene terraced alluvial deposits (about 20 m) with encrusting limestone embedded, in turn with overlying marine Piacenzian clayey sediments. Furthermore, the occurrence of a carbonate reservoir at shallow depths can be presumed. The present-day Terme San Giovanni fissure-ridge consists of a calcareous body resulting from the coalescence of small cones (Fig. 5B, D). It is characterised by marginal slopes with flanking bedded travertine asymmetrically distributed with respect to the fissure (wider in the southern part than in the northern one) and dipping gently away from the crest (Fig. 5F). The different travertine lithofacies recognised in the bedded travertine have been interpreted as derived by superposed depositional events, corresponding to waterfalls, shallow pools, fan-slope shaped, cones, terraced slopes, and smooth slopes (Chafetz and Folk, 1984; Guo and Riding, 1999). Their presence suggests different episodes of deposition along the ridge, as is also attested by numerous angular unconformities (Fig. 5E). The profile of the ridge is asymmetric: the northern slope is higher than the southern one by about 10 m. At the top of the ridge, along its crest, a continuous fissure with a maximum width of 30 cm occurs (see also Fig. 5C). The width of the fissure decreases towards its extremities, where it becomes about 1 mm wide. At the western and eastern ends of the ridge, the fissure is apparently missing because it is concealed by new travertine deposited by hot waters issuing from small cones aligned along the crest. The cones, commonly rising tens of centimetres high and decimetres in diameter, bubble vigorously when active and deposit thin, white, and dense micritic layers (Fig. 5D). The internal fabric of the cones is mainly characterised by superposed crystalline crusts, forming a thinly layered structure reflecting the growth of the cone surface. The marginal slopes of the fissure-ridge present various inclinations ranging from almost vertical to less than 20°. The hot waters flowing out from the cones give rise to the accretion of the ridge, with three main depositional morphologies: smooth, microterraced, and terraced slope. The smooth slope is composed of the superposition of white to dark-grey crystalline crust formed by large feather calcite crystals or fan calcite crystals growing perpendicular to the depositional surface. The microterraced slope is characterised by dense small terraces formed by a smooth, narrow edge some millimetres high, damming each very shallow pool. The age of this fissure ridge can be not older than 24±3 ka (Late Pleistocene; Brogi and Capezzuoli, 2009; 2014).

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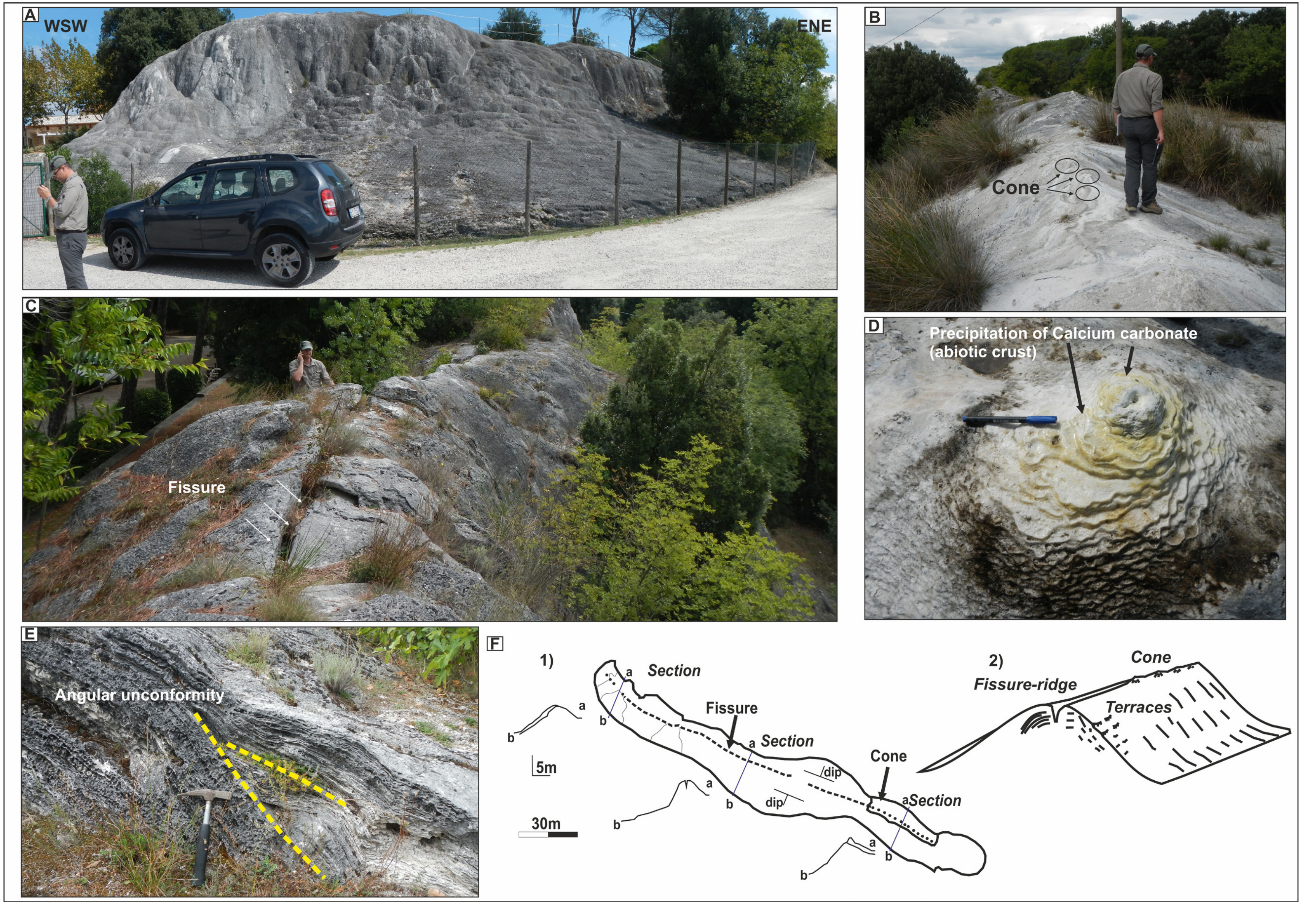

Fig. 5 - A) The travertine fissure-ridge located close to the San Giovanni thermal resort. This structure, ESE striking, shows an asymmetrical profile. On the top of the fissure-ridge, a fissure ranging from 0,1 to 30 cm, is located (B, C). To notice that during an earthquake (M=3.6) occurred the 18 of March 2013 and 20 km far from Terme di San Giovanni, a new fissure, reaching 0.25 mm in width, propagated for 22.5 m in the eastern ridge-end, while in the western side the fissure propagated for 4 m, affecting and crossing the existing travertine deposits. Cones with precipitation of Calcium carbonate are also observable in the SE part of the fissure-ridge structure (B, D). Angular unconformity, associated to non-deposition or diversion of the water flow are common (E). F) schematic draw of the Terme San Giovanni Fissure ridge (modified from Brogi and Capezzuoli, 2009).

Stop 1.2 - Cava Oliviera Quarry

Coordinates: Lat. 43°13’59.57’’N, Long. 11°36’44.19’’E

The travertine deposits of Cava Oliviera Quarry are located along a tract of the Rapolano Fault where this regional structure was dissected by a Pleistocene WSW-ENE striking fault, known as the Violante Fault (Brogi et al., 2010b). Travertine deposits exposed in the Oliviera Quarry are up to 30 m thick. They derived from multiple depositional events interrupted by periods of non-deposition. Pedogenesis and colluvial deposition took place during the depositional hiatus, indicating long periods of inactivity of the thermal springs or diversion of thermal flows. From a panoramic view, it is possible to observe a diverse depositional architecture. The travertines of Oliviera Quarry can be grossly subdivided in two successions because of their deformational record and stratigraphic features (Fig. 6A). The deeper succession (Succession A) was pervasively fractured and affected by block tilting mainly in the southern part of the quarry. In contrast, the overlying succession (Succession B) is unaffected by tectonic activity and unconformably overlies Succession A. Minor angular unconformities typically characterise Succession B, indicating intermittent periods of hydrothermal activity. Succession A is at least 15 m thick. Its base coincides with the deeper part of the quarry, while its top is marked by an erosive surface. This surface, locally enhanced by the presence of a 30 cm thick layer of dark clay, is clearly recognizable in the whole quarry (Fig. 6B). Succession A shows the evolution from a Depression Depositional System (DDS) occurring in the eastern part of the travertine body, to a Slope Depositional System (SDS) exposed in the western part. The DDS is formed by wide, horizontal travertine deposits dominated by typical facies of stagnant/low energy water (Marsh-pool facies; Guo and Riding, 1998) (Fig. 6C). These are represented by: i) thin bedded shrub-like growths (Shrub travertine) alternating with dense concentrations of millimetre diameter spherical incrustations (Coated bubbles) (Fig. 6C); ii) sheets fragments of millimetre thick brittle crystalline laminae (Paper-thin rafts) (Fig. 6D); iii) centimetre thick cylindrical moulds formed around stems or roots composed of micritic to crystalline calcite (Reed travertine) (Fig. 6E); and iv) millimetre thick micritic laminae. The SDS represents the frontal part of the system and is mainly dominated by thin, bedded travertine formed by thick layers of ray calcite (Chafetz and Folk, 1984; Folk et al., 1985) or feather calcite (Guo and Riding, 1992) developed perpendicular to a 20° NW dipping surface slope (Fig. 6F). These layers, defined as crystalline crust, locally alternate with lenticular bodies of coated bubbles, paper-thin rafts and reed travertine (Fig. 6G). These facies, present in varying proportions, are characteristic of a gentle slope environment, where waters usually move by laminar flow (smooth slope; Guo and Riding, 1998), locally evolving to small vertical terrace walls, pool and rims confining the margins of the pools (terraced slope; Guo and Riding, 1998) (Fig. 6H).

The inclination of the travertine beds and sedimentological features indicate that the water was flowing towards the NW side of the travertine body. Evidence of poorly developed palaeokarst is locally present (Fig. 6H, I). Succession B (about 15 m thick) consists of a complex superposition of travertine depositional events. At least six main depositional events, separated by angular unconformities, can be recognised (de1-de6; Fig. 6K). Travertines of all depositional events belonging to the Succession B are characterised by facies and sedimentologic features similar to those of Succession A, with the dominance of a generally west-north-westward progradation of the fan-like, high spring-

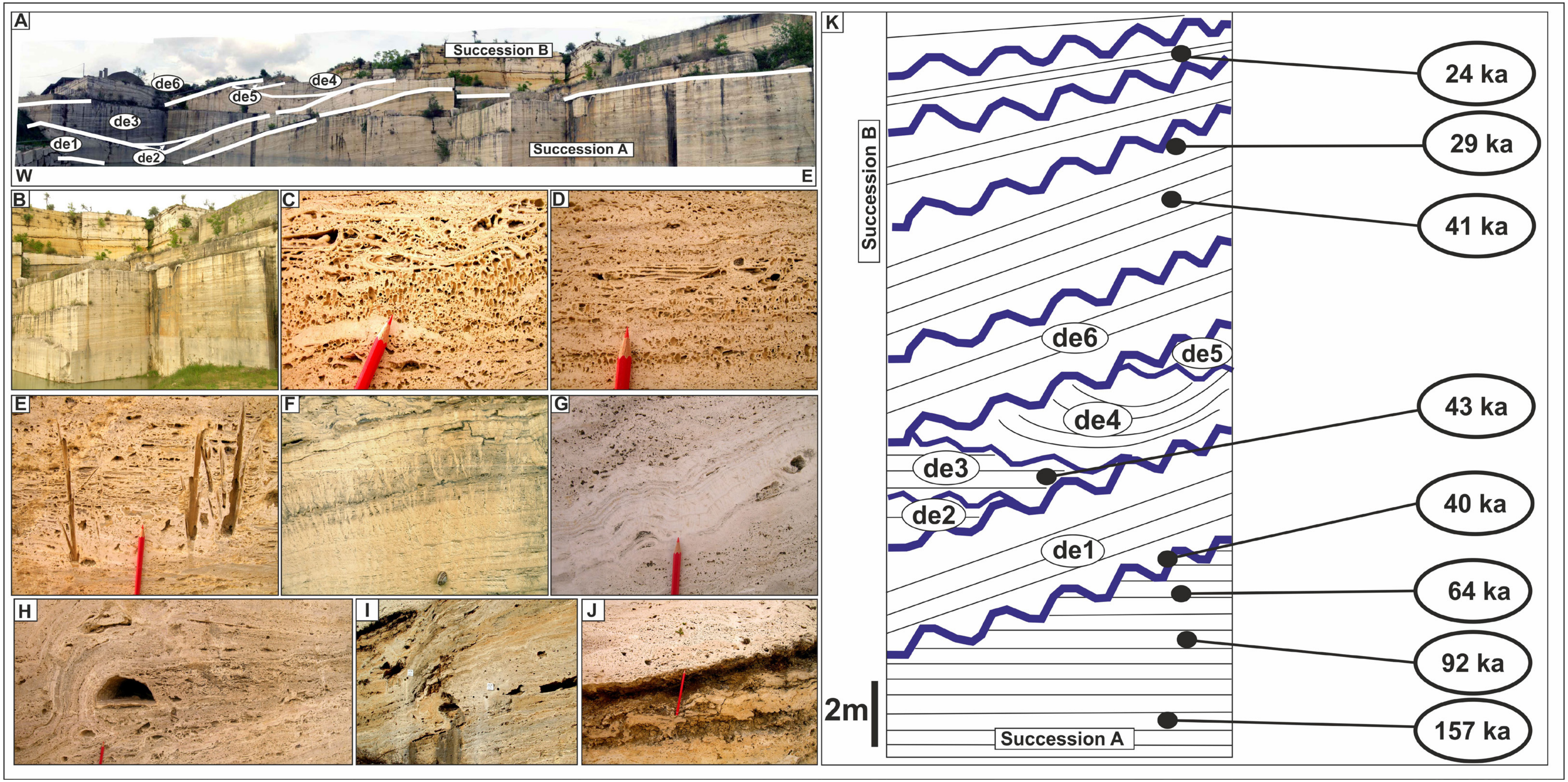

Fig. 6 - A - B) Panoramic view of the northern part of the Oliviera quarry. The main angular unconformities delimiting the travertine depositional events (de1-de6) are highlighted (modified from Brogi et al., 2010b); C) layer with high concentration of spherical/elongated coated bubbles; D) sheets of millimetric paper-thin travertine; E) vertical, encrusted moulds of stems (reed travertine) intercalated to paper-thin rafts; F) thin, bedded crystalline crust travertine formed by fan calcite perpendicular to stratification; G) Detail of the Slope Depositional System (SDS) with the superposition of crystalline crust travertine, coated bubbles travertine, paper-thin raft travertine; H - I) Example of terrace pool in the SDS with local examples of palaeokarst (voids with accumulation of residual reddish silt); J) Angular unconformity between A and B Successions highlighted by a palaeosoil and intense alteration of the rocks (after Brogi et al., 2010b); K) cartoon showing the relationships between the reconstructed travertine deposits at Cava Oliviera quarry and the corresponding U/Th ages.

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water flow depositional systems (SDS; de1; Fig. 6K) and the presence of flat, low spring-water flow depositional system (DDS) in the eastern-south eastern part nearest to the location of the thermal springs (e.g., de2, de3; Fig. 6K). Succession A (U/Th age: 154±15 - 64±5 ka; Brogi et al., 2010b - Fig. 6K) underwent brittle deformation in the southern side of the quarry. Here, it appears pervasively fractured and tilted by about 10°-15° toward the south. Succession B (first U/Th age: 43±3 - 24±4 ka; Brogi et al., 2010b - Fig. 6K) is untectonised and unconformably overlies Succession A, post-dating the tectonic events that deformed Succession A. However, the deposits of Succession B show the presence of a layer characterised by soft sediment deformation structures related to a seismic event (Brogi et al., 2018).

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DAY 2

The Acque Albule Basin and the *Lapis Tiburtinus* travertine: general overview

The Acque Albule (meaning "white waters") Basin is probably one of the most famous continental carbonate deposits (see Fig. 7 for the position of the field stops). Travertine derives from the Latin name *Lapis Tiburtinus*, meaning the "stone of Tibur" by the ancient name of Tivoli village (Faccenna et al., 2008). The Roman architects used the *Lapis Tiburtinus* travertine since the II century as ornamental stone (the Colosseum represents an example of such use). From the Renaissance the most important quarry, known as Barco and located close to the Aniene River (*Teverone*), was used for the extraction of travertine blocks, successively loaded in boats and carried out till the city of Rome. Since 1450 *Lapis Tiburtinus* was used by the most important architects as Borromini and Bernini. Successively, the *Lapis Tiburtinus* was largely employed again in the 1920s in the fascist architecture, for the construction of several buildings as the University Campus of Sapienza designed by the architect Marcello Piacentini. Nowadays, the *Lapis Tiburtinus* is still largely used as ornamental stone and exported in different countries all over the world, as India, Japan, China, and the United States of America.

Despite the interest as ornamental stone, the *Lapis Tiburtinus* travertine developed inside the Acque Albule Basin between 115 and 30 ka (Late Pleistocene) with a deposition starting just after or concurrently with the last phase of volcanic activity in the region (Faccenna et al., 2008). Travertine is mostly covered by widespread facies known as "*Testina*" consisting of a poorly compact and poorly lithoid travertine capping most parts of the Tivoli plateau (Scalera et al., 2021). The *Testina* unit is the youngest travertine of the Tivoli plateau (29 ± 4 ka, Faccenna et al., 2008) with variable thickness, reaching its maximum values at the central part of the Acque Albule Basin (10 m; Faccenna et al., 2008; Scalera et al., 2021).

The *Lapis Tiburtinus* travertine, with its 1.1 km^3 volume, is characterised by ten depositional units bounded by superposed unconformity surfaces and related to non-deposition and erosion (Mancini et al., 2021). The several quarries of the Acque Albule Basin offer the possibility to observe the different lithofacies that characterise *Lapis Tiburtinus* travertine (Erthal et al., 2017; Della Porta et al., 2017, 2019; Mancini et al., 2021). Shrub lithofacies association, composed of clotted peloidal dendrite boundstone, has a high lateral continuity (more than 100 m) with a thickness of more than 40 m (Chafetz and Folk, 1984; Chafetz et al., 1991). The other most common lithofacies association, the laminated deposit, is characterised by finely laminated micrite boundstone with a thickness up to 40 m, forming tabular or lenticular bodies. Lenticular convex upward geometries characterise instead the crystalline crust lithofacies association with a thickness of 10 m. Such lithofacies is organised in laminated bands composed of a vertical fan of dendritic crystals forming cementstone. Plane parallel, sub-horizontal beds with a maximum thickness of 5 m, similar to the laminated deposit in terms of texture and components and composed of mudstone, wackestone, and packstone with peloidal micrite, gastropods, mould of plants, ostracods, *Charophyte* stems, and intraclast typify the non-laminated deposit lithofacies. The reworked deposit lithofacies occurred as dark lenticular bodies with erosional surfaces at the base and lenticular-concave

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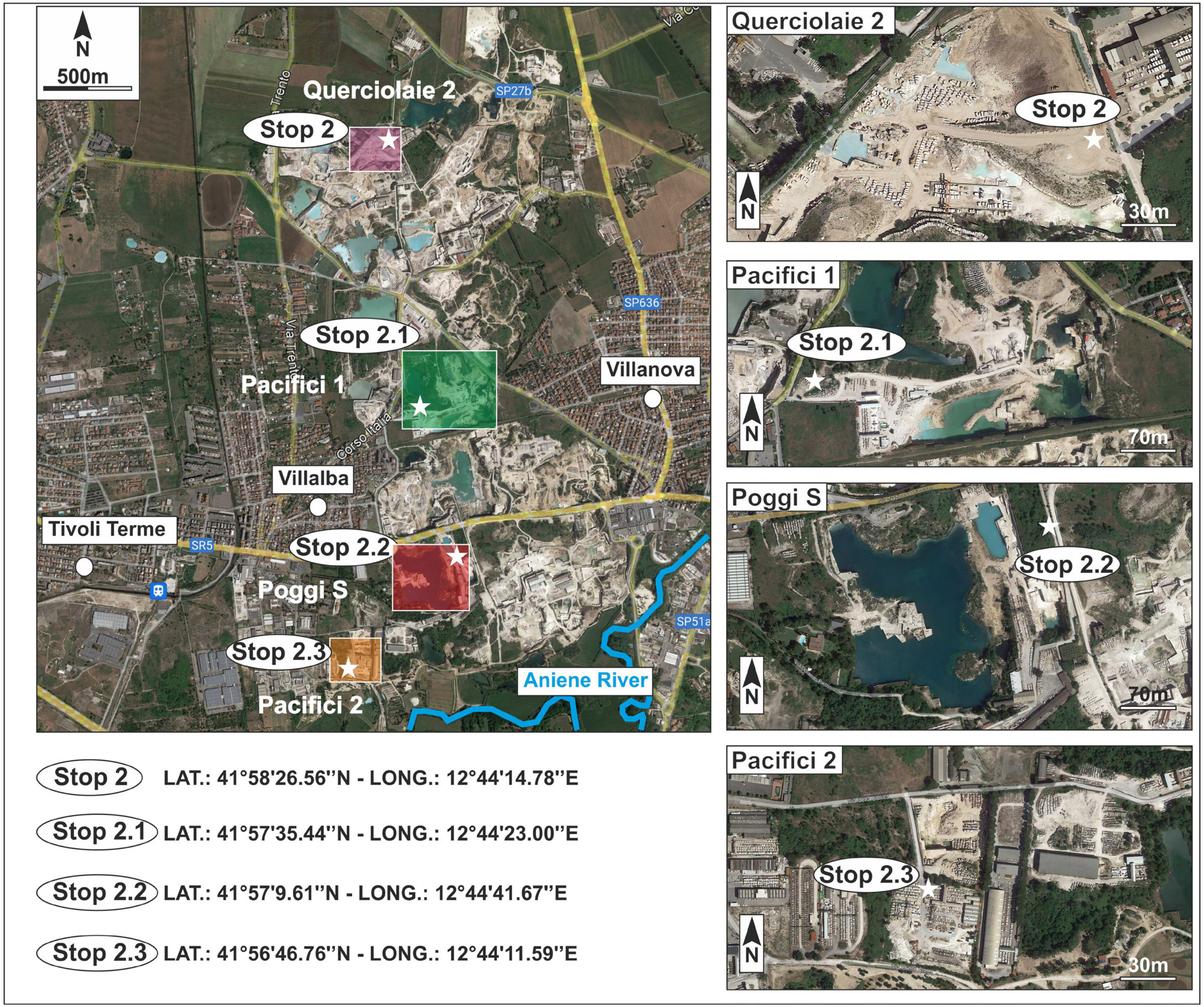

Fig. 7 - Position of the stops in the Acque Albule Basin: Querciolaie 1 - Stop 2.1; Pacifici 1 - Stop 2.2; Poggi S - Stop 2.3; Pacifici 2 - Stop 2.4; (modified from Google Earth-Digital Globe 2018).

upward geometry, with a maximum thickness of 1.5 m. Packstone to rudstone/floatstone with well-rounded to sub-angular intraclast and extraclast, showing in general palaeocurrent clast-imbrication are common in the reworked deposit lithofacies. Ubiquitous and with a maximum thickness of 2 m is the coated reed and phytoclast lithofacies association. Boundstone with cylindrical moulds, still in growth position or as broken fragments of plant stems, coated by grey to brown-orange micrite, are common. Floatstone/wackestone, packstone, and rarely rudstone with reworked angular intraclast beds, forming laterally discontinuous beds of maximum 2 m, characterise instead the intraclast deposits lithofacies association. Other sediments alternating with the travertine lithofacies are represented by the terrigenous and volcanic deposits (Mancini et al., 2021). Terrigenous deposits are mainly characterised by palaeosoil, claystone, marlstone, sand, sandstone, and conglomerate, with these last three related to the Aniene River depositional system. The volcanic deposits, showing different colours varying from brown, black, grey to red, are related to the Colli Albani and Sabatini volcanoes (Della Porta et al., 2017). The lithofacies associations of the *Lapis Tiburtinus* travertine are related to different depositional environments (Fig. 8). The subaqueous environment, characterised by shallow lakes, waterlogged flats – pools is composed by the alternation of lithofacies associations related to shrub and laminated deposit. The palustrine environment is instead associated with swamps, sometimes evolving into shallow lakes and associated with non-laminated and laminated deposits, coated reed, and phytoclast lithofacies, alternating with intraclast deposits and palaeosoils. A higher hydrodynamic setting, characterised by the presence of the reworked travertine lithofacies, is associated with the travertine channel environment. The orientation of the N-striking channels is always towards the Aniene River, located in the southern part of the Acque Albule Basin. Crystalline crust associated with laminated deposit and occasionally coated reed and phytoclast lithofacies, characterise instead the slope environment, with an inclination of 7-10° toward the south (Della Porta et al., 2017; Mancini et al., 2019a).

Stop 2 - Querciolaie 2 quarry

Coordinates: Lat. 41°58’26.56’’N, Long. 12°44’14.78’’E

Querciolaie 2 is one of the northern quarries of the area, located at 73 m above sea level and excavated until a depth of 17 m below the topographic surface. The quarry is organised in two levels: the first one (upper part) is well excavated with respect to the second one (lower part) (Fig. 9 A-D). The dimension is 229 x 295 m. The predominant lithofacies is constituted by the laminated deposit in the eastern and in northern part of the quarry. Sometimes, laminated deposit lithofacies is intercalated with some shrub layers separated by erosional surfaces, attesting to a subaqueous environment. The inclination to the eastern part of the units suggests the influence of faults present in the area that created the accommodation space. Fractures are oriented along three main trends, N-S, E-W (N250), and N120 (Fig. 9C). Fractures related to the E-W (N250) and N120 trends are characterised by high mineralization mainly composed of FeO (marcasite and limonite) and mm – cm crystals of gypsum. According to Mancini et al. (2021), the accommodation space could be also related to local subsidence. In the upper part of the quarry is possible to observe a porous carbonate deposit passing toward the top to a palaeosoil interdigitated with claystone attesting for an input of freshwater, higher than the environment where travertine develops (Fig. 9A, C, D). This is testified by the presence of *Lymnaea stagnalis* (Fig. 8I). Such pulmonate gastropod species is indicative of slowly running water to standing water bodies. Such carbonate deposits, locally known as *Testina*, represent the end of travertine deposition with the same lithofacies present in the lower *Lapis Tiburtinus* but with a reduced lithoid characteristic and thickness (Fig. 9F, G, H, I). The contact between the travertine of the *Lapis Tiburtinus* and the *Testina* is characterised by the presence of a clay layer maybe of volcanic origin (Fig. 9E). This unit shows tabular geometries with an increase in thickness in the central part of the Acque Albule Basin.

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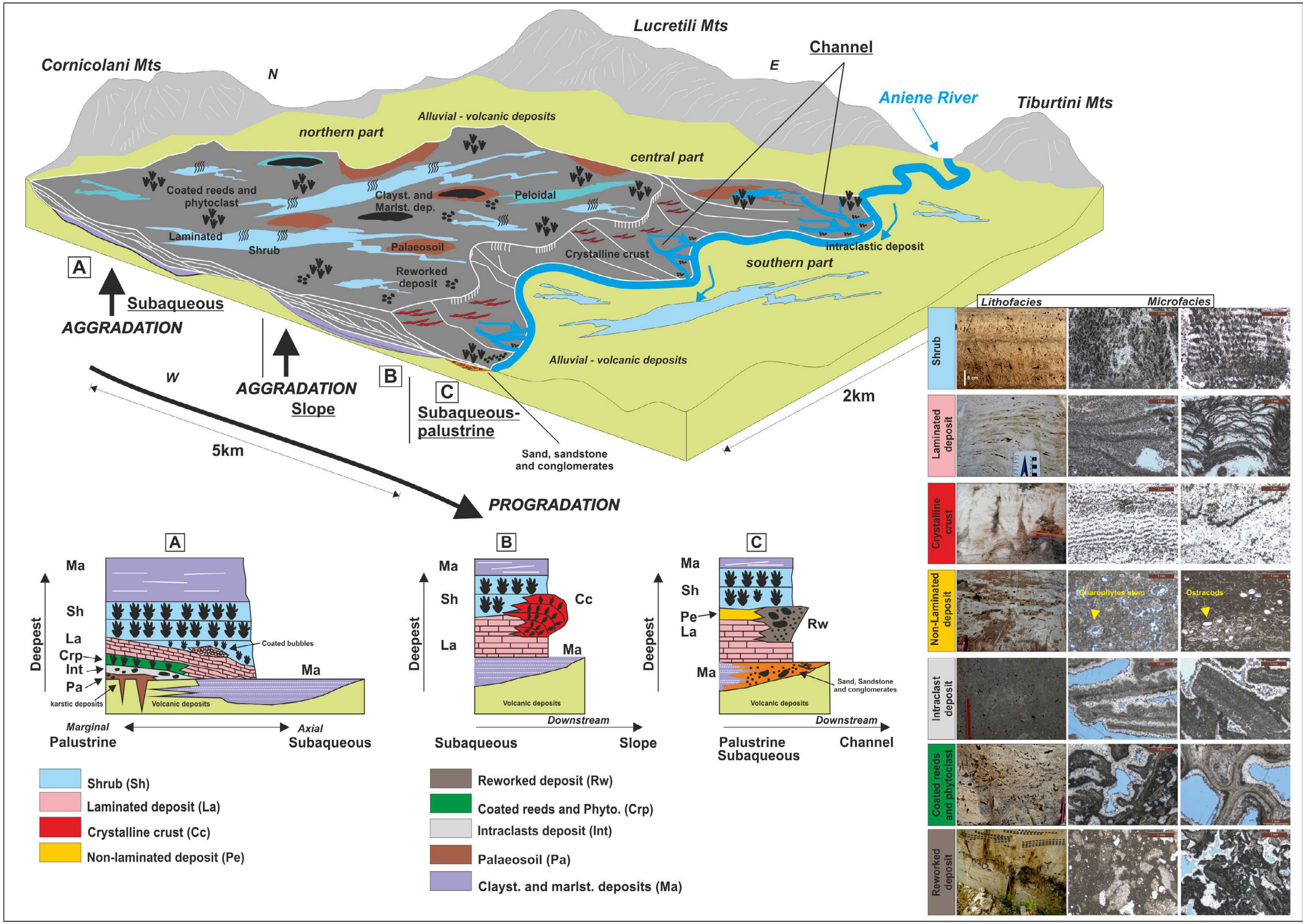

Fig. 8 - Depositional model of the Acque Albule Basin and travertine lithofacies (modified from Mancini et al., 2021).

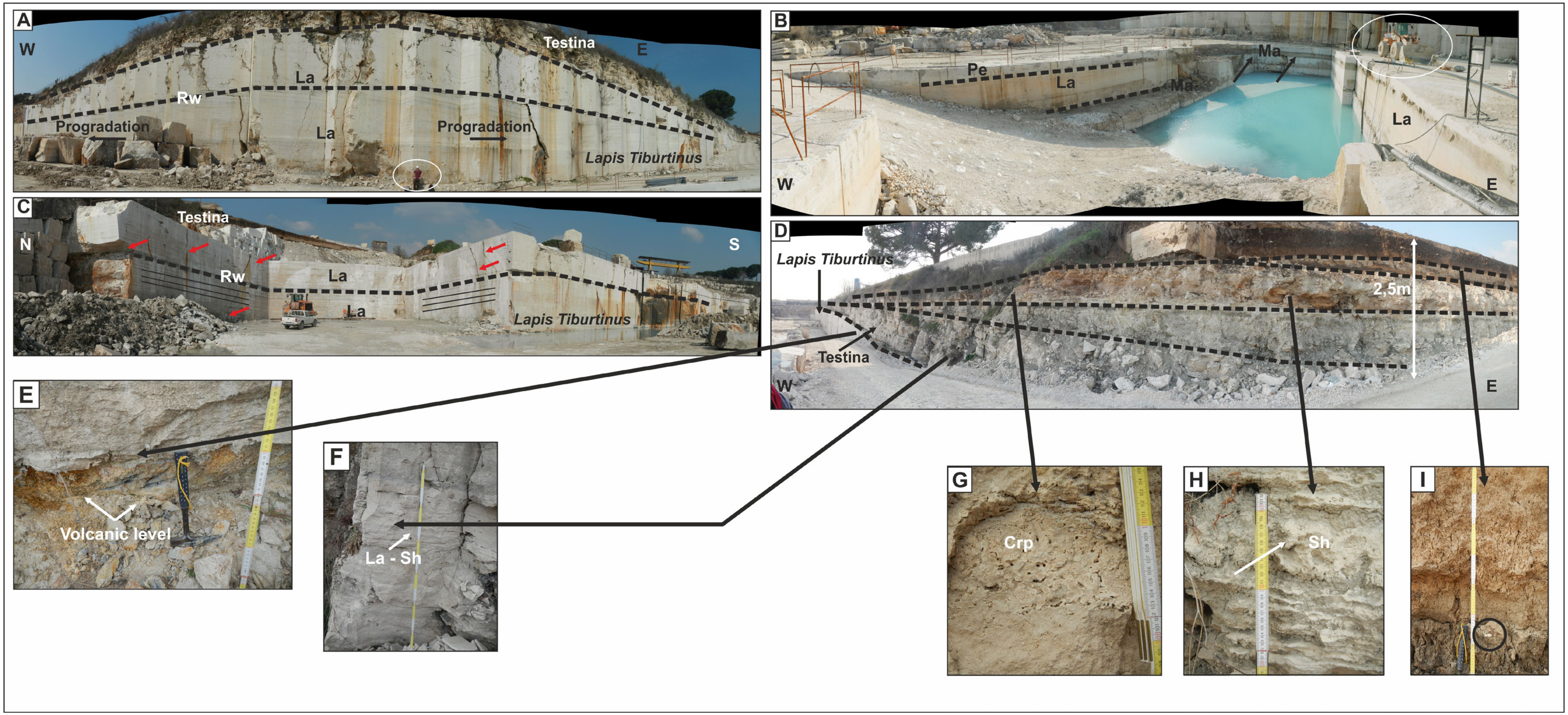

Fig. 9 - A) Panoramic view of the northern quarry wall of Querciolaie 1, showing the progradation of the travertine deposits toward the E and W of the Acque Albule Basin. In the panoramic view is possible to see also the boundary with the *Lapis Tiburtinus* and the *Testina*. B) Panoramic view of the lower part of Querciolaie 1 quarry showing the relationships with marlstone and travertine deposits. C) panoramic view showing the tilting of the travertine deposits toward the eastern sector. The fractures affecting travertine deposits are indicated by the red arrows – D) panoramic view of the *Testina* unit and the uppermost palaeosoil; E) volcanic level between the *Lapis Tiburtinus* and the uppermost *Testina* unit. F) *Testina* laminated deposit and shrub lithofacies associations. G) Phytoermal boundstone of the coated reed and phytoclast lithofacies. H) A detail of the shrub lithofacies in the *Testina* unit. I) Palaeosoil at the top of the *Testina* unit, with *Lymnaea stagnalis* gastropod (black circle) (La: laminated deposit; Rw: intraclastic deposit; Pe: non-laminated deposit; Ma: claystone and marlstone; Sh: shrub; Crp: Coated reed and phytoclast).

Stop 2.1 - Pacifici 1 quarry

Coordinates: Lat. 41°57'35.44''N, Long. LONG.: 12°44'23.00''E

Located in the eastern – central part of the Acque Albule Basin at 63 m asl, Pacifici 1 quarry is excavated to a depth of 25 m (Fig. 10A, B). This quarry is organised in two sectors: one in the northern part divided into three layers: upper, middle, well excavated, and lower less excavated. The dimension is 316 x 248 m. The southern part of the quarry is instead divided into two layers and the upper one more developed than the lowest, has a dimension of 478 x 136 m. The total dimension of the quarry is 568 x 444 m. The northern part of the quarry is characterised by the presence of laminated deposit lithofacies bounded by a layer of intraclast deposit lithofacies (Fig. 10B). Karstic features are present and well-developed in the entire walls and are located in the eastern part of the walls (Fig. 10B). The presence of laminated deposit lithofacies suggest a subaqueous environment, sometimes affected by erosional processes implying a change in the hydrodynamic conditions, while the karstic features indicate groundwater level fluctuations. The southern part of the quarry is instead characterised by the predominance of the crystalline crust and laminated deposit lithofacies associations (Fig. 10A). Such lithofacies associations reveal that this part of the quarry is located in the ancient slope system of the Acque Albule Basin, with an inclination of 7 – 10°. Furthermore, crystalline crust lithofacies indicate the presence of surfaces where the water was flowing toward the southern sector of the basin, to the Aniene River (Fig. 10C).

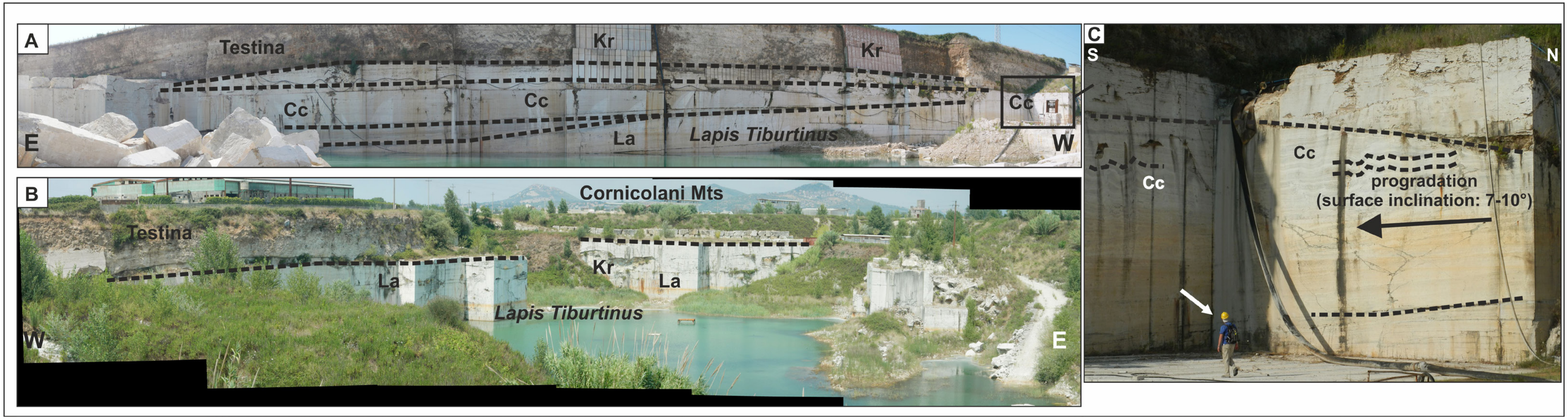

Fig. 10 - A) The southern walls of Pacifici 1 quarry. In the pictures is possible to see the geometry of the travertine units and the boundary between the *Testina*. B) the northern walls of Pacifici 1 quarry. In the panoramic view is possible to see the relationships between the different units and the karsts affecting the *Lapis Tiburtinus* travertine associated to ground water-table fluctuations. C) In this picture is possible to see the progradation toward the south of the crystalline crust lithofacies on a surface inclined 7-10° characterizing the slope system of the Acque Albule Basin (La: laminated deposit; Cc: crystalline crust; Kr: karstics features and breccia deposits).

Stop 2.2 - Poggi S quarry

Coordinates: Lat. 41°57'9.61''N, Long. 12°44'41.67''E

The Poggi S quarry (Fig. 11) is in the southern part of the study area at an elevation of 58 m above sea level. It is excavated to a depth of 27 m. This well-excavated quarry is organised into two sectors, one to the north, and another to the south. The major lithofacies are also in this case represented by the laminated deposit and crystalline crust lithofacies associations. The geometry of the depositional units shows strong dipping to the S and to the E, with a clinoform shape (Fig. 11A). The western part of the quarry is composed of different lithofacies associations, mainly related to laminated deposit, crystalline crust, and reed and phytoclast lithofacies associations (Fig. 11E, F, G). Travertine lithofacies associations are interdigitated with palaeosoil and alluvial deposits (Fig. 11D, F). Moreover, reworked deposit lithofacies occurred, attesting to a channel depositional environment, related to a water flow towards the Aniene River, revealing the strong influence of the fluvial system on the deposition of the *Lapis Tiburtinus* travertine (Mancini et al., 2021).

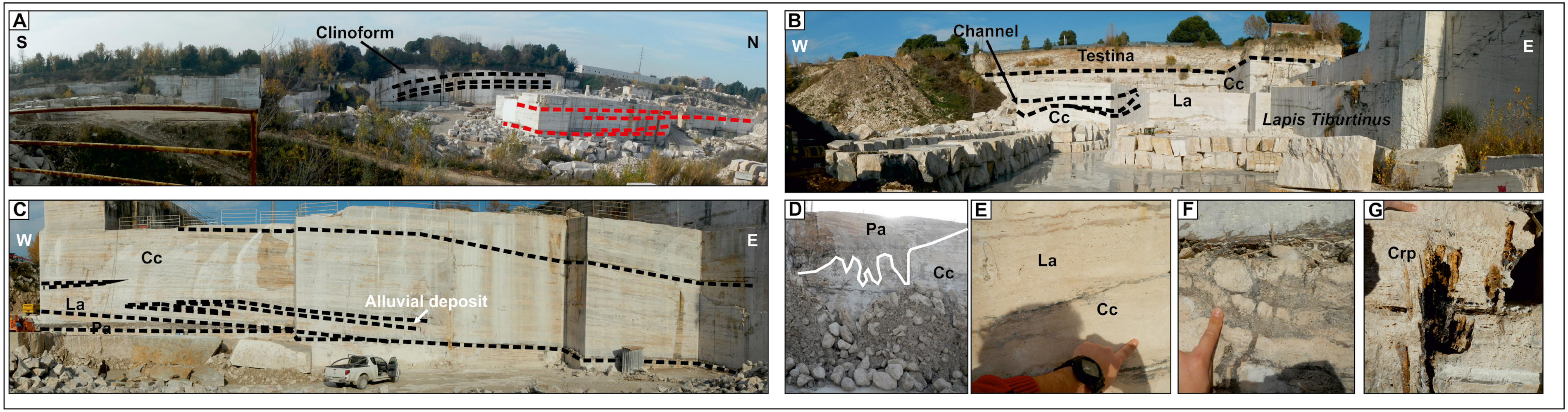

Fig. 11 - A) Panoramic view of the units present in Poggi S quarry. In the pictures is possible to see the relationships between progradation and aggrdation trends. Observing the geometry of the deposits that compose the unit in red is possible to see a gently slope with units prograding toward the Aniene River (progradation=aggradation). If we observe the geometries of the second one, in black, a stepped slope where the aggradation is more than the progradation, is clear (aggradation>progradation). This relationship is also influenced by the variation of the water table and by the accomodation space of the basin. The aggradation higher than the progradation maybe can also explain the presence of palaeosoils well developed in the S part than in the N (emersion?). B) An example of channel geometry filled by alluvial deposit and the boundary between the *Lapis Tiburtinus* and the *Testina*. C) Panoramic view of the eastern wall of Poggi S quarry. Depositional units are mainly characterised by laminated deposit and crystalline crust (E), palaeosoil (D) and alluvial deposit (F). Locally sometimes coated reed and phytoclasts lithofacies occurred (G). (La: laminated deposit; Cc: crystalline crust; Pa: palaeosoil; Crp: coated reed and phytoclasts).

Furthermore, the quarry walls located in the western part show the relationships between progradation and aggradation phenomena (Fig. 11A) of the *Lapis Tiburtinus* travertines related to the inclination of the slope toward the southern sector of the Basin in the direction of the Aniene River. The interdigitation of laminated deposit, crystalline crust, and palaeosoil, observable instead in the eastern part of the quarry, suggests that this quarry is in a slope passing to an alluvial plain environment (Fig. 11B, C).

Stop 2.3 - Pacifici 2 quarry

Coordinates: Lat. 41°56'46.76''N, Long.12°44'11.59''E)

It is one of the southernmost quarries of the Acque Albule Basin at 53 m above sea level and it is excavated to a depth of 17 m (Fig. 12). It is organised in two layers, the lower well excavated and the upper one less excavated. The quarry has a total dimension of 84 x 126 m. The major lithofacies associations are mainly composed of laminated deposits interdigitated with crystalline crust, observable in the eastern part (Fig. 12A) of the quarry, together with intraclastic deposits and well-developed palaeosoil. The geometry of the units is flat, gently dipping to the S. In the upper part of the quarry instead, the *Testina* travertine is well developed (Fig. 12A). In this quarry the *Testina* travertine has different lithofacies in comparison with Querciolaie 2 quarry. Reed and phytoclast and the crystalline crust are

Fig. 12 - A) The western wall of Pacific 2 quarry. Units are characterised by laminated deposit and crystalline crust interdigitated with palaeosoil. Toward the top of the quarry *Testina* unit crops out. In comparison with Querciolaie 1 quarry the *Testina* unit of the Pacifici 2 quarry is mainly characterised by crystalline crust (B) and coated reed and phytoclast (D) passing to palaeosoil deposits (C). The crystalline crust indicates a progradation trend toward the southern part of the basin in direction of the Aniene River (E) (Cc: crystalline crust; La: laminated deposit; Pa: palaeosoil; Crp: coated reed and phytoclast; Int: intraclastic deposit).

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predominant and sometimes divided by recent palaeosoil (Fig. 12B-E). These two lithofacies testify to a slope and a palustrine environment with water flowing toward the southern sector of the quarry in the direction of the Aniene River (Scalera et al., 2021).

CONCLUSION

The field trip between the Rapolano Terme area and the Acque Albule Basin (The *Lapis Tiburtinus* travertine) offers the possibility to observe a complete travertine depositional setting, highlighting the scale independence of such systems (Fig. 13) (Mancini et al., 2019a). The proximal zone is characterised by convex geometries, as the fissure-ridge observed in stop 1 of Terme San Giovanni, in the intermediate zone is instead observable variably inclined geometries (i.e., slope, channel) has observed in Stop 1.2 of Cava Oliviera quarry and in stops 2 and 2.1 of the Acque Albule Basin (Querciolaie 1 and Pacifici 1 quarries), while planar to tabular geometries (alluvial plain) occurred in the distal part of the

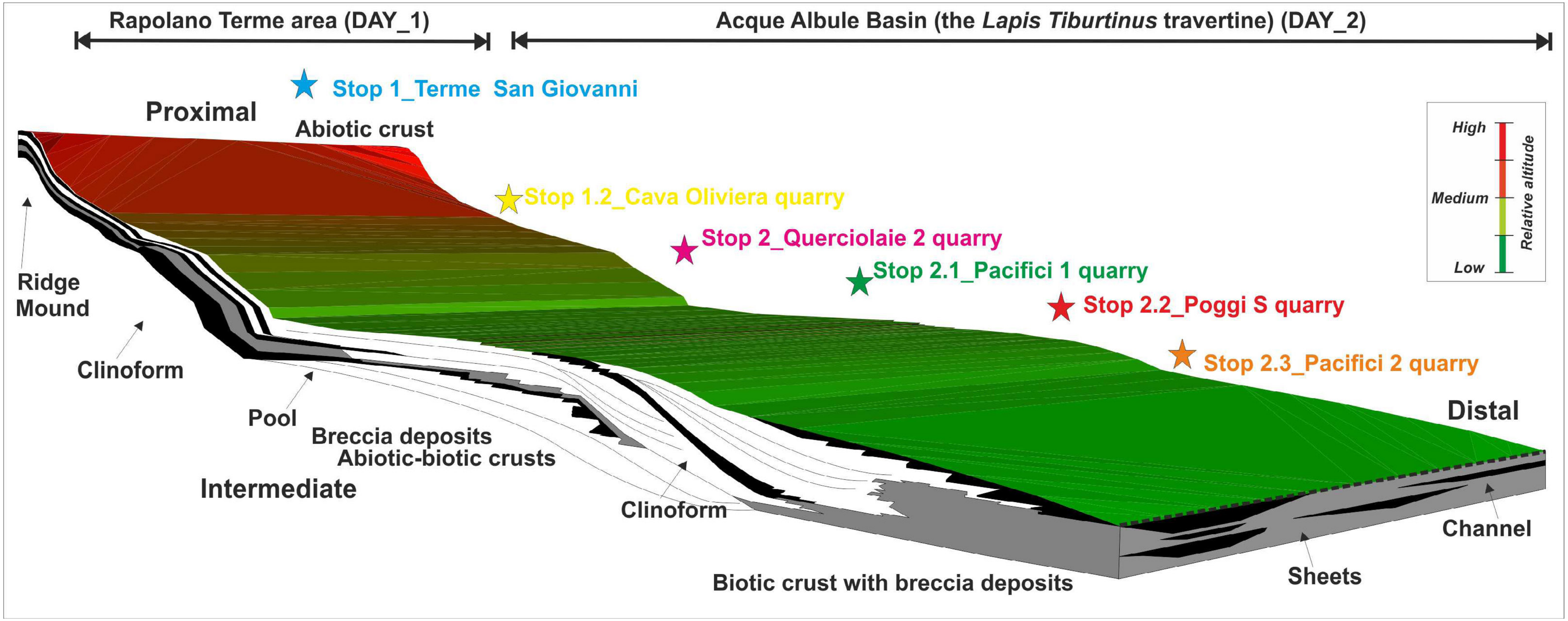

Fig. 13 - Schematic draw of a travertine depositional system with the position of the stops done in the field trip.

depositional system were observed in the stop 2.2 and 2.3 of the Acque Albule Basin (Poggi S and Pacifici 2). Furthermore, the depositional zones observed are characterised by different lithofacies associations. The abiotic crust is mainly observable in in the proximal zone as stop 1 of the Rapolano Terme area, interdigitated in the intermediate zone with the biotic crust (stop 1.2 of Rapolano Terme area, stops 2, 2.1, and 2.2 of the Acque Albule Basin) and becoming predominant in the distal depositional zone of travertine system (stop 2.3 of the Acque Albule Basin).

Such field trip permits us to understand the complexity of the travertine depositional system and the important role played by physical, chemical, and biological processes on calcium carbonate precipitation in continental settings.

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Such guide is not related to a specific event but it was awarded as “best geological field trip guide” by the GeoSed-SGI associations on 2022. The prize was received in Turin during the SGI congress (Geosciences for a sustainable future 19-21 September 2022) and in Rome during the assembly of the Geosed-SGI associations (University of Rome Sapienza, Department of Earth Sciences, 1 December 2022).

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