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A section of Italian Geological Society
Perugia, June 16-20, 2017

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Pliocene-Pleistocene continental deposits of central Tuscany. Fieldtrip guide book

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1. INTRODUCTION AND AIM OF THE FIELDTRIP

The main aim of the field trip will be to illustrate examples of continental depositional environments documented in Pliocene to Pleistocene basin-fill succession of Northern Apennines exposed in central Tuscany. The sites which will be visited during the trip were selected among others basing on quality of exposures, accessibility and presence or recently acquired/published data. The sites are distributed in the Upper Valdarno Basin and Siena Basin (Fig. 1). The Upper Valdarno Basin represents, since the Renaissance, a milestone for geological and palaeontological researches focused on continental Pliocene to Pleistocene deposits of Northern Apennines. Leonardo da Vinci was enchanted by the natural exposures of alluvial deposits along the NE margin of the basin. The same outcrops inspired Nicholas Steno in formulating the basic principles of the modern stratigraphy. The Siena Basin has a Pliocene marine infill which has been recently investigated in terms of modern sedimentology and tectono-stratigraphy. The Pleistocene portion of the infill succession is mainly made of travertine deposits, which are superbly exposed in artificial cuts and quarries. An outstanding example of an active fissure ridge allows also to observe how these deposits are accumulated in modern setting.

During this two-days trip, deposits of the Upper Valdarno and Siena Basin will allow to observe and discuss:

- Fluvio-eolian interaction;
- Channel bars and overbank deposits developed by sinuous fluvial channels;
- Alluvial fan deposits and their relation with active basin-margin faults;
- Low-sinuosity gravel-bed rivers;
- Carbonate deposition in fossil/active thermal and fluvial settings, with their relation with tectonics.

2. GENERAL OVERVIEW ON THE GEOLOGICAL SETTING OF INNER NORTHERN APENNINES

The inner Northern Apennines are a fold-and-thrust belt developed since the Late Cretaceous by the convergence and consequent collision between Africa and Europe (Molli, 2008 for a review).

During Late Oligocene-Early Miocene times, convergence and collision gave rise to a tectonic pile composed by stacked tectonic units derived from different palaeogeographical domains that, from the top, are (Fig. 2):

a) The Ligurian Units, formed by portions remnants of Jurassic oceanic crust and its Jurassic-Eocene sedimentary cover.

b) The Subligurian Units, composed of Cretaceous-Oligocene arenaceous and calcareous turbidites.

c) The Tuscan Nappe composed by sedimentary rocks (Late Triassic evaporates, Jurassic-Cretaceous carbonate and Cretaceous-Early Miocene marine clastic sediments).

d) The metamorphic Tuscan succession composed by low-grade metamorphic rocks deriving from a Triassic-Early Miocene succession, similar to the one characterizing the inner Tuscan Domain. The substratum of the Tuscan Domain (i.e., The Tuscan Metamorphic Complex, Auctt.) was involved in the collisional stage determining isoclinal folds and duplex structures. It is composed, from the top, of Triassic quartzite and phyllite (Verrucano Group Auctt.) and Palaeozoic phyllite.

e) The Umbro-Marchean Domain consists of continental-margin deposits from Trias to Late Miocene and representing the external Zone of the Northern Apennines, where a fold-and-thrust belt developed during Neogene.

After the emplacement of the tectonic units, from the Early-Middle Miocene to Quaternary the inner Northern Apennines was affected by an eastward migrating extension (i.e., northern Tyrrhenian Basin and southern Tuscany, Fig. 2) (Jolivet et al., 1990; Carmignani et al., 1995; Brunet et al., 2000), whereas the eastern Adriatic Domain (Barchi 2010) underwent to coeval compression (Elter et al., 1975).

According to several authors (Bertini et al., 1991; Brogi and Liotta, 2008; Brogi, 2011), extension in Tuscany area took place through two main extensional stages:

- the first stage (Middle-Late Miocene) gave rise to the thinning of the tectonic pile and to the lateral segmentation of the Tuscan Nappe and metamorphic Tuscan succession, through extensional detachments (Baldi et al., 1994; Dallmayer and Liotta, 1998; Brogi, 2004, 2011; Brogi and Liotta, 2008). This process led the Ligurian Units, the highest units in the orogenic tectonic pile, to overlie the Late Triassic evaporite or the Palaeozoic phyllite. Thus, this geological process determined the tectonic omission of several, previously stacked, tectonic units, as well as the lateral segmentation of the Tuscan Nappe and the metamorphic Tuscan succession (Fig. 3).

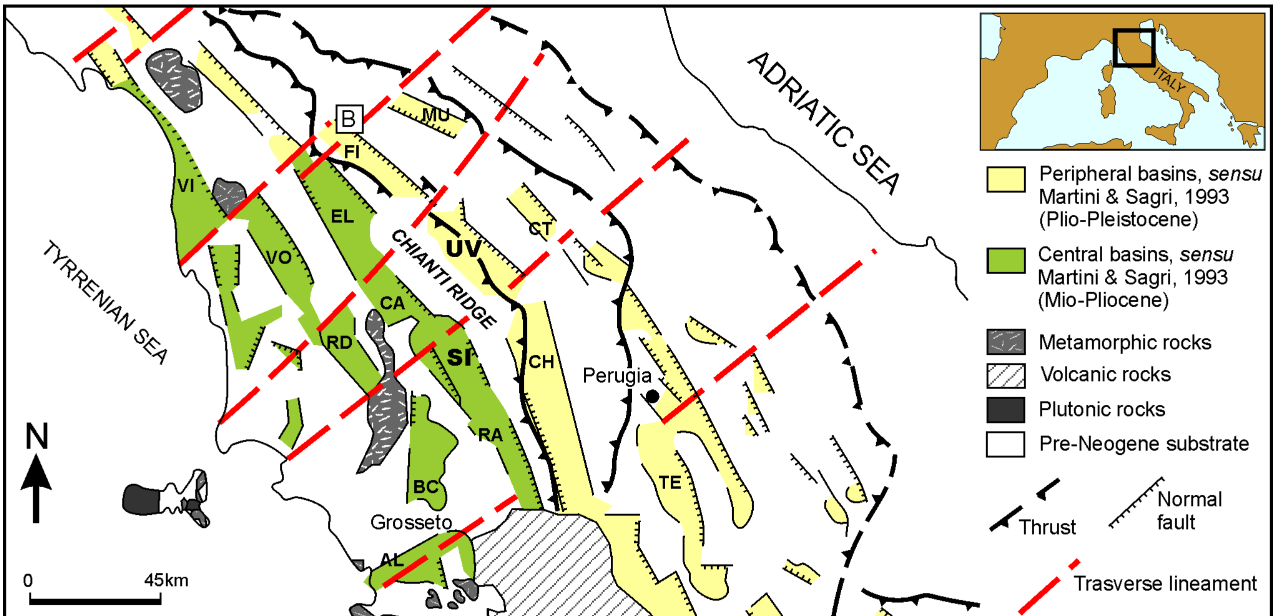
- during the second stage (from the Early Pliocene) high-angle normal and oblique to strike-slip faults dissected the extensional detachments (Brogi, 2011) and gave rise to about N-S trending structural depressions mainly filled by marine sediments, delimited by roughly parallel ranges (Martini and Sagri, 1993), where exhumed successions widely crop out. Structural depressions (Neogene basins of southern Tuscany) and the interposed ranges were separated by near orthogonal transfer zones (Liotta, 1991). Minors structures related to these transfer zones were active until the latest Pleistocene (Brogi et al., 2010a) and are considered the main controllers for the hydrothermal circulation (Brogi et al., 2010a).

Alternatively to such "extensional" interpretation, in the last decade few authors considered the Northern Apennines affected by compressional tectonics active from the Cretaceous to Pleistocene. In this view, the Neogene basins of southern Tuscany are interpreted as thrust-top basins related to deep-seated thrusts (Bonini and Sani, 2002).

Regardless of their tectonic evolution, the Northern Apennines basins (Fig. 1) are filled with up to 3 km of upper Miocene to Quaternary deposits. The basins west of the Chianti-Cetona Ridge are filled with upper Miocene-Pliocene fluvio-lacustrine and shallow-marine deposits (central basins, sensu Martini and Sagri, 1993; such as the Siena Basin). Differently, those east of the Chianti-Cetona Ridge (such as the Valdarno Basin) contain middle Pliocene-Pleistocene continental deposits (peripheral basins: sensu Martini and Sagri, 1993).

Six regional unconformity-bounded units (Pascucci et al., 2007) have been recognized in the Neogene-Quaternary succession (Fig. 4).

- Sequence 1 is made of shallow-marine sandstones with occasional marlstones, capped by conglomerates (Serravalian to early Tortonian in age).
- Sequence 2 consists of conglomerates, sandstones and clays. The lower part contains thin layers of lignite, whereas the upper one hosts thin gypsum layers, marine clays and local patch-reefs (late Tortonian to early Messinian).
- Sequence 3 is mostly composed of lacustrine to brackish clays with some layers of sandstone and conglomerate, although some marine gypsum layers are present in the lower part (late Messinian).
- Sequence 4 is manly made of marine clays with a few interstratified conglomeratic and sandy layers, which are common along the basins margins (Early Pliocene).
- Sequence 5 is composed of marine clays with thin sandstone units and biocalcarenites (Middle Pliocene).
- Sequence 6 is made of deposition in shallow-marine settings near the Tyrrhenian Sea and fluvio-lacustrine settings inland (Pleistocene).



Basins: AL, Albegna; BC, Baccinello; CA, Casino; CH, Chiana; CT, Casentino. EL, Elsa; FI, Firenze; MU, Mugello; RA, Radicofani; RD, Radicondoli; **SI, Siena**; TE, Tiberino; VI, Viareggio; VO, Volterra. **UV, Upper Valdarno Basin**

Fig. 1 - Neogene to Quaternary basins of Northern Apennines (modified after Martini and Sagri, 1993).

After such common sequence, during Quaternary all basins were characterized by local continental evolution and a widespread, fluvial-lacustrine, terrigenous deposition, especially in the easternmost basins. In southern Tuscany these deposits are often interbedded with carbonate deposits (lacustrine limestone, calcareous tufa and travertines). This deposition is strictly linked to the regional karstic groundwater circulation that characterize the Tuscan carbonate-rich formations, and by the occurrence of widespread geothermal anomalies (such as those of Larderello and Monte Amiata) producing hydrothermal circulation mainly channelled along damage zones related to faults.

Normal faults and related transfer zones were coeval with the emplacement of granitoids, volcanic rocks and widespread dike formation whose magma has both crustal and mantle geochemical signature (Serri et al., 1993; Dini et al., 2005). The emplacement and final crystallization of these granitoids determined, during Late Miocene-Pleistocene regional thermometamorphism and widespread hydrothermal circulation depositing mixed sulfides and silicates within tectonic breccias and fractured rock masses (Musumeci et al., 2002), and give rise to two main geothermal anomalies mainly centred in the Larderello and Amiata Mt. area, where heat flow values of 1000 and 600 mW/m^2 were estimated, respectively (Batini et al., 2003) (Fig. 5).

Large fluxes of crustal and mantle-derived CO_2 released in the geothermal areas, caused large scale carbonate dissolution when it came in contact with the carbonate sediments (Minissale and Sturchio, 2004). For this reason the many thermal springs that emerge in southern Tuscany (and widespread in central-southern Italy) near the margins of the carbonate formations are $CaCO_3$-oversaturated; many of them have CO_2 effervescence and several of them precipitate travertine. Travertines are actively forming or associated with thermal spring emergences (even if not travertine-precipitating) or CO_2 emission, but many more springs are currently inactive (Minissale et al., 2002; Minissale, 2004).

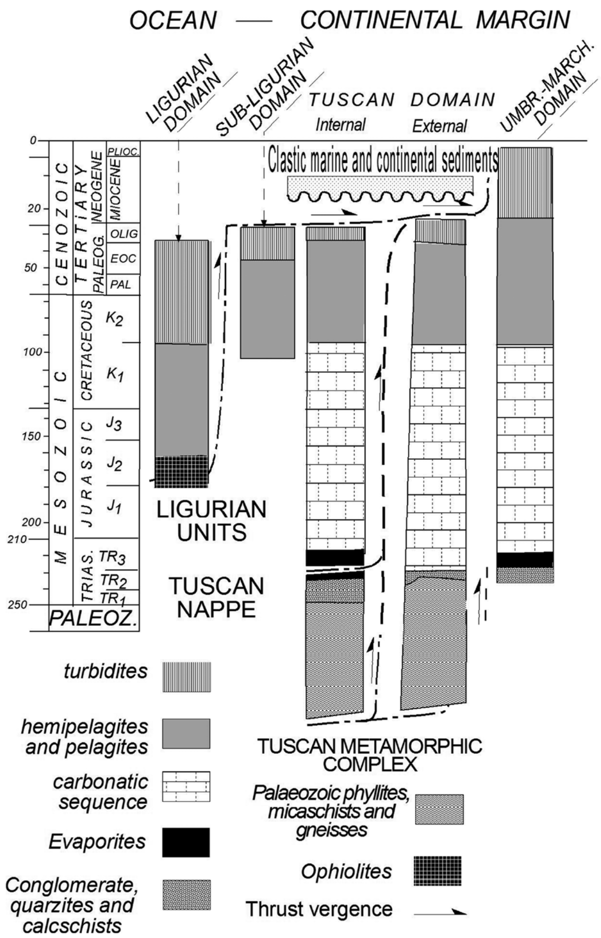


Fig. 2 - Relations among the different tectonic units of Northern Apennines and related palaeogeographical domains (after Carmignani et al., 1995, modified).

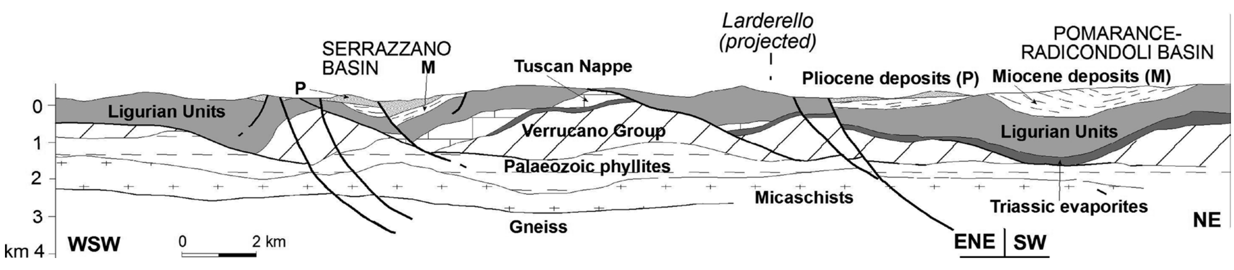


Fig. 3 - Geological section across the Larderello-Travale geothermal area in southern Tuscany, highlighting the geological process which gave rise to the thinning of the overthickened continental crust and the lateral segmentation of the previously stacked tectonic units (after Baldi et al., 1994 modified).

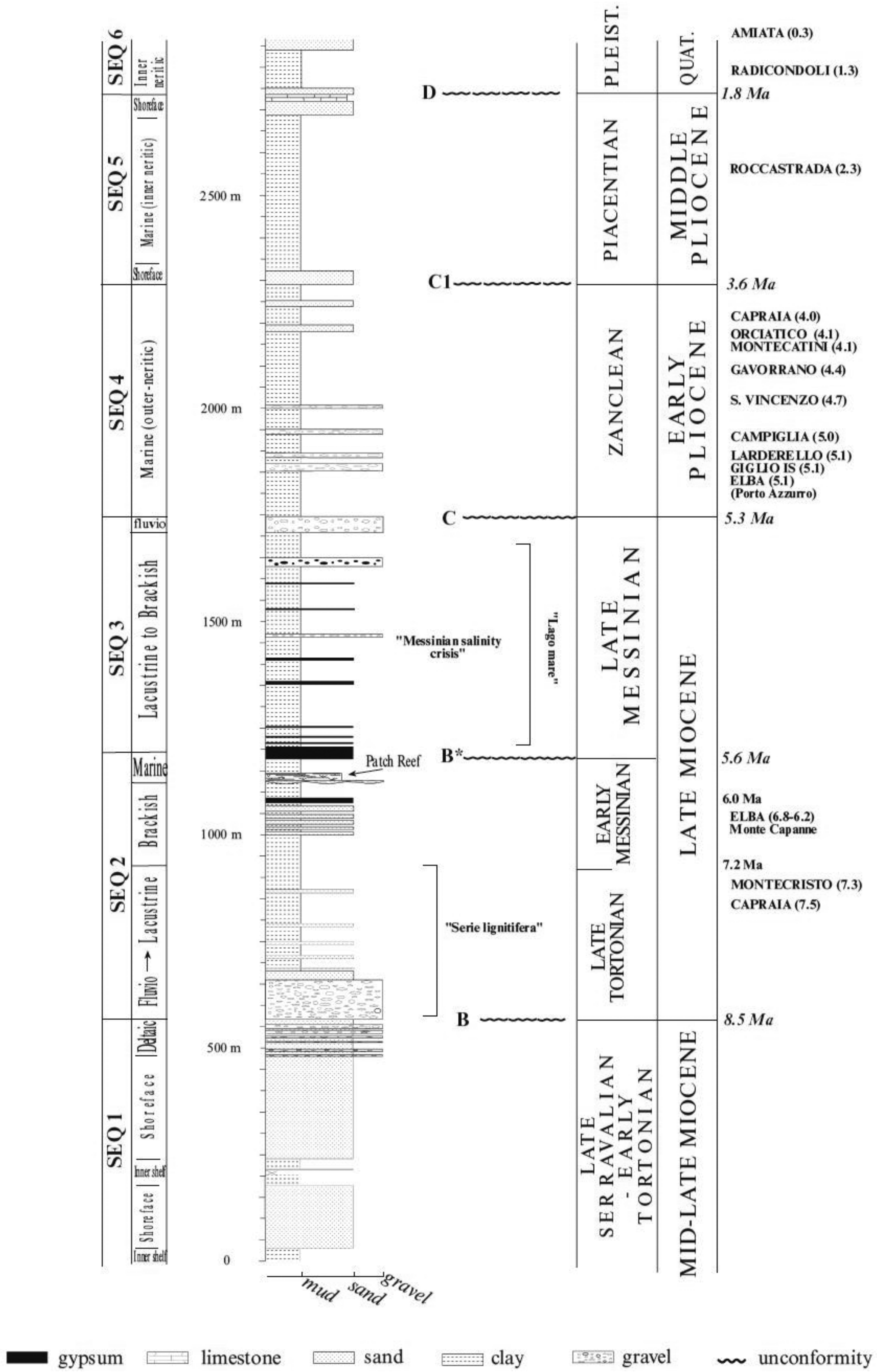


Fig. 4 - Sedimentary sequences detected in the Neogene-Quaternary basins of inner Northern Apennines.

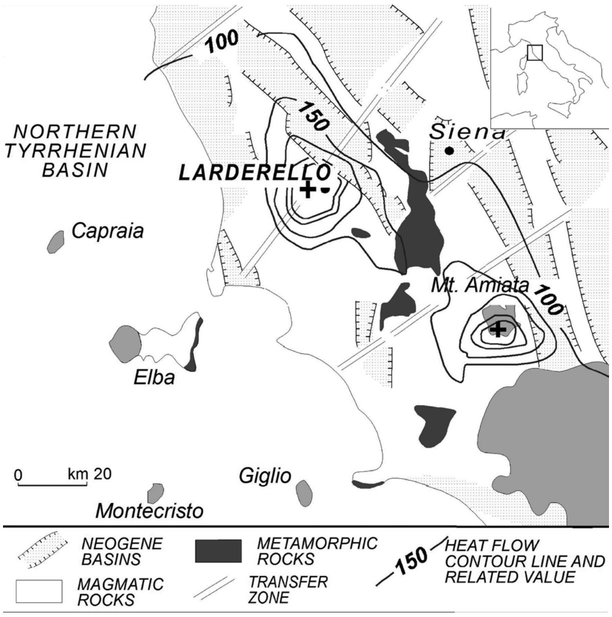


Fig. 5 - Structural sketch map of southern Tuscany with regional heat flow contour lines (equidistance: 50 mW/m^2). The plus signs show the Larderello and Amiata Mt. geothermal fields where heat flow reaches 1000 mW/m^2 and 600 mW/m^2, respectively (redrawn from Baldi et al., 1994).

I° DAY

3. ALLUVIAL AND FLUVIO-EOLIAN DEPOSITS OF THE PLIO-PLEISTOCENE UPPER VALDARNO BASIN

3.1. The Upper Valdarno Basin

The Upper Valdarno Basin (Fig. 6) to stand out from most the Neogene-Quaternary basins of the Northern Apennines for its exceptional fossil mammal record, along with the good quality of natural and artificial outcrops (Abbate, 1983; Sagri and Magi, 1992; Martini and Sagri, 1993; Torre et al., 1993; Albianelli et al., 1995; Ghinassi et al., 2004, 2005, 2013; Mazza et al., 2004, 2006; Ielpi, 2012; Esu and Ghinassi, 2013; Fidolini et al., 2013a, 2013b; Rook et al., 2013; Ielpi and Ghinassi, 2014; Bianchi et al., 2015) and has been used as key case to formulate new hypotheses on the latest phases of the Apenninic chain evolution and formation of the Neogene-Quaternary intermontane depressions (Sagri and Magi, 1992; Martini and Sagri, 1993; Bonini and Sani, 1993; Boccaletti and Sani, 1998; Martini et al., 2001; Bonini et al., 2013; Brogi et al., 2013).

The Valdarno Basin is located 35 km SE of Florence between the Chianti Mountains and the Pratomagno Ridge (Fig. 6). It is a 15 km wide half-graben elongated 35 km in a NW-SE direction. Southwest dipping master normal faults, bound the basin to the northeast, whereas small synthetic and antithetic normal faults occur along the southwest margin. The sedimentary fill of the basin consists of over 550 m of palustrine, lacustrine and alluvial deposits.

The basin-fill succession, which consist of over 550 m of palustrine, lacustrine and alluvial deposits, has been recently revisited and subdivided into four synthems (Fidolini et al., 2013a), which are, from the bottom up: Castelnuovo dei Sabbioni (CSB), Montevarchi (VRC), Fosso Salceto (OLC) and Torrente Ciuffenna (UFF) synthems. Synthems CSB, VRC and UFF occur in the Upper Valdarno Basin (Fig. 7), whereas synthem OLC was deposited in the Palazzolo sub-Basin and is almost coeval with the upper part of the VRC Synthem. The CSB Synthem (Late Pliocene) is exposed along the Chianti margin and shows a maximum thickness of about 200 m. It consists of basal fluvio-deltaic gravel and sand (CSBa in figure 7), grading upward into lacustrine mud with lignite levels (CSBb in figure 7), in turn overlain by fluvio-deltaic sand (CSBc in figure 7). The VRC Synthem (Late Pliocene-Early Pleistocene) consists of two parts separated by a minor unconformity surface which passes into a conformable surface moving from the Chianti margin to the basin. The lower part (Late Pliocene-Early Pleistocene) crops out only along the SW margin, where is at least 40 m thick. This part is made of alluvial fan gravels (VRCa in figure 7) grading upward into aeolian-reworked alluvial sand (VRCb in figure 7), which grades into mollusc-rich alluvial sand (VRCc in figure 7). The upper part is exposed at the basin scale and is about 30 m thick along the Chianti margin and thickens moving toward NE, reaching at least 100 m at the toe of the Pratomagno Ridge. This part is made of axial fluvial sand and mud (VRCd, VRCe and VRCf in figure 7) interfingering with gravelly alluvial fans (VRCg in figure 7) sourced from the margins and palustrine deposits. The OLC Synthem is exposed in the Palazzolo sub-basin, located in the NW sector of the Valdarno basin (Fig. 7). It consists of palustrine mud (OLCa in figure 7) making lateral transition to and passing upward into alluvial fan deposits (OLCb in figure 7). These palustrine and alluvial deposits are considered almost coeval with VRCe and VRCg deposits developed in the main Valdarno basin. The UFF Synthem (late Early to Middle Pleistocene) includes fluvial gravel and sand in the central portion of the basin (UFFa in figure 7) and alluvial fan gravels and sand developed at the margins (UFFb in figure 7). Both UFFa and UFFb deposits are covered by muddy, heavily pedogenized alluvial deposits (UFFc in figure 7).

3.2. Tectono-sedimentary evolution

Fidolini et al. (2013a) summarized the tectono-sedimentary evolution of the Upper Valdarno Basin as follow (Fig. 8):

1. (Fig. 8 A-C) - The basin was generated during Late Pliocene through a tectonic damming of a north-eastward flowing drainage. The onset of this damming is documented by fluvial, valley-fill gravels (CSBa) at the base of the Castelnuovo dei Sabbioni Synthem, whereas the definitive damming is indicated by development of fully lacustrine conditions (CSBb) at about 3.1 Ma. The lake was progressively filled by deltas fed from the SW margin (CSBc).

2. (Fig. 8C) - A tectonic phase, occurred before 2.58 Ma, caused uplift of the basin margins (Chianti Mountains and Pratomagno ridge) and partial erosion of the Castelnuovo dei Sabbioni Synthem westernmost deposits.

3. (Fig. 8 D-E) - Deposition of the lower part of the Montevarchi Synthem testifies a marked basin broadening and re-equilibrium of the morphological profile resulted from the previous tectonic deformation. Such a re-equilibrium allowed accumulation of FU alluvial fan successions (VRCa), which were capped by aeolian-reworked alluvial sand (VRCb) deposited at about 2.5 Ma.

4. (Fig. 8F) - A new deformative phase caused a basin widening, erosion along the SW margin and deposition in distal areas. As a consequence of this tectonic pulse, a topographic low developed in the S.Cipriano area where lacustrine facies accumulated (VRCc).

5. (Fig. 8G) - Deposition of the upper part of the Montevarchi Synthem started at about 2.2 Ma and testifies re-equilibrium of the morphological profile derived from the previous tectonic deformation. Such basin reorganization leaded to the establishment of an axial fluvial drainage (VRCd and f) and marginal alluvial fans (VRCg).

6. (Fig. 8 H-I) - During the Early Pleistocene (Olduvai Subchron, 1.95-1.78 Ma), a further subsidence pulse

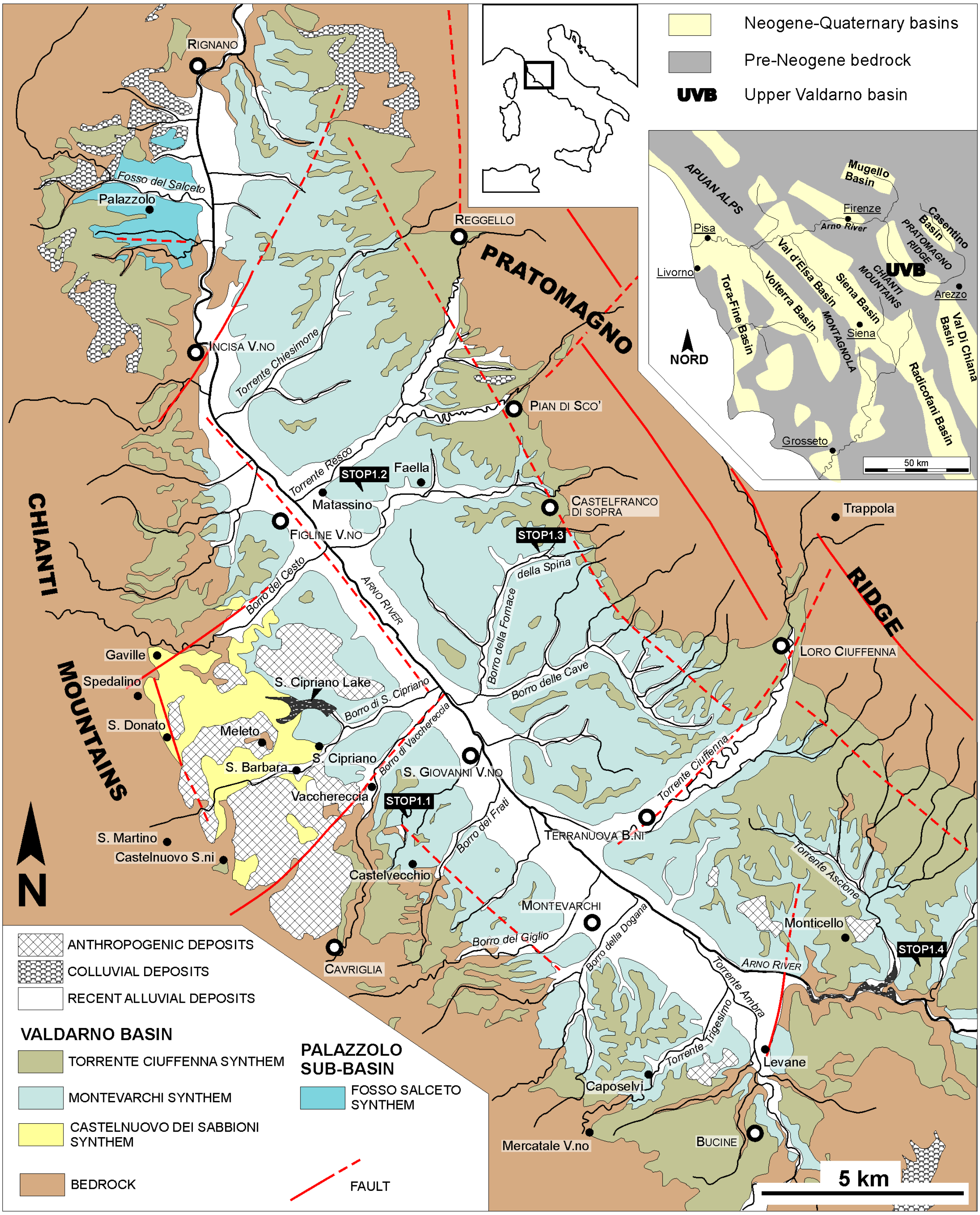


Fig. 6 - Geological sketch map of the Upper Valdarno Basin (after Fidolini et al., 2013a). Location of stops is indicated.

triggered a new morphological disequilibrium along the margins and subsidence in the axial portion, where floodplain lakes and swamps developed (VRCe). The alluvial fans progradation, which stemmed out as response to the morphological disequilibrium, led to development of small isolated fan-delta systems (VRCg).

7. (Fig. 8L) - During late Early Pleistocene, a tectonic pulse and the entrance of the palaeo-Arno River into the basin caused development of a marked unconformity, whereas the subsequent re-equilibrium (late Early Pleistocene to Middle Pleistocene) led to formation of a FU depositional trend both in fluvial (UFFa) and alluvial fans (UFFb) successions at about 0.781 Ma (Matuyama-Brunhes boundary). During the Late Pleistocene the

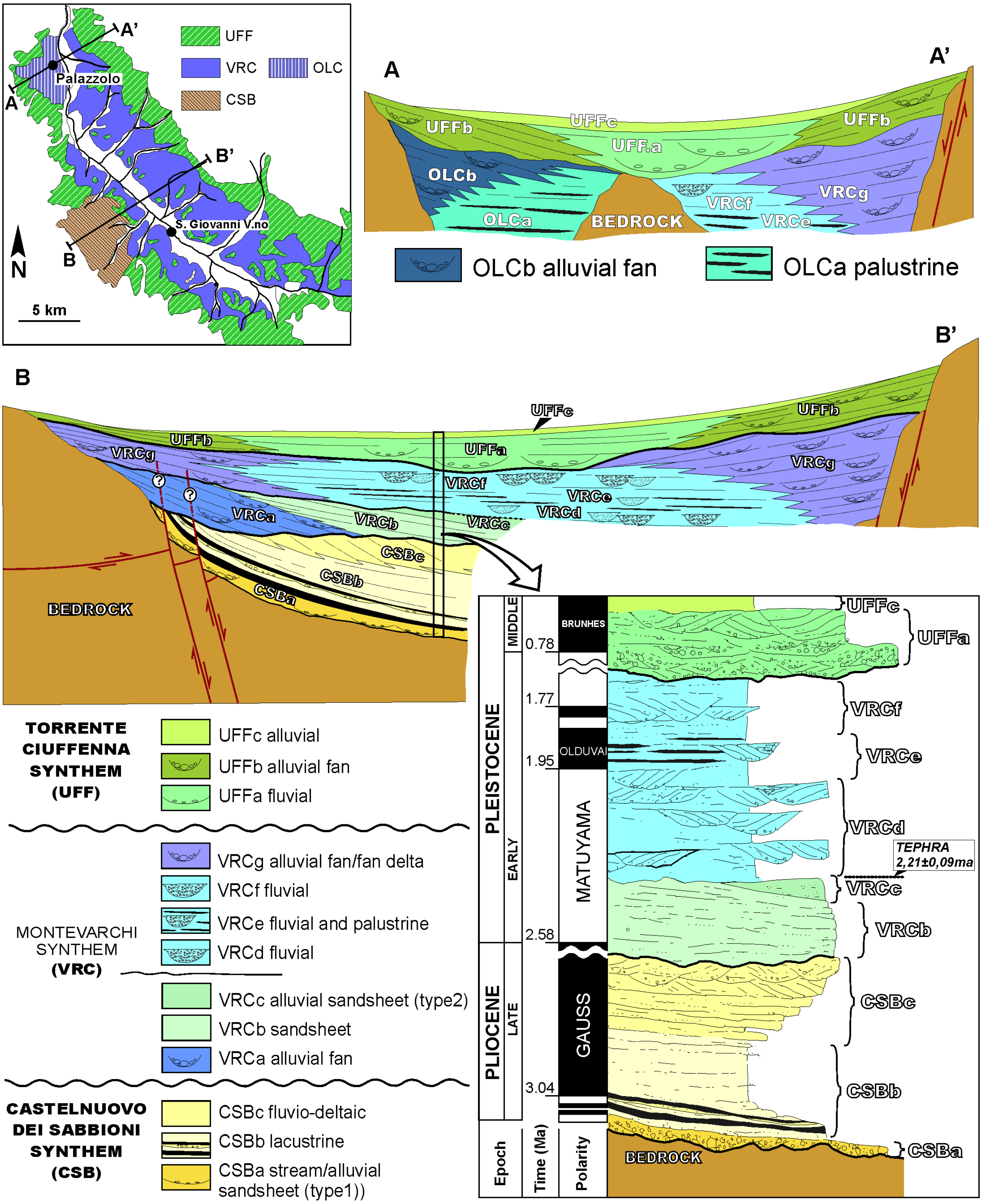


Fig. 7 - Stratigraphic scheme of the Upper Valdarno Basin and Palazzolo sub-basin (after Fidolini et al., 2013a). Palaeomagnetic calibration shown in the lower, right side is referred to a composite section measured across the axial part of the basin.

palaeo-Arno River and its tributaries cut down through the basin fill forming terraced deposits and allowing the basin to reach the modern configuration.

STOP 1.1: Fluvio-eolian sandsheet deposits (unit VRCb)

Google Earth Coordinates: Lat. 43°33’1.51”N. Long. 11°30’59.46”E

Things to observe: dominance of tabular stratal

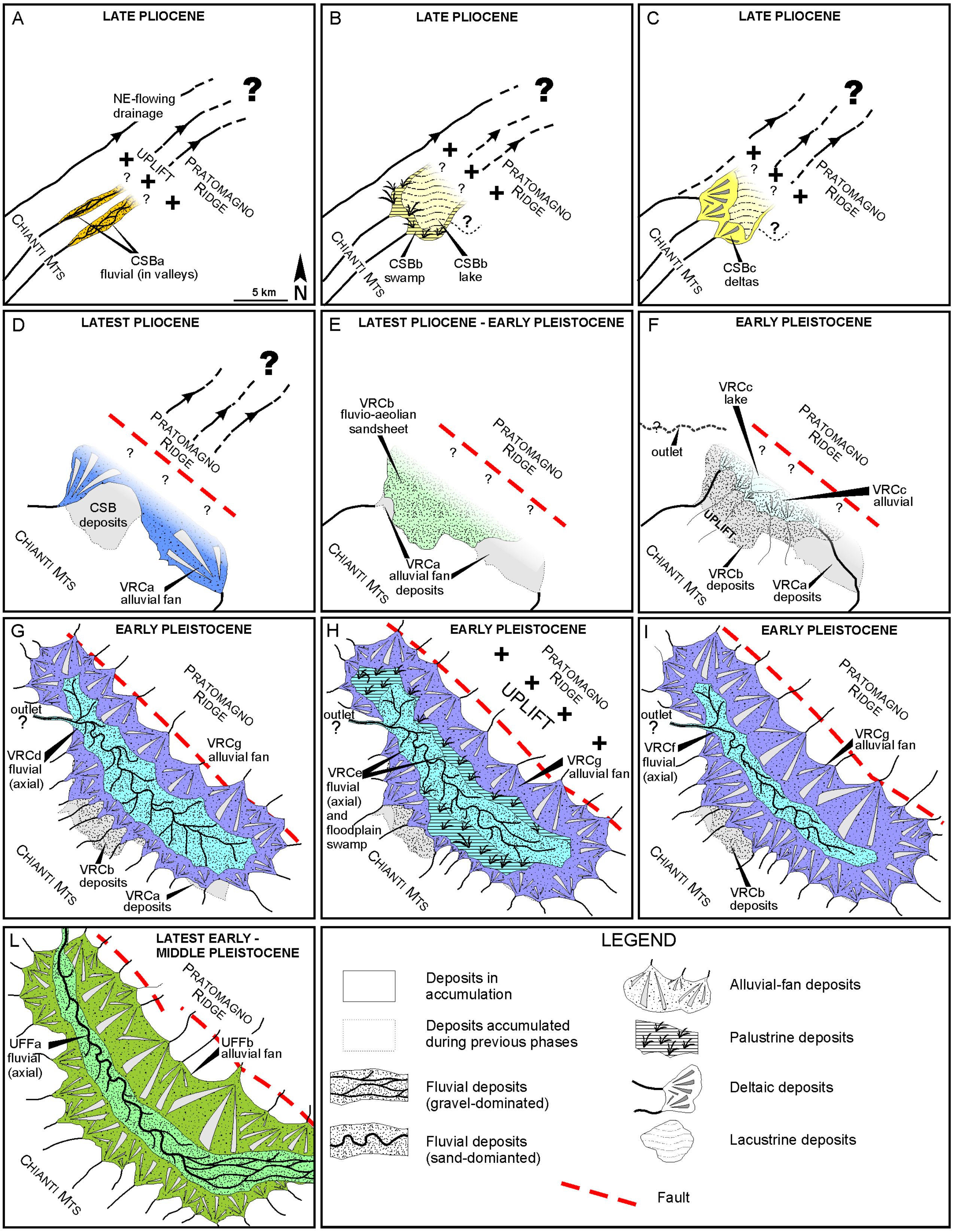


Fig. 8 - Tectono-stratigraphic evolution of the Upper Valdarno Basin (after Fidolini et al., 2013a).

geometries, eolian sedimentary structures.

Things to discuss: fluvio-eolian interaction, reworking and preservation of eolian deposits, forcing of eolian deposition.

Fluvio-eolian sandsheet deposits are locally characterized by a high textural and compositional maturity, and consist of (i) vertically stacked tabular sandy beds (Fig. 9A), which, at few places, are cut by (ii)

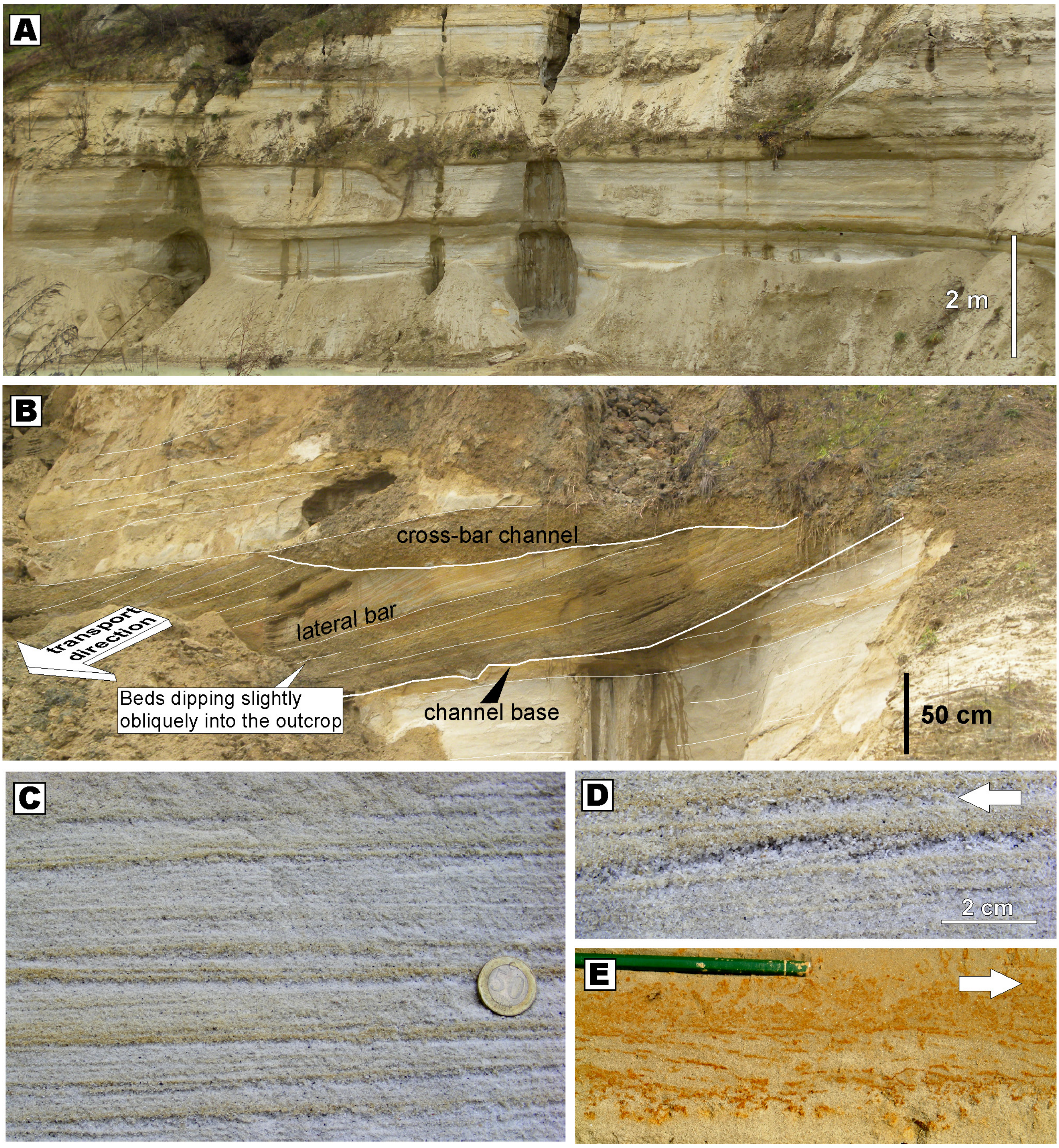


Fig. 9 - (A) Tabular beds made of well- (whitish) and poorly-sorted (brownish) sand respectively. (B) Channelized gravelly-sand deposits. Bedding transverse to the transport direction (white arrow) points to a lateral accreting bar; (C) Low-angle, translatent eolian ripple lamination; (D) Cross lamination on the crest of an aeolian grain ripple. White arrow points to wind direction; (E) Crinkly, cross lamination generated by upwind accretion of adhesion ripples. White arrow points to wind direction.

lensoid sandy lithosomes (Fig. 9B).

i) Tabular beds (up to 1 m thick) are made of fine to medium sand, which can vary from moderately to very well sorted. Moderately sorted sandy beds show a sharp base and can be ungraded or normally graded. Plane-parallel and cross stratification, along with ripple-cross lamination, are very common and locally disturbed by fluid-escape structures. Well-sorted sandy beds show a marked lateral persistence and are associated with encrustations of iron oxides. Well-sorted sandy beds are characterized by a diffuse planar stratification (Fig. 9C). Single strata range from horizontal to very gently inclined (3°-5°) with occasional internal inverse grading. At places, isolated ripple forms (Fig. 9D) are preserved with the coarser sand grains concentrated in the crest zone. Well-sorted sand can locally show cross stratification, both at the ripple and dune scale, and commonly associated with millimetric mud layers. The iron encrustations associated with the well-sorted sand show a remarkable lateral persistence and can be up to 50 cm thick. Sand associated with these crusts is characterized by a diffuse crinkly lamination (Fig. 9E), which varies from sub-horizontal to gently inclined (10°-15°).

ii) Lensoid sandy units (Fig. 9B), up to 1 m thick and 10-15 m wide, are commonly associated with moderately sorted deposits. These units show a concave-upward base and flat top and are characterized by a fining-upward trend. The lowermost part of these lenses is commonly floored with fine pebbles and subangular, pebble-size mudclasts. This basal gravelly interval is covered by gently inclined beds (5°-10°) dipping toward the lens axis. Inclined beds consist of plane-parallel stratified to ripple-cross laminated medium to coarse sand with scattered gravels. Muddy layers may occur between these sandy beds.

STOP 1.2: Fluvial sand and mud (unit VRCe-f)

Google Earth Coordinates: Lat. 43°37'34.67"N. Long. 11°30'3.13"E

Things to observe: channelized sandbodies, tabular overbank deposits, cross-stratification.

Things to discuss: channel lateral migration, crevasse-splay geometries.

These deposits (Fig. 10) consist of lenticular sandy bodies (i) embedded within horizontal-bedded mud and sand (ii).

i) The lenticular sandy bodies (i.e. channel forms) show concave, erosive base and flat top (Fig. 10A) and are 3-4 m thick and 20-30 m wide. These lensoid units show a fining-upward trend (from sand to mud) and are floored with very coarse pebbly sand. The lenses consist of large-scale inclined beds defining wedge-shaped sets in

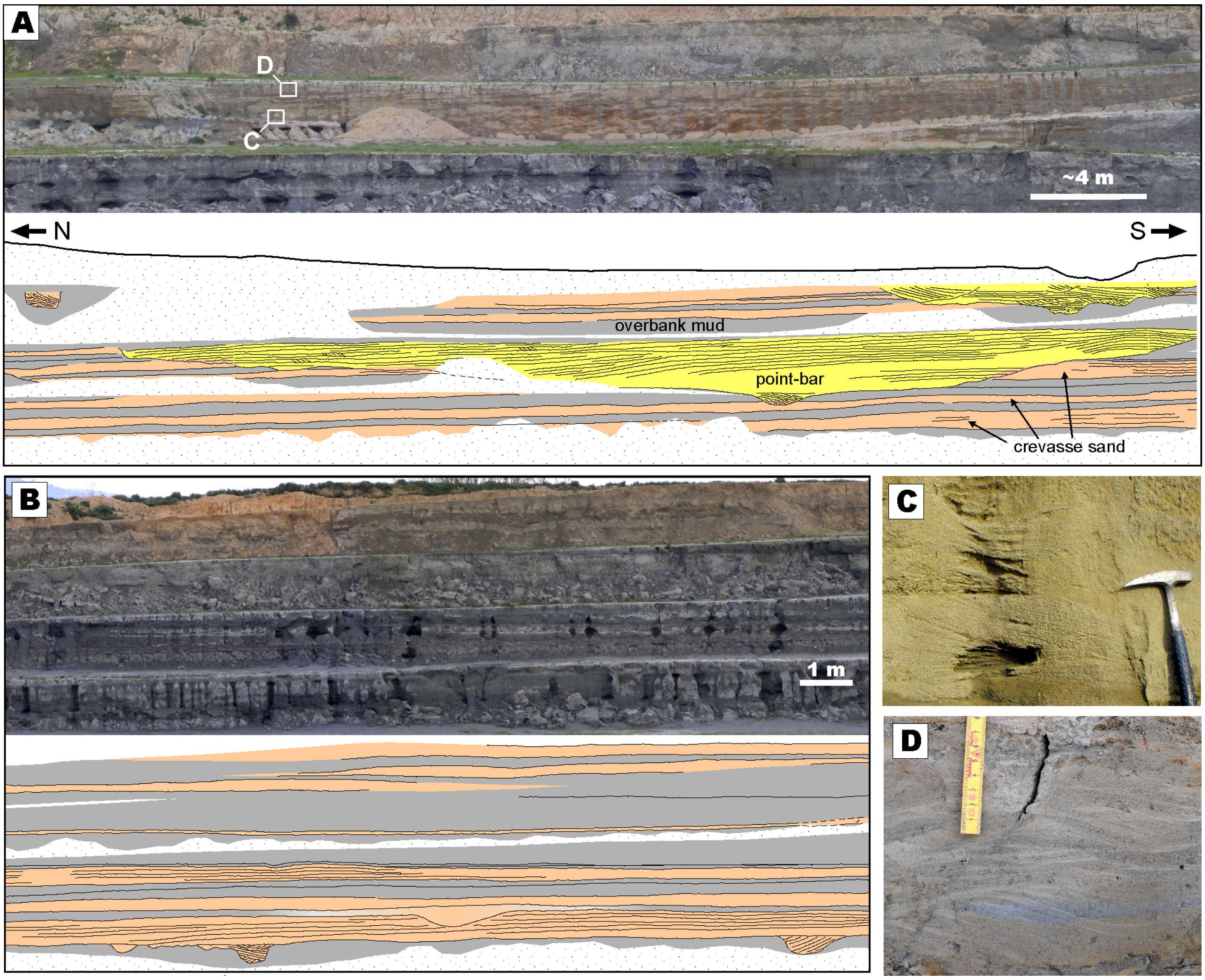


Fig. 10 - (A) Channelized sand cut in and overlain by horizontally-bedded overbank sand and mud. Channelized sand consists of planar to cross-stratified beds dipping transverse to the main transport direction (i.e. out of the photo); (B) Tabular bedded overbank deposits consisting of massive, pedogenized mud and planar to cross stratified sand locally showing a markedly erosive base; (C) Cross-stratified coarse sand in the lower part of the channelized sand shown in A; (D) Climbing ripples developed in the upper part of the channelized sand shown in A.

section transversal to the palaeotransport direction. Beds dip from 5° to 20° toward the basal surface and consist of plane-parallel, trough-cross stratified and ripple-cross laminated sand (Fig. 10E and D). Palaeotransport direction from cross strata and from imbricated basal pebbles was transverse to the dip of beds. Minor erosive surfaces can occur within these bodies.

ii) Horizontal-bedded mud and sand consist of laterally continuous, tabular muddy beds with subordinate sand (Fig. 10B). Muddy beds, up to 2 m thick, are massive or faintly laminated. They commonly contain well-developed soils, although pedogenic evidences are lacking where they contain abundant organic matter and plant debris. Sandy beds, up to 1.5 m thick, are made of coarse to fine sand, which can be massive, plane-parallel stratified or ripple-cross laminated. Beds are commonly normally graded, erosive-based and show gravel-filled, basal scours up to 1 m deep. They are commonly affected by pedogenic processes in their uppermost part and pinch laterally over distances ranging from few to several tens of meters.

STOP 1.3: Alluvial-fan deposits (unit VRCg)

Google Earth Coordinates:
Photo A-B: Lat. 43°36'41.93"N. Long. 11°33'12.87"E
Photo C: Lat. 43°36'38.06"N. Long. 11°33'29.20"E

Things to observe: coarsening- and fining-upward grain size trends at the scale of the sedimentary succession, sin-sedimentary tilting of beds, stratal architecture of channel bars.

Things to discuss: origin of coarsening- and fining-upward grain size trends, tectonic control on sedimentation, palaeomorphodynamics of fluvial bars.

Alluvial-fan deposits consist of lenticular gravels (i) and horizontal-bedded sand with subordinate mud (ii) combined in a different proportion.

i) Lens-shaped gravelly deposits are made of moderately rounded clast-supported pebbles to boulders. These lenses are 1 to 2 m thick and 5 to 30 m wide and show a basal gravelly pavement made of well-imbricated a(t) b(i) clasts indicating a palaeoflow parallel to the lens axes. This pavement is covered by stratified gravels showing a variable stratal organization.

ii) Horizontal-bedded sandy deposits consist of medium-to-coarse grained sand with scattered pebbles, dispersed or concentrated in strings in the lower part of the beds. Bedding is hardly discernible due to extensive bioturbation, root traces and pedogenetic processes, including caliche horizons and mottling. Beds are up to 50 cm thick with flat tops and sharp, non erosive to undulating erosive bases. These beds are mainly plane-parallel stratified or ripple-cross laminated and, in places, show a basal massive interval up to 20 cm thick overlying an erosive base. Laterally discontinuous silty beds (up to 20 cm thick) bearing plant debris are locally present.

Different combination between gravel and sand-dominated deposits characterize proximal (i.e. gravel-dominated), middle (i.e. gravel and sand in similar proportion) and distal (i.e. sand-dominated) alluvial fan segments. In the area of Stop 1.3, vertical stacking of alluvial-fan deposits form a 40-45 m thick coarsening (CU)- to fining (FU)-upward sedimentary succession (Fig. 11A). In this area, beds forming the basal CU interval are tectonically tilted and show a progressive upward decrease in dip angle (from 15° to 0°).

The mid-fan gravelly deposits, channelized gravels show a variable stratal organization. Commonly they consists of planar beds composing gently convex barforms, which are up to 2 m thick and 40 m wide, and frequently coarsen upward. Where these deposits range in gran size between cobbles to boulders (Fig. 11B), planar bedding is only crudely traceable. In section transverse to palaeoflow (Fig. 11B), these barforms are flanked by minor erosive-based sandbodies. Subordinate channelized gravels are characterized by, coarsening-upward inclined stratasets dipping transversely to palaeoflow (Fig. 11C). Inclined strata dip at 10° to 20° and rest onto a lag of cobbles, forming up to 1.5 m-thick successions of large pebbles grading upward into cobbles, and laterally continuous up to 20 m downdip. Vertically stacked, inclined stratasets display in places opposite accretionary directions (Fig. 11C), and are further separated by prominent erosional surfaces.

STOP 1.4 (optional): Fluvial gravelly deposits (unit UFF.a)

Google Earth Coordinates:
Photo A: Lat. 43°31'18.82"N. Long. 11°37'10.03"E
Photo B-E: Lat. 43°31'16.69"N. Long. 11°38'40.33"E

Things to observe: tabular to large-scale inclined bedding, matrix-rich to openwork gravels, cross stratification, imbricated clasts.

Things to discuss: morphodynamics of fluvial bars, flow discharge and bedforms.

These gravels consist of multilaterally arranged bodies showing a flat top and a planar to concave-upward base (i.e. channel forms). In outcrop sections that are nearly perpendicular to the overall palaeotransport direction, gravelly bodies are up to 6 m thick and 80-90 meters wide, and consist of superimposed sets of large scale-inclined beds (Fig. 12 A,B) forming wedge-shaped units. Large scale-inclined beds commonly dip transverse (Fig. 12 A,B) to the main palaeotransport direction and overlay a layer of coarse pebbles and cobbles showing a well-developed a(t)b(i) imbrication. Beds are mainly made of relatively-sorted, clast-supported pebbles and sandy pebbles. Pebbly beds are up to 80 cm thick and show a well developed, plane-parallel to planar-cross stratification (Fig. 12C), which is highlighted by alternation of matrix-free and matrix-rich strata (Fig. 12 D,E). Sandy lenses, up to 50 cm thick and 2.5 m wide, are commonly plane-parallel to cross stratified. The large-scale inclined beds are locally covered by sandy deposits. These sands are wedge-shaped and are up to 4-5 m thick and several tens of meters wide.

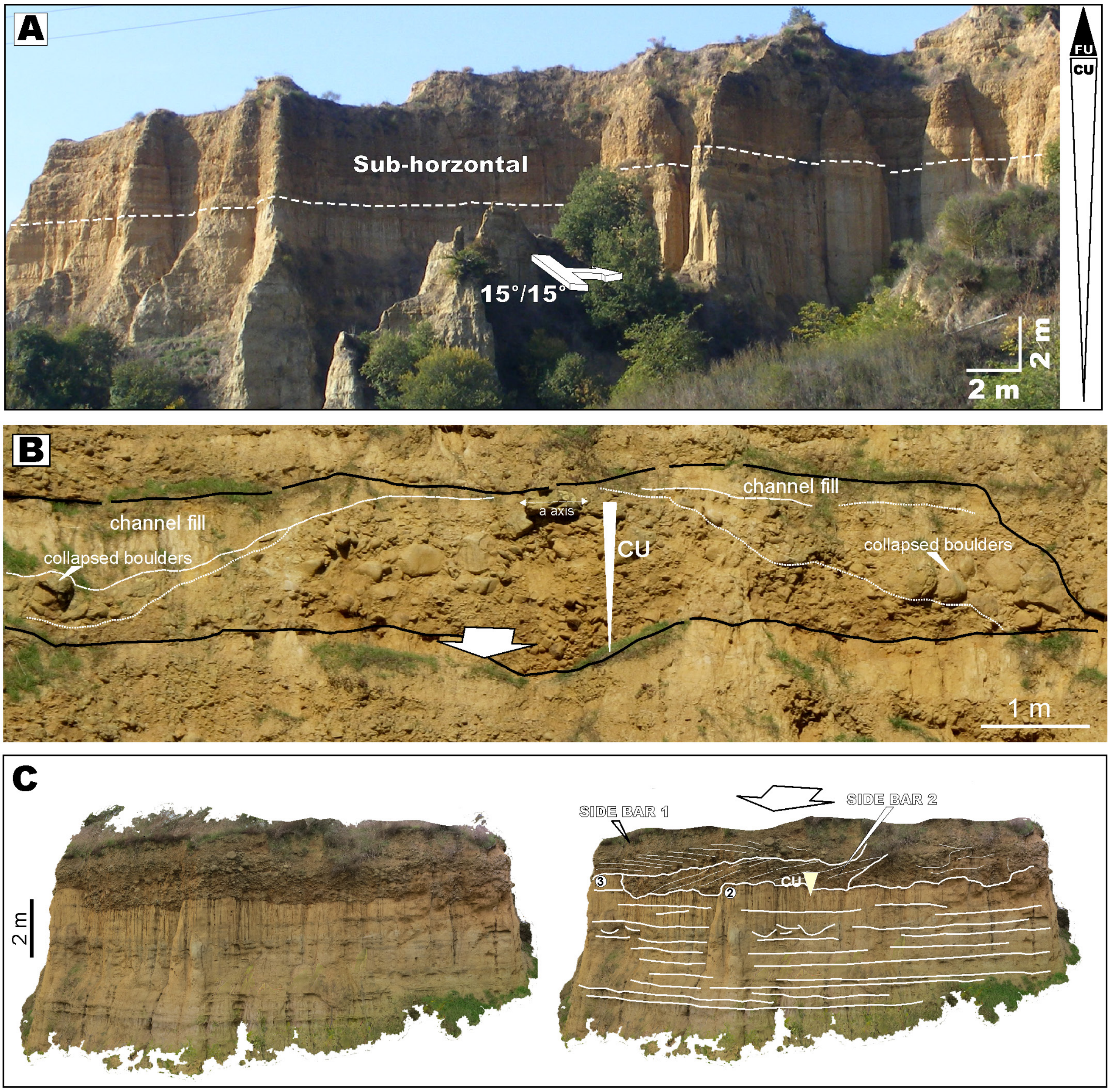


Fig. 11 - (A) CU-FU alluvial-fan deposits showing different bed attitudes. Note how the medial to distal deposits forming the lower part of the CU interval dip toward the right (i.e. toward the Pratomagno Ridge), whereas the upper part of the CU interval is characterized by sub-horizontal bedding; (B) Crudely stratified, coarsening-upwards cobbles and boulders accumulated during a high-energy event. Dotted lines mark erosive surfaces generated during falling-stage reworking. Boulders capping these surfaces collapsed from the uppermost part of the exposure. Palaeotransport direction (white arrow) is out of the outcrop; (C) Photogrammetric model showing two vertically stacked strata sets generated by downstream migration of bank-attached bars.

The sand consists of lensoid, erosively based beds up to 50 cm thick, characterized by a diffuse plane-parallel to cross-stratification. The bases of beds are commonly floored by a(t)b(i) imbricated pebbles. Rare muddy lenses, up to 10 cm thick may be interbedded within the sandy deposits.

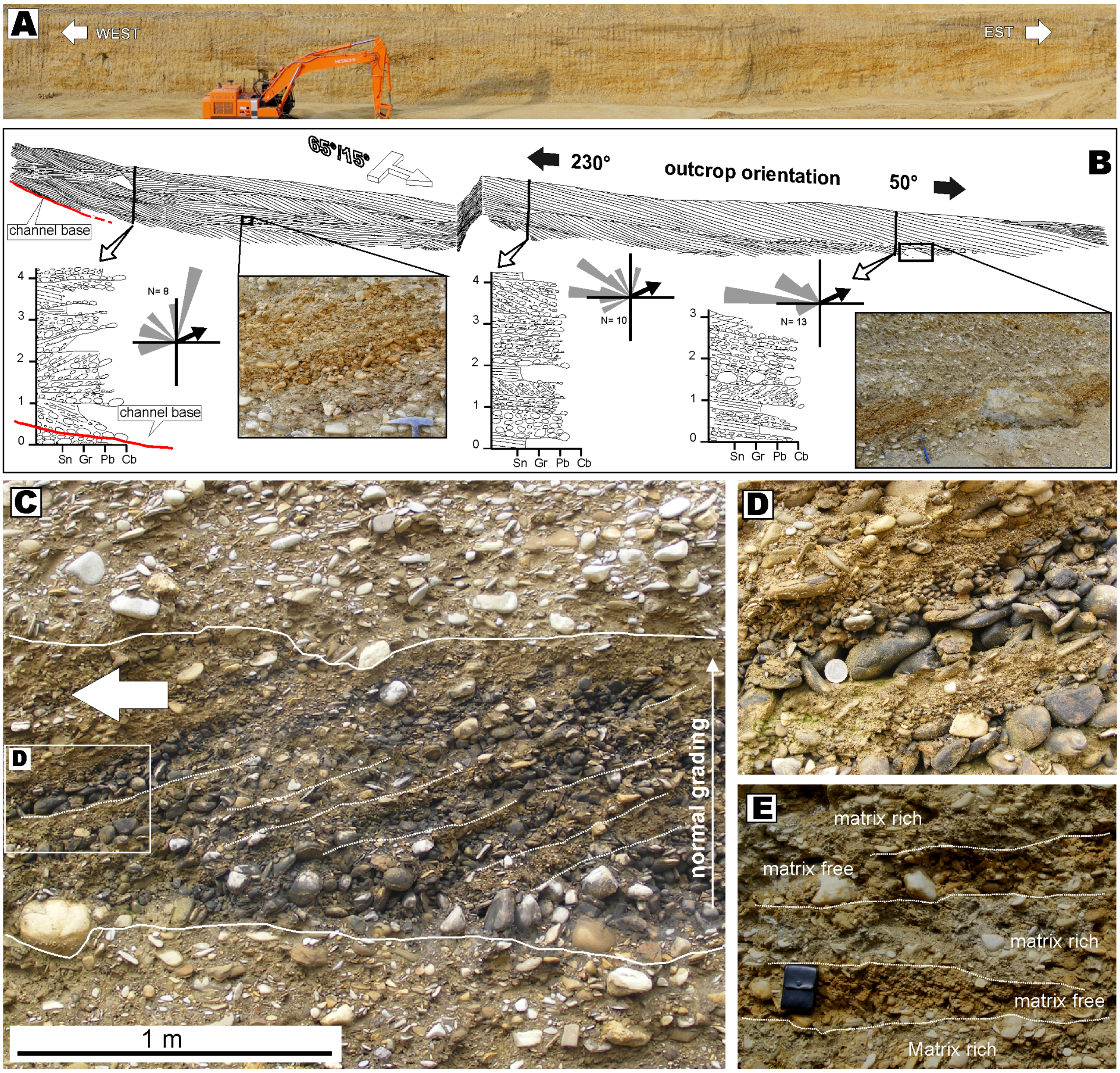


Fig. 12 - (A) Large scale inclined gravelly beds in a section transverse to the main transport direction; (B) Linedrawing of large scale inclined beds ascribed to a lateral gravelly bar. Note that the main transport direction is almost transverse to the bed dipping direction; (C) Cross stratification developed by a downstream migration of an avalanching front (dune or unit bar). White arrow indicates the flow direction; (D) Alternating openwork and matrix-rich strata developed on the avalanching front shown in C; (E) Sub-horizontal openwork and matrix-rich strata generated by migration of low-relief bedforms (bedload sheets).

II° DAY

4. CARBONATE DEPOSITS OF THE PLEISTOCENE SIENA BASIN

4.1. Geological framework of the Siena Basin

The Siena Basin is a segment of a NNW–SSE oriented, wider tectonic depression (Siena-Radicofani Basin-Bossio et al., 1993) and extending from the southern part of the Monti del Chianti to the northern part of the Latium mounts (Fig. 13).

In its northern sector, the Siena Basin is delimited by the Casino Basin with of late Serravallian-Messinian continental to brackish sediments (Lazzarotto and Sandrelli, 1977), while the southern part (the Radicofani Basin) is characterized by widespread Early-Middle Pliocene marine sediments (Bossio et al., 1993; Liotta, 1994, 1996; Liotta and Salvatorini, 1994; Pascucci et al., 2007). Older Middle-Late Miocene deposits deposits are reported only from drillings at depth (Radicofani 1 and Paglia 1 boreholes; Liotta, 1996).

The Siena Basin is dominantly characterized by Early-Middle Pliocene marine and Quaternary continental deposits at the surface (Bossio et al., 1993; Aldinucci et al., 2007), while Bonini and Sani (2002) hypothesized the occurrence of Miocene sediments in the western side of the basin buried by Pliocene ones.

The Pliocene sediments consist of marine clay, marly-clay, sand, gravel and conglomerate better described in the next paragraph. They were unconformably overlain by fluvio-lacustrine Pleistocene gravel, sand, clay and locally by Middle-Late Pleistocene travertine (Cipriani et al., 1972; Carrara et al., 1998; Brogi et al., 2007, 2010b).

4.2. Depositional and structural evolution

According to Brogi, (2011) the Siena Basin is an example of tectonic depression taking place in an extensional environment characterized by the superimposition of two generation of normal faults active since the Serravallian. During the Serravallian-late Messinian the basin originated as a bowl-shaped structural depression related to the activity of staircase extensional detachments

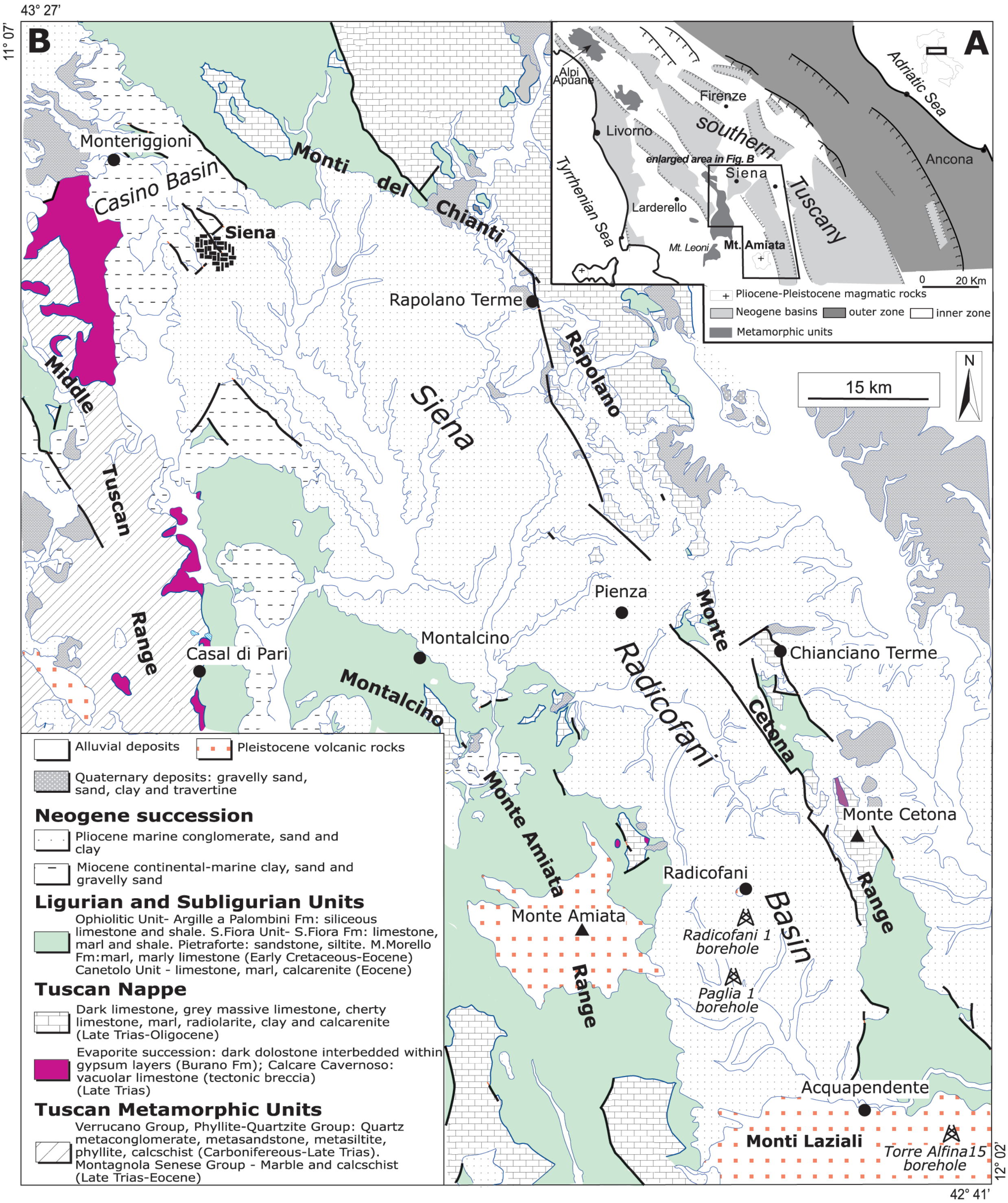


Fig. 13 - (A) Tectonic sketch of the inner and outer zones of the Northern Apennines; southern Tuscany is mainly located in the inner part; (B) Geological sketch-map of the Neogene Siena-Radicofani structural depression; the Casino (sub-)Basin corresponds to the northern part of the Siena–Radicofani Basin (from Brogi, 2011, redrawn).

and favoured by the multilayered composition of the substratum, here represented by Triassic siliciclastic succession of the Verrucano Group, Mesozoic-Cenozoic rocks belonging to the Tuscan Nappe and Jurassic-Eocene oceanic successions of the Ligurian Units.

The activity of the extensional detachments gave rise to the lateral segmentation of the most competent levels and particularly of the Verrucano succession, which played a fundamental role in controlling the space accommodation for the Miocene and Pliocene sediments. The basin width was progressively conditioned by the gap between the competent segments, whereas the basin depth was defined by the interplay between the thickness of the competent levels and the depth of the main detachment horizon.

Such gap produced a synformal structural depression, not delimited by faults, filled by late Serravallian-late Messinian marine to continental clay, sand and conglomerate sediments. From the latest Zanclean to the Piacenzian the architecture of the basin was modified in its eastern side by a west-dipping high-angle normal fault system (the Rapolano Fault is the most important fault) which produced new accommodation space for marine sediments formed by marine clay, marly-clay, sand, gravel and conglomerate. The latter faults defined a half-graben during the latest evolution of the basin (Fig. 14).

Such Pliocene marine succession is unconformably overlain by fluvio-lacustrine Pleistocene gravel, sand, clay and locally by Middle-Late Pleistocene travertine (Cipriani et al., 1972; Carrara et al., 1998; Brogi et al., 2007, 2010b).

The Siena-Radicofani Basin is also characterized by heat flow values locally reaching 140 mW/m^2 (Mongelli et al., 1982; Mongelli and Zito, 1991), in the range of the average value of the southern Tuscany geothermal anomaly (Della Vedova et al., 2001). For this reason the basin is therefore characterized by widespread geothermal manifestations, consisting of structurally controlled thermal springs and gas vents (Minissale et al., 2002; Brogi, 2004; Etiope et al., 2005; Brogi and Capezzuoli, 2009; Brogi et al., 2014b), mainly concentrated in the Rapolano Terme area.

4.3. Travertine in the Rapolano Terme Area

Together with Tivoli, (Italy: Faccenna et al., 2008; Erthal et al., 2017), Pamukkale (Turkey: Ozkul et al., 2013; Brogi et al., 2014a; Toker et al., 2015) and Yellowstone (USA: Fouke et al., 2000; Fouke, 2011), the Rapolano Terme is one of the most well-studied travertine deposits around the world (Cipriani et al., 1972; Barazzuoli et al., 1988; Guo et al., 1996; Carrara et al., 1998; Guo and Riding, 1998, 1999; Minissale et al., 2002; Minissale and Sturchio, 2004; Brogi et al., 2007; Brogi and Capezzuoli, 2009).

The area around Rapolano mainly consists of Mesozoic-Cenozoic rocks belonging to the Tuscan Nappe and the so-called "crete senesi" Pliocene clays which are buried by banks of travertine and gravels. It was the abundance of travertine, together with the presence of the hydrothermal springs, which dictated Rapolano as an important Etruscan-Roman settlement along an important road of that period (Via Cassia Adrianea - Lecchini and Rossolini, 1993). 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 in travertine.

The Rapolano Terme travertines cover about 14 km^2 and consist of isolated masses up to 50 m thick. Travertines deposited during the Pleistocene and Holocene (Barazzuoli et al., 1988; Carrara et al., 1998; Brogi et al., 2010b) by hot waters issuing from thermal springs. From a geological point of view these bodies are mainly located along the NNW-SSE striking normal fault, named as the Rapolano Fault, separating the Mesozoic limestones from the Pliocene clayey sediments filling the eastern side of the Siena Basin (Fig. 15). Nevertheless, travertines and thermal springs are strictly related to Pleistocene-Holocene(?) WSW-ENE and WNW-ESE oriented strike- to oblique-slip and normal faults dissecting, at high angle, the Rapolano Fault (Brogi, 2004).

Travertines deposited different depositional geometries and morphologies (tabular and fan-slope bodies, fissure ridges, terraced mounds, cones and waterfall deposits; Guo and Riding, 1992, 1994, 1998, 1999) with peculiar sedimentological and isotopic characteristics (Gandin and Capezzuoli, 2008, 2014) in a time ranging from Middle Pleistocene to Holocene.

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., 2002). The highest temperature spring is about 38 °C (the San Giovanni spring) and is located in an area of active travertine deposition (Brogi and Capezzuoli, 2014). 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.

Travertine is magnificently exposed in the machine cut Rapolano quarry faces. Here, a succession of depositional episodes separated by angular unconformities and enhanced by colluvial sediments, are recognisable.

STOP 2.1: Terme di San Giovanni

Google Earth Coordinates: Lat. 43°16'56.29"N. Long. 11°35'38.85"E

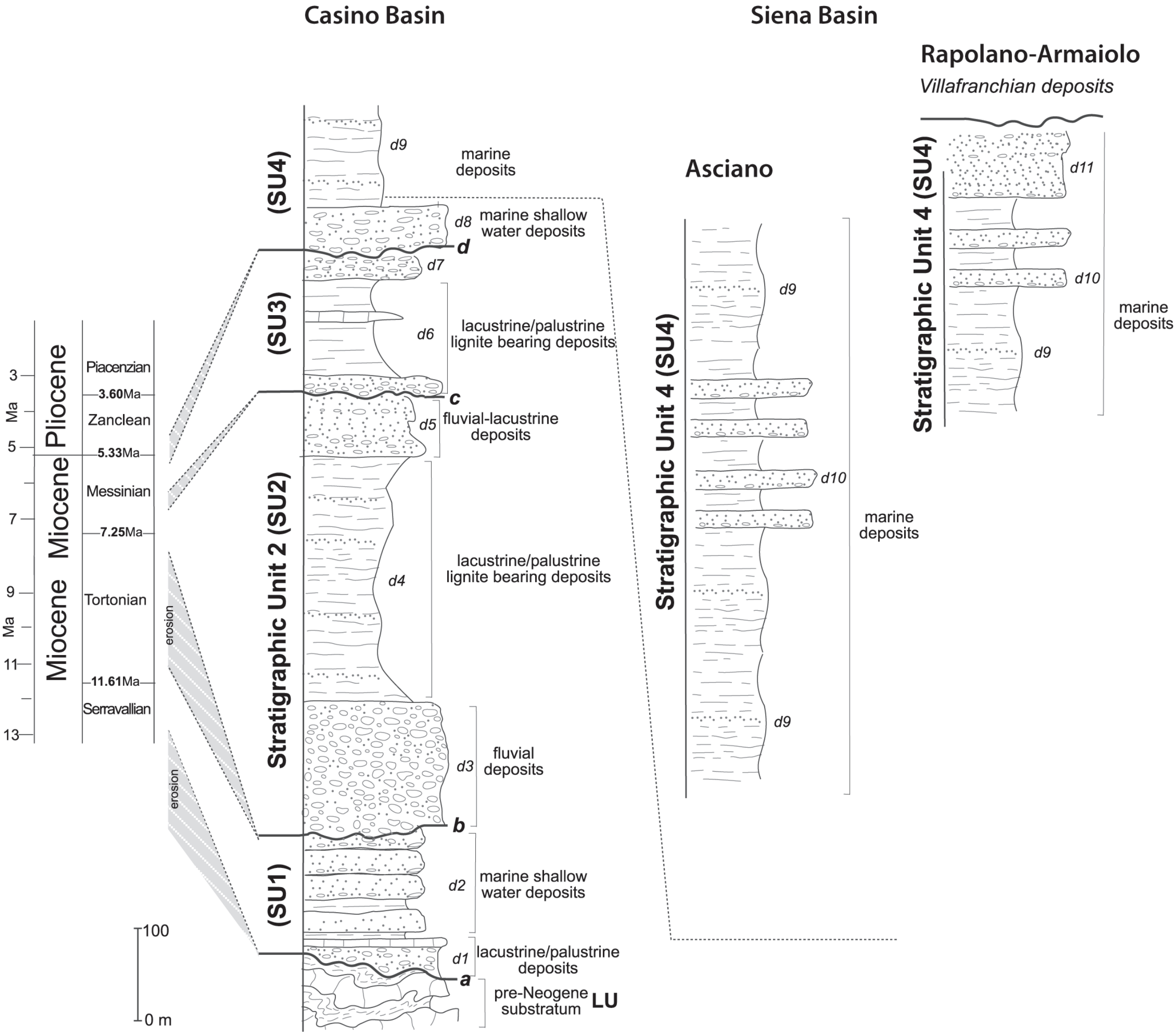


Fig. 14 - Stratigraphic columns of the filling sediments exposed in the Siena Basin and its northern prolongation (Casino Basin). a, b, c and d are the main unconformities that separate the indicated stratigraphic units (SU1–4). Key: d1 - conglomerate composed of carbonate and sandstone clasts deriving from the Ligurian Units, mainly; d2 - marly limestone and marl; d3 - sandstone and pebbly-sandstone; d4 - grey clay and sandy-clay; d5 - red conglomerates; d6 - lignite-bearing clay and sandy-clay; d7 - fluvio-lacustrine polygenic conglomerate; d8 - polygenic conglomerate, gravel and sandstone; d9 - marine clay and sandy-clay; d10 - marine sand interbedded within clay; d11 - marine gravel, sand and conglomerate (from Brogi, 2011, redrawn).

Things to observe: Fissure-ridge mound and the related depositional environments.

Things to discuss: travertine lithofacies and their distribution.

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 water is rich in calcium, bicarbonate and sulphate, with pH of 6,2-6,9 and temperatures of 38-39 °C (measured between the years 1955 and 1983; Barazzuoli et al., 1987).

The travertine fissure-ridge located at the Terme San Giovanni area (1 km SW of Rapolano) represents a travertine body occurring away from the Rapolano Fault trace. This morphotectonic feature, about 250 m long, 30 m wide and maximum 10 m high, has been recently described by Brogi and Capezzuoli (2009) (Fig. 16).

It is located on a fluvial terrace linked to the morphological evolution of the Ombrone river (FT2 in figure 17), running about 1 km west of the study area. The base of this fissure-ridge has been drilled in order to increase the hot water inflow in the nearby thermal resort. The stratigraphic log indicates that the travertine fissure-ridge overlies Pleistocene terraced alluvial deposits (about 20 m) with encrusting limestones embedded, in turn with overlying marine Middle Pliocene clayey sediments. Furthermore, the occurrence of a carbonate reservoir at

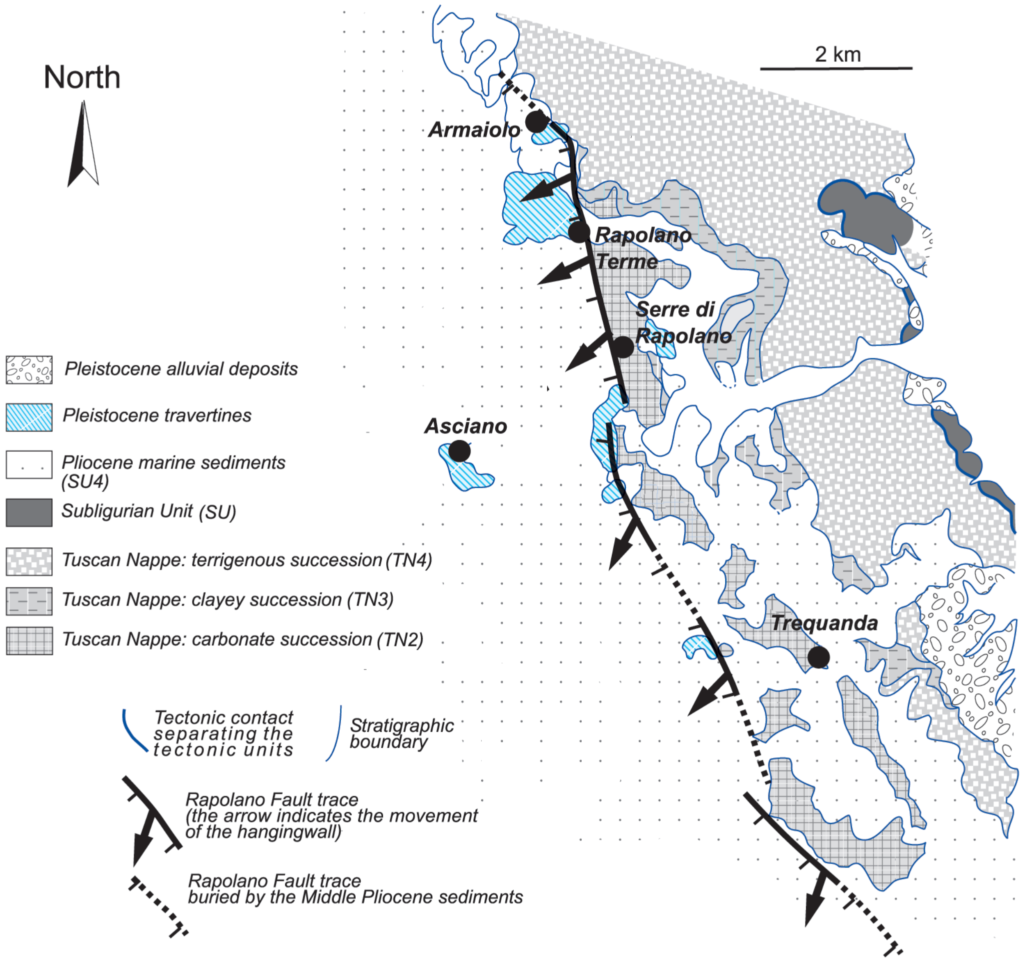


Fig. 15 - Geological map of the eastern side of the Siena Basin and Rapolano Terme region where the widespread travertine masses are located (modified after Brogi, 2011).

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. 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. Small quarries excavated in the past, cut along the transverse profile of the ridge, reveal its internal structure which appears to be formed by superposed thin crystalline crusts parallel to the depositional surface. 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. 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. 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. 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. Active fissuring is documented by the dilation fracture across the cones. The dilation took place within about 50 years, and is characterised by horizontal displacements corresponding to a maximum of about 1 cm (Brogi and Capezzuoli, 2009). Such dilatation is today still active, especially as consequence of seismic events (Brogi and Capezzuoli, 2014).

The marginal slopes of the fissure-ridge present various inclinations ranging from quasi-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 slopes. The smooth slope is composed of the superposition of white to dark-grey crystalline crusts formed by large feather calcite crystals or fan calcite

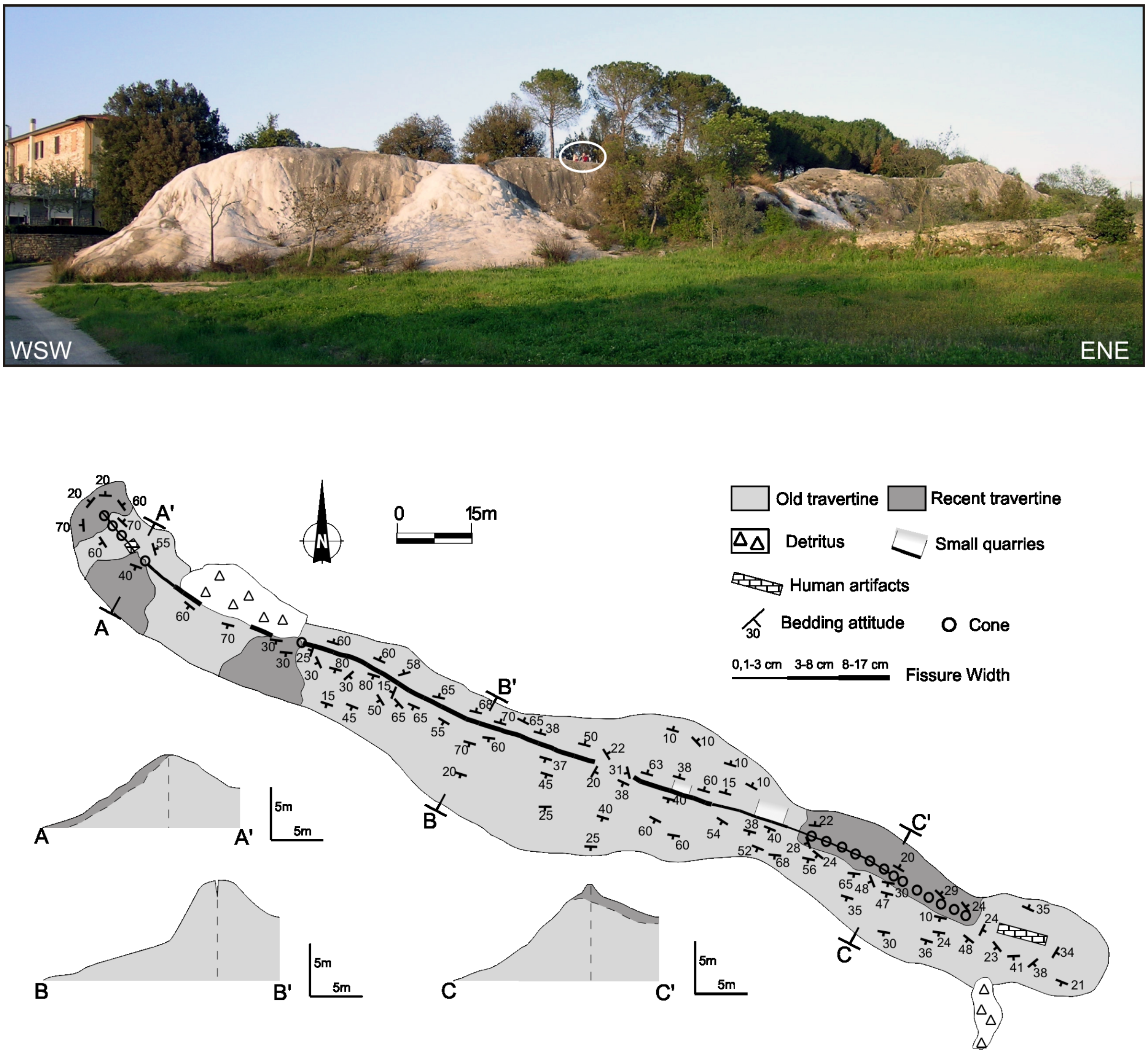


Fig. 16 - The travertine fissure-ridge located close to the San Giovanni thermal resort. This structure, ESE striking, shows an asymmetrical profile. On the top of the fissure-ridge, a fissure ranging from 0,1 to 17 cm in width is located. In the white circle, men for scale (after Brogi and Capezzuoli, 2009, slightly modified).

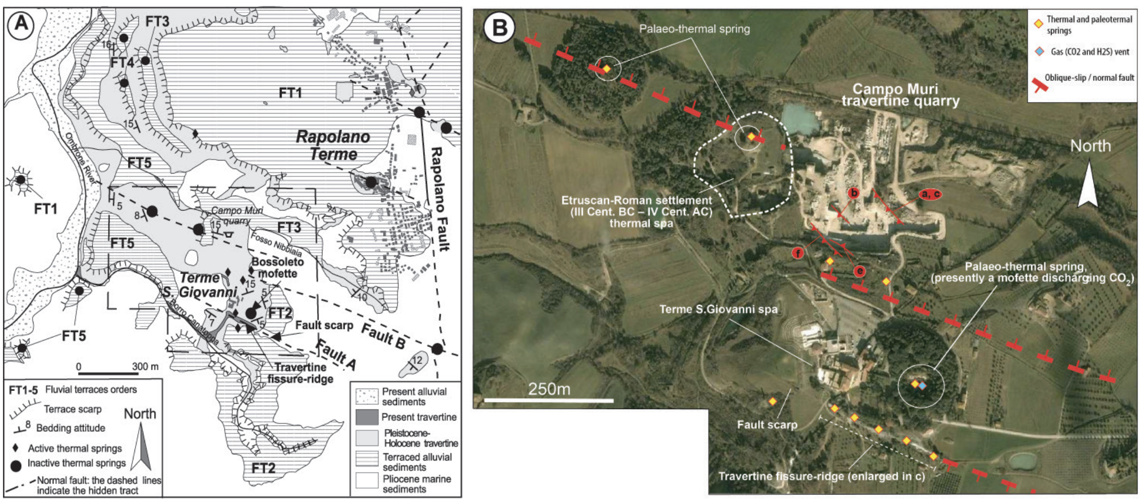


Fig. 17 - (A) Geomorphological sketch-map of the study area; the dashed rectangle is enlarged in B). (B) Aerial photograph of the Terme San Giovanni area, where Campo Muri quarry and the Etruscan-Roman settlement are located. Letters a-e indicate faults (from Brogi et al., 2017, modified).

crystals growing perpendicular to the depositional surface. The microterraced slopes are characterised by dense small terraces formed by a smooth, narrow edge some millimetres high, damming each very shallow pool. These pools are a few centimetres wide, and encourage the development of micritic globular deposits (micro-shrubs). Lithoclast travertine deposits form on the pool floor. Lithoclast travertine and shrubs are the typical infilling deposits of even the large pools forming on the terraced slope. Here, the thermal water flows over the edge of the raised rim and down the vertical side to the terrace below, depositing laminated, crystalline travertine over all overflow surfaces.

The age of this fissure ridge can be determined as it lies on an erosional surface cutting the FT2 terrace. Consequently, the fault dissecting both travertines and the fluvial terrace must be related to the hypothetical older age of faulting to 24±3 Ka (Late Pleistocene) (Fig. 17).

On the south of the fissure ridge, we will follow the path of water discharge to see the morphologies and sedimentological structures created by the thermal water flowing to the local Borro Cantoppa Creek. Previously spring water reached the valley along a drainage channel from the ridge, depositing thick masses of valley slope travertine (Guo and Riding, 1992) and stream-fill deposits. The diversity of these Recent and sub-Recent travertines near Terme San Giovanni offers a mosaic of the facies normally seen on a much larger scale in older travertines bodies in the area (see Guo and Riding, 1998, 1999). At the confluence between the thermal water discharge channel and the fresh-water Canatoppa Creek, the mixed paludal environmental gives rise to the distal travertine facies merging in calcareous tufa.

STOP 2.2: Campo Muri Area

Google Earth Coordinates: Lat. 43°17'4.33"N. Long. 11°35'18.03"E

Things to observe: Fissure-ridge mound and the related depositional environments.

Things to discuss: travertine lithofacies and their distribution.

On the north of the fissure, we will visit the area around Campo Muri quarry, where an up to 35 m thick stratigraphic succession allows the reconstruction of the geometry and architecture of the depositional events (Carrara et al., 1998) (Fig. 17). The travertine succession filled a NW–SE-trending palaeovalley and has been dated to 24±3 ka to Present on the basis of U-Th and radiocarbon ages (Carrara et al., 1998) (Fig. 18).

The general gently NW-dipping beds and the slope environment suggest the occurrence of a (palaeo)thermal spring and probably coinciding with the active Bossoleto mofette, a large crater located close to the Terme San Giovanni fissure ridge and from which 10-100 tons per day of CO_2 are escaping.

The Campo Muri area was an important Etruscan–Roman worship settlement located in correspondence of a thermal spring (as indicated by findings of several ex-voto). The village was suddenly abandoned after the fourth century AD for a cause that can be reasonably attributed to an earthquake (see Brogi et al., 2017). The thermal waters were probably artificially channelized out from the settlement, but they were able to create up to 2 m-high self built channels as the ones described in the area of Pamukkale (Altunel and Hancock, 1993).

STOP 2.3: Asciano

Google Earth Coordinates: Lat. 43°14'6.93"N. Long. 11°33'24.81"E

Things to observe: Travertine-related tufa deposits.

Things to discuss: Depositional evolution from travertine to tufa deposition.

Rabatta Creek and Bestinino Creek are two small left tributaries of the Ombrone River. Their catchments include Serre di Rapolano and areas of travertine outcrop. Along their courses (flatland connecting Serre di Rapolano with the Asciano - Bestina flatland), silty-muddy alluvial deposits are exposed, but at Asciano, just before the confluence in the Ombrone River, these deposits are exposed in several terraces from the higher (240 m a.s.l.) to the present day alluvial plan (180 m a.s.l.). In several steep outcrops surrounding the village, it is possible to examine the sedimentological characters of these deposits which are composed of calcareous tufas (Fig. 19) deposited along cascades and in a lower palustrine wetland.

These lithofacies associations are typical of barrage and cascade tufas with related back-barrage environments and represent the distal deposition of the formerly thermal, travertine-depositing waters issuing in the Serre di Rapolano area (about 5 km far).

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Fig. 18 - The travertine deposits exposed in the Campo Muri quarry. (A) Panoramic view of the western quarry wall. The Etruscan–Roman ruins are located at the top of the largest white-dashed rectangle; (B) Detail of the western wall where the three main depositional events, separated by angular unconformities, are highlighted. Radiometric ages are from Carrara et al. (1998); (C, D) Details of the palaeosoil and colluvial deposits (with embedded Etruscan bricks) separating two depositional events and laterally passing into a thick lacustrine–alluvial deposit; (E) Etruscan bricks within the colluvial deposit separating the CCMTr.U.1 and CCMTr.U.2 depositional events (from Brogi et al., 2017).

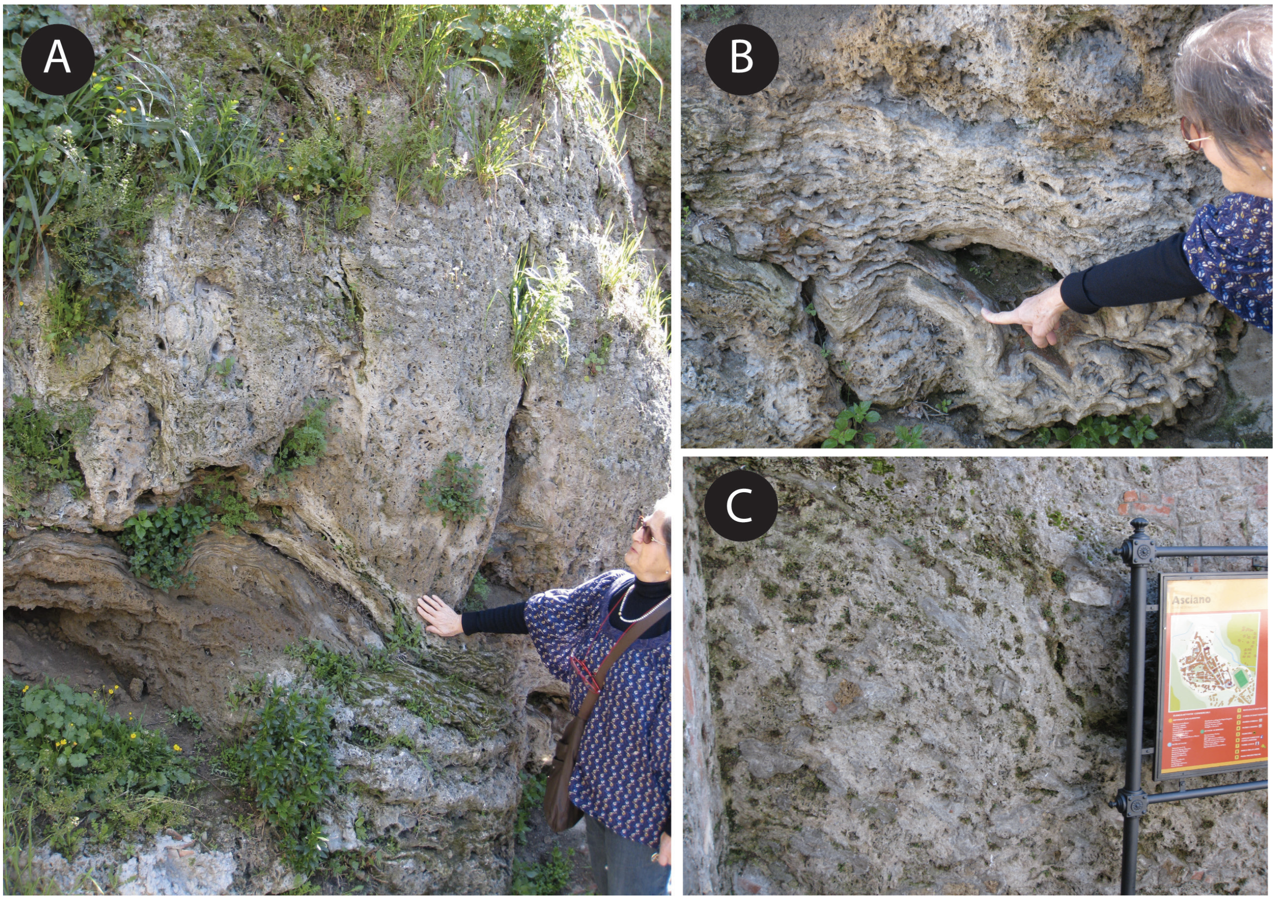

Fig. 19 - Different aspects of the Asciano Tufa. (A) Encrusted framestones (phytohermal build ups) over posed on bedded undulated microbial laminae; (B) Detail of the laminated microbial mats forming in high-energy water environment; (C) high inclined laminated microbial mats with intercalation of phytohermal framestone indicating waterfall/cascade environment. The high presence of macrobiota (plants) indicates how the waters (far and cooled from the thermal springs of Rapolano) could be colonized by organisms.

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