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Geology of the San Colombano hill, a Quaternary isolated tectonic relief in the Po Plain of Lombardy (Northern Italy)

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ABSTRACT

The 1:10,000 geological map of the San Colombano hill covers 60 km² in the Po Plain, south of Milan. The new and the historical surface geological data-sets are managed by a GeoDB aiming to contribute to re-interpret the Quaternary evolution at the Po Plain-Northern Apennine border. On the hill, the Calabrian shallow marine San Colombano Fm. unconformably overlies the truncated deeper-marine Miocene formations, up-thrusted by the external fronts of the Apennine Emilian Arc during Mio-Pliocene. Late Pleistocene alluvial units rest in unconformity above the marine succession both on the uplifted hilltop and on the surrounding plain. Fault-related offset of Late Pleistocene units, stratigraphic and morpho-structural evidences (facets, relic surfaces and drainage patterns), document the Quaternary tectonic history. Early to Middle Pleistocene ongoing thrust-folding at the northernmost buried reaches of the Emilian Arc was followed by Latest Pleistocene-Holocene transtension, possibly relating to the NNE striking Pavia-Casteggio lateral ramp.

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Geological map; Lombardy; Northern Apennines; Po Plain; Quaternary; San Colombano hill

1. Introduction

The San Colombano hill (Lombardy, Italy, [Figure 1](#)) develops above one of the buried frontal arcs of the Northern Apennine thrust belt in the Po Plain ([Alfano & Mancuso, 1996](#); [Ariati, Cotta Ramusino, & Peloso, 1988](#); [Burrato, Ciucci, & Valensise, 2003](#); [Desio, 1965](#); [Pieri & Groppi, 1981](#)). It represents a key-sector to understand the geological evolution at the Northern Apennine-Po Plain border. Nowadays, only the small-scale geological and geomorphological maps ([Anfossi et al., 1971](#); [Benedetti, Tapponnier, Gaudemer, & Manighetti, 2003](#); [Boni, 1967](#); [Castiglioni & Pellegrini, 2001](#); [Pellegrini, Boni, & Carton, 2003](#)) exist on the study area. Therefore, a detailed cartography is necessary to constrain any new reconstruction of the geological evolution of this region.

The San Colombano hill interrupts the regional, SEwards low gradient slope of the 'Po Plain Main Level' ([Castiglioni & Pellegrini, 2001](#)). Below the uplifted Late Pleistocene alluvial units, the hill exposes the evident hiatus between the marine Sant'Agata Fossili Marls (SAF, Miocene; [Anfossi et al., 1971](#); [Boni, 1967](#)) and the San Colombano Formation (SCF, Calabrian; [Figure 2](#)). Some uncertainty affects the presence of Pliocene sediments above the SAF at the hillslopes ([Anfossi & Brambilla, 1980](#)). This sequence differs from that exposed southwards in the Epiligurian, post-Messinian and Tertiary Piedmont Basin sequences of the Northern

Apennine outcrops, which show more complete Mio-Pliocene successions, as well as from the Po Plain subsurface sequences which record the coeval tectonic stages ([Figure 1](#); [Barbero, Festa, Fioraso, & Catanzariti, 2017](#); [Ghielmi, Minervini, Nini, Rogledi, & Rossi, 2013](#); [Rossi, 2017](#); [Rossi, Minervini, Ghielmi, & Rogledi, 2015](#); [Vercesi et al., 2015](#)). Furthermore, the Calabrian San Colombano Fm. contains clasts of former alpine provenance, recycled twice from the Messinian succession of the Apennine thrust-top basins ([Vercesi & Scagni, 1984](#)) after Messinian thrusting. On the hill, the Lower Pleistocene marine succession is unconformably overlain by alluvial units (Cascina Parina Unit and Invernino Unit; [Pellegrini et al., 2003](#)). The hillslopes are framed by the latest Quaternary terraces of the 'Po Plain Main Level *Auct*'.

The hill corresponds to the complex zone of maximum curvature and uplift of the San Colombano structure (SCS in [Figure 1](#)), that belongs to the regional N30-115°E buried front of the Apennine Outer Emilian Arc ([Bigi, Cosentino, Parotto, Sartori, & Scandone, 1990](#); [Costa, 2003](#); [DISS Working Group, 2015](#); [Perotti, 1991](#); [Pieri & Groppi, 1981](#); [Rossi et al., 2015](#)). The N30°E-striking Pavia-Casteggio lateral ramp (PCLR; [Figure 1](#)) drove the N and NNE migration of the Emilia arc ([Boccaletti, Corti, & Martelli, 2011](#); [Ghielmi et al., 2013](#); [Michetti et al., 2012](#); [Perotti & Vercesi, 1992](#); [Toscani, Seno, Fantoni, & Rogledi, 2006](#)) and was reactivated during the Quaternary ([Benedetti et al., 2003](#); [Gobetti & Perotti, 1990](#); [Vercesi et al., 2015](#)). Thrusting

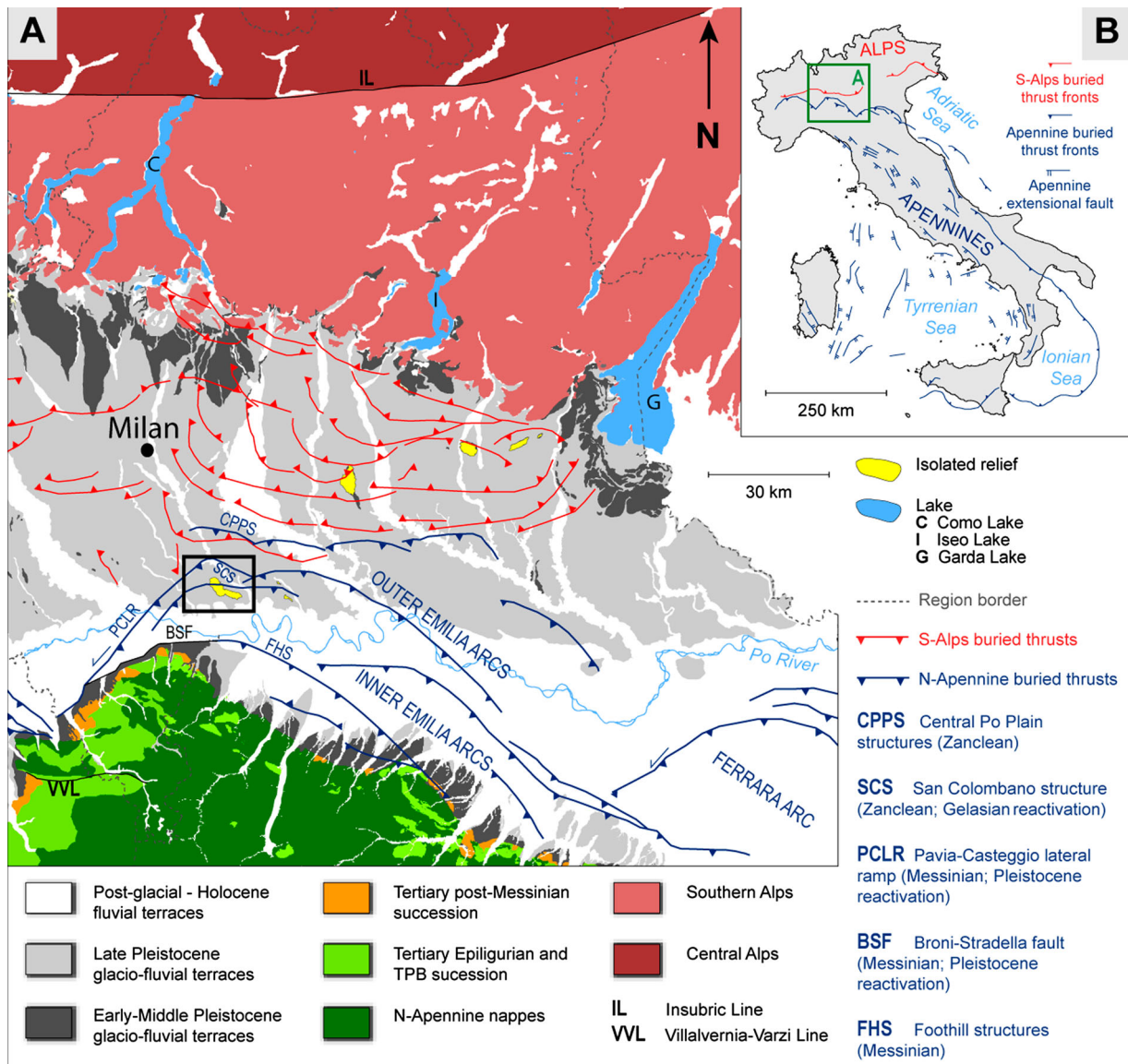


Figure 1. (A) Location of the study area in the structural framework of the Po Plain (Italy). San Colombano hill (black frame) is the southernmost of a set of isolated reliefs described in the Po Plain. N-Apennine thrusts located from [Benedetti et al. \(2003\)](#), [Bigi et al. \(1990\)](#), [Rossi et al. \(2015\)](#); names and activation chronology from [Benedetti et al. \(2003\)](#), [Toscani et al. \(2006\)](#), [Ghielmi et al. \(2013\)](#), [Rossi \(2017\)](#); Buried S-Alpine thrusts simplified from [Fantoni et al. \(2004\)](#). (B) Location of Figure 1(A) in the simplified structural map of Italy (modified from [Scrocca, 2006](#)).

shaped the Apennine foothills (FHS, [Figure 1](#)) since the Late Miocene, reaching as far North to intersect the outermost thrust front of the Southern Alps ([Fantoni, Bersezio, & Forcella, 2004](#)) during Zanclean (CPPS, [Figure 1](#)). The Gelasian reactivation has been documented by basin-wide tectonic unconformities known in the literature ([Ghielmi et al., 2013](#) and references therein). Some evidences of WNW-ESE-striking Quaternary extension at the N-Apennine border were described more eastwards ([Bertotti, Capozzi, & Picotti, 1997](#)), and hypothesized from morphological data along the Broni-Stradella scarp (BSF, [Figure 1](#)) 15 km South of the hill ([Pellegrini & Vercesi, 1995](#)). As an alternative, [Costa \(2003\)](#) hypothesized that the N-Apennine front migrated along a set of WNW-ESE-striking transpressive faults during Messinian-Pleistocene.

The objective of this work is to present the surface geology of the San Colombano hill area, based on a new 1:10,000 geological map. The map aims to provide new surface geological constraints to contribute to interpret the Quaternary evolution of the Po Plain–Apennine border, based on new stratigraphic, micropaleontological, geomorphological and structural data. The map is implemented on a hierarchic Geo-Database comprehensive of the new and historical data.

2. Analytical methods and management of the data-set

The study relies on geological mapping at 1:10,000 of an area of approximately 60 km². Stratigraphic, structural, pedological, morphological micropaleontological and petrographic analyses complement field mapping. The

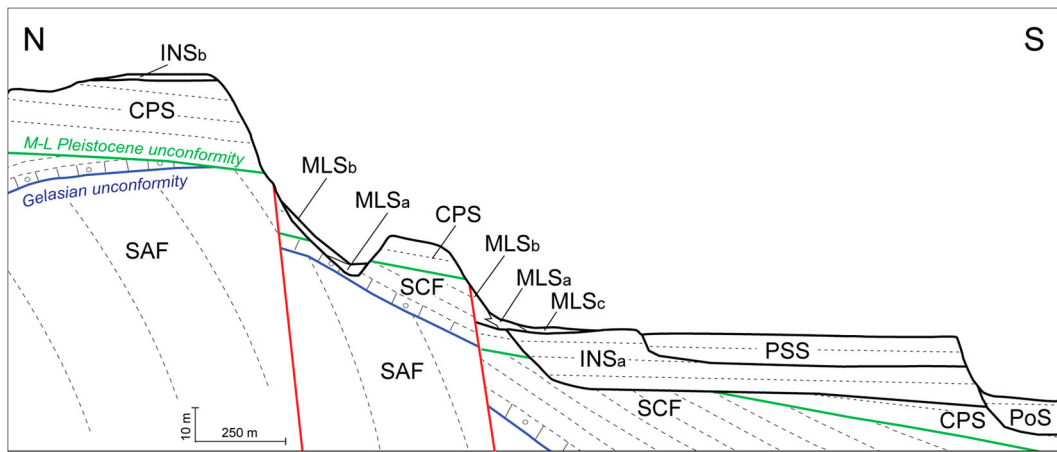


Figure 2. Stratigraphic scheme of the San Colombano hill area. Marine stratigraphic succession (Miocene-Calabrian): SAF: Sant'Agata Fossili Marls; SCF: San Colombano Fm (basal conglomeratic facies rest above the Gelasian unconformity); Continental stratigraphic succession (Late Pleistocene-Holocene): CPS: Cascina Parina Synthem (alluvial facies); INS: Invernino Synthem (a: alluvial facies; b: loess facies); MLS: Monteleone Synthem (a: alluvial-torrential and fan facies; b: slope facies; c: reworked aggradation of alluvial plain facies); PSS: Paleo-Sillaro Synthem; PoS: Po Synthem. Red lines = faults.

data-set, which includes literature and unpublished historical data concerning the Miocene-Pleistocene marine substratum, is stored into a hierarchic ArcGis® Geo-Database (Appendix: Figure 7 and Figure 8). An example of the geomorphological database is presented in Figure 9 (Appendix) as a key to the reading of the Main Map.

We adopted a hierarchic stratigraphic classification based on lithostratigraphic units and UBSU (NACSN, 2005). The UBSU classification was applied to units identified by their unconformable boundaries, which were correlated throughout the area. Mapping of soil textures and colours (Main Map) and the description of the weathering profiles contributed to characterize the top boundaries of the stratigraphic units. Facies associations and composition of sediments were used to describe and interpret the UBSU but did not contribute to their definition. We maintained the existing terminology for the lithostratigraphic units as in the 1:100,000 Geological Map of Italy (Anfossi et al., 1971; Boni, 1967); we adopted some already existing informal terms (Pellegrini et al., 2003) to denominate the UBSU (Figure 2).

The relative chronology and age constraints of the Quaternary units are based on morpho-stratigraphic correlations, nature of the weathering profiles (Cremaschi et al., 2015 and references therein), cross-cut relationships, existing radiocarbon and optical stimulated luminescence age determinations, existing and new micropaleontological data (Appendix).

3. Stratigraphy

3.1. The outcropping marine succession

3.1.1. Sant'Agata Fossili Marls (Anfossi et al., 1971; Boni, 1967). Langhian – Tortonian

The SAF is exposed in very few outcrops nowadays, mainly in the eastern sector of the relief, on the northern hill scarp and in some deeply incised valleys (Main

Map; Appendix Figure 8). It consists of greyish marls and clays, interbedded with centimetre-to-metre thick, parallel-bedded fine-grained sandstones. Age assignment is based on the co-occurrence of Middle Miocene planktonic foraminiferal species, including *Orbulina universa*, and on the absence of typical uppermost Tortonian species such as *Neogloboquadrina acostaensis* (Appendix Figure 8). The estimated thickness is tens to hundred metres (Anfossi et al., 1971; Boni, 1967). Facies and foraminiferal assemblage suggest a shelf to shelf-edge environment.

3.1.2. San Colombano Formation (Anfossi et al., 1971; Boni, 1967). Calabrian

The lower boundary of SCF is an angular unconformity above the SAF, including the Gelasian Unconformity of Ghielmi et al. (2013). The upper boundary corresponds to the composite erosional unconformity at the base of the continental succession (Figure 2). From bottom to top the SCF includes lens-shaped, massive organogenic limestone bodies with abundant fragments of molluscs, brachiopods, echinoids, bryozoans, foraminifera and ostracods. These bodies are associated to bedded biocalcarenite, biocalcirudite, and hybrid conglomerates (Figure 3(A)) with macrofossils mixed with high-grade metamorphic rocks, serpentinites, porphyrites, Verrucano Lombardo-like sandstones, cherty limestones and dolostones. Crudely bedded to massive, blue to olive-green clays, more than 10 m thick follow upwards. Cold-water microfossils (Appendix) record a phase of transgression and climate cooling, in accordance to Coggi and Di Napoli Alliata (1950), Farioli (1954). On top, blue clays and marly clays of decametric thickness are interbedded with fine-grained sands (Figure 3(B)) of transgressive coastal to shallow shelf environment, as previously suggested by Anfossi and Brambilla (1980). The Calabrian age assignment of SCF is based on the co-occurrence of typical Early Pleistocene

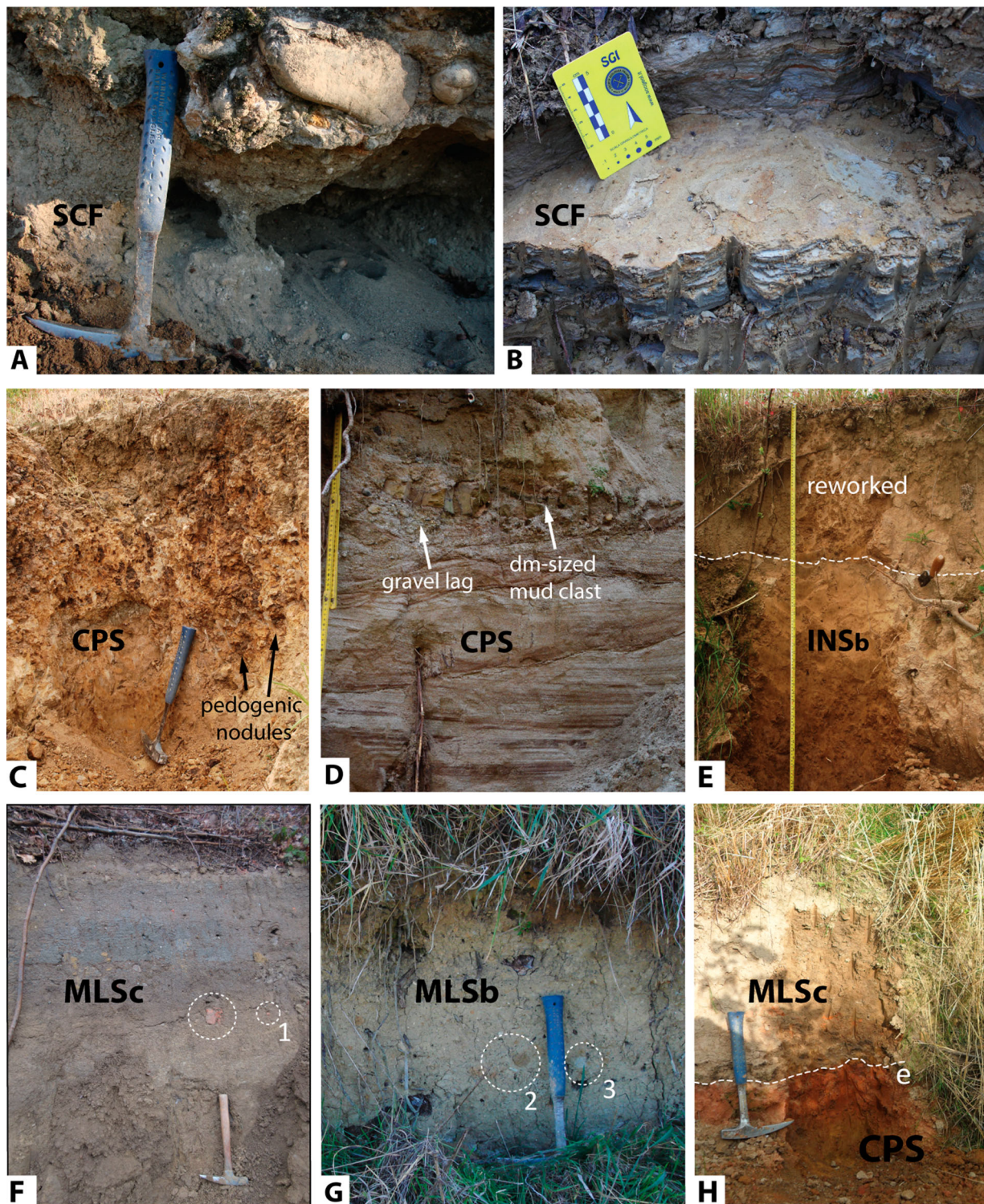


Figure 3. (A–B) San Colombano Formation (SCF); (A) conglomeratic, fossiliferous facies at the lower boundary of the SCF; (B) grayish-blue clays and local sand intercalations of the upper lithozone of the SCF. (C–H) Late Pleistocene continental synthems: (C) Cascina Parina Synthem (CPS), centimetre-sized Fe–Mn nodules characterize the well-developed hydromorphic soils on top; (D) CPS: cross-stratified sands. Erosional boundaries are often marked by gravel lags and mud clasts; (E) Invernino Synthem, weathered loess (INSb) outcropping on top of the San Colombano hill marks the upper boundary. The uppermost 50 cm are reworked by agricultural activities; (F) Monteleone Synthem (MLS): reworked facies of the aggrading plain (MLSc). Archaeological findings are common (1: fragments of Roman-Age bricks adjacent to a Roman grave); (G) colluvial facies on slopes (MLSb) are heterometric and polygenic (2: relic of soil; 3: fossiliferous mud clast); (H) erosional boundary (e) between MLSc and the deeply weathered, truncated profile of CPS; ground surface corresponds to the upper border of the pictures.

species and on the absence of *Truncorotalia truncatulinoides* (Appendix). According to the micropaleontological data, no sediments are preserved in the area between the Tortonian and Calabrian formations.

The Gelasian unconformity records the Early Pleistocene uplift and erosion of the Neogene succession in shallow-water conditions; the overlying stacking-pattern suggests a subsequent transgression.

3.2. The continental succession

3.2.1. Cascina Parina Synthem ('Cascina Parina Unit', Pellegrini et al., 2003; 'Diluvium Antico', Boni, 1967; 'Mindel glacio-fluvial deposits', Anfossi et al., 1971). Late Pleistocene

The Cascina Parina Synthem (CPS) lies above an angular unconformity (M-L Pleistocene unconformity, Figure 2) carved into the marine units. Its upper boundary is an erosional surface. Locally, at its top, a m-thick, rubefied hydromorphic paleosol (7.5 YR to 5 YR; Munsell[®], 1994) is preserved (Figure 3(C)). The CPS is composed, from the bottom, of grey-brown to olive-green silty and sandy clays, at least 1 m thick, dm- to m-thick beds of grey gravelly sands and coarse- to medium-grained laminated sands, sometimes showing trough-cross stratification (Figure 3(D)); medium- to fine-grained sands forming planar and ripple cross-laminated beds, organized in m-thick fining upward sequences, follow upsection. The very rarely preserved top of CPS (quarry site near C.na Belfuggito, Main Map) is characterized by reddish, massive silt and sandy silt, with abundant clays of pedogenic origin. Thickness of CPS ranges from 5 m corresponding to the deeply eroded sequences on top of the hill, to more than 30 m in the central hill (H2–H4 sectors, Geomorphological Scheme). Lithic fragments in sands consist of metamorphic (predominant high-grade) and magmatic rocks, rare to absent limestones. The Late Pleistocene age of CPS is suggested by stratigraphic correlation with informal stratigraphic units previously mapped in the Southern Po Plain (Baio, Bersezio, & Bini, 2004; Bersezio et al., 2004; Bersezio, Cavalli, & Cantone, 2010; Pellegrini et al., 2003). The described lithofacies characterize the CPS as an alluvial system, capped by very rarely preserved loess deposits.

3.2.2 Invernino Synthem ('Invernino Unit', Pellegrini et al., 2003; 'Diluvium Medio', Boni, 1967; 'Riss glacio-fluvial deposits', Anfossi et al., 1971). Late Pleistocene

The Invernino Synthem (INS, Figure 2) unconformably overlays either CPS, or the SCF as along the northern hill slope. The upper boundary is a polycyclic and moderately rubefied (10 YR to 7.5 YR) soil profile, truncated by the terrace scarps. In its lower part, INS consists of fine- to medium-grained sands with very fine-grained gravel, forming dm-thick beds, with planar and trough-cross stratification. Medium- to fine-grained (gravelly) sands, rarely showing trough-cross stratification, follow upsection. This alluvial succession (INSa; Figure 2) is capped by a metre thick, massive, yellowish silt and sandy silt (INSb, Figure 2; Figure 3 (E)), which is interpreted as a loess deposit, both in-situ and reworked. Thickness ranges from about 4 m on top of the eastern-central sectors of the relief,

where only INSb is present, to at least 10 m in correspondence of the INSa terraces which frame the western, northern and southern hill slopes (Main Map). Sands and gravels are composed by abundant sedimentary clasts, low-grade metamorphic rocks and variable amounts of porphyritic volcanites showing a marked compositional change compared to the CPS sediments. The INS on the northern and southern sides of the hill is uplifted of approximately 15 m above the adjacent INS of the terraced plain (Main Map) and are cut by steep escarpments progressively less elevated from east to west. Cross-cut relationships with the adjacent synthems suggest a Late Pleistocene age, in agreement with Pellegrini et al. (2003). This is also supported by comparison of the weathering profile of INSb loess with the loess soil profiles on the other relic reliefs of the Po Plain (Cremaschi, 1987; Cremaschi et al., 2015; Trombino, Zerboni, Livio, Berlusconi, & Michetti, 2013).

3.2.3. Monteleone Synthem (comprises the equivalent facies included into the 'Diluvium Antico' and 'Diluvium Medio' by Boni, 1967 and into the 'Mindel' and 'Riss glacio-fluvial deposits' by Anfossi et al., 1971). Late Pleistocene to Holocene

The Monteleone Synthem (MLS, Figure 2) is a polyphasic and polygenetic unit, comprising sediments recycled from the older units. Cross-cut relations show that it includes all the sediments formed during the Late Pleistocene to Holocene morpho-tectonic evolution of the San Colombano hill. MLS covers both INS and CPS by means of a composite unconformity, while its top boundary is either the present-day topography or the terrace scarp of the Po Synthem. The weathering profile at the top is weak to absent. MLS consists of torrential and alluvial fan facies (MLSa), colluvial deposits driven along slopes (MLSb), and reworked deposits of the aggrading alluvial plain (MLSc; Figure 3(F)). The MLSb decimetre-to-metre thick deposits consist of sand and silt with sparse clasts (Figure 3(G)), often laminated. MLSb is heteropic with the alluvial stratified gravel, sand and silt (MLSa) deposited within the recent incised valleys and along abandoned, even hanging valleys of the San Colombano hill. Fine-grained sandy and silty deposits, locally poorly laminated, crop out on the plain adjacent to the hill, corresponding to the reworked aggradation above the alluvial plain (MLSc). Such deposits are rich of artefacts, hosting Bronze Age, Roman and Middle Age archaeological findings (Valle, 1984; Pellegrini et al., 2003; a roman grave was discovered during our surveys on the terrace to the NW of the hill; Figure 3(F,H)) and modern remains. This latter facies of MLS was not mapped, because of its limited thickness (<1.5 m), below the map resolution.

3.2.4. *Paleo-Sillaro Synthem ('Santa Cristina and Bissone unit' p.p., Pellegrini et al., 2003; 'Diluvium Recente', Boni, 1967; 'Wurm glacio-fluvial and alluvial deposits', Anfossi et al., 1971). Latest Pleistocene*

The Paleo-Sillaro Synthem (PSS, Figure 2) lies above an erosional unconformity carved into CPS and INS. The upper boundary corresponds either to the topographic surface, or to the unconformities at the base of the MLS and Po Synthem. A thin and weak topsoil caps the PSS (10 YR to 2.5 Y hues, <1 m thick; Main Map); no evidence of loess deposits has been found. The PSS is composed of brownish-gray, medium- to coarse-grained gravelly sands, showing trough-cross and planar stratification, up to 5 m thick. Gravels of PSS contain abundant limestone and arenite clasts in the eastern map area; porphyritic volcanites get abundant in the western sector. PSS deposits are cut by the Holocene Lambro and Po valleys (Po Synthem). Cross-cut relations, together with subsurface correlations and ¹⁴C age determinations at the base of the correlative units from adjacent areas (Baio et al., 2004; Bersezio et al., 2004), allowed to constrain PSS age to the latest Pleistocene. The PSS boundaries correspond to the scarps of several abandoned river traces of the Lower Po Plain (Palaeo-Olona, Palaeo-Sillaro, Palaeo-Po; Benedetti et al., 2003; Bersezio, 1986; Veggiani, 1982) which are run at present by underfit streams.

3.2.5. *Po Synthem ('Sintema Emiliano-Romagnolo Superiore', Di Dio, Piccin, & Vercesi, 2005; 'Badia Pavese unit', Pellegrini et al., 2003; 'Alluvium Antico and Alluvium Recente', Boni, 1967; 'Alluvioni antiche e attuali', Anfossi et al., 1971). Latest Pleistocene (?) – Holocene*

The Po Synthem (PoS, Figure 2) unconformably overlies the Pleistocene Units. Its lower boundary corresponds to the erosional surface carved during the latest entrenchment of the river network; its top boundary corresponds to the topographic surface. PoS comprises gravels and sands interbedded with silt, locally hydromorph. Loess deposits are absent and the weathering profile is weak to absent. The coarsest and thickest alluvial deposits characterize the Lambro and Po River valleys infillings. Thickness of PoS is up to 10 m in the main valleys. The age attribution is suggested by cross-cut relations and archaeological findings (Pellegrini et al., 2003).

4. Tectonics and geomorphology

In the San Colombano isolated hill, in addition to the observed thickness and facies lateral variations of the stratigraphic units (Figure 2 and Main Map Cross-sections), evidences of syn- to post-depositional tectonics are apparent both as directly observed tectonic structures and as tectonic-related geomorphic features.

Here we present at first the tectonic structures, then the morpho-structural features and some GIS-assisted elaborations which helped to describe the Quaternary structural evolution of the region.

4.1. Structural elements

The hill partly develops in correspondence of the buried N115E-striking San Colombano ramp anticline (Figure 1 and references therein; Main Map-Tectonic scheme), which deformed the Miocene marine substratum. The measured field of bedding attitude of the SAF (Appendix Figure 8) shows that only the southern upright, S-dipping backlimb of the pre-Gelasian fold is preserved in outcrops, because its N-dipping forelimb is downthrown by subsequent faulting. The Gelasian angular unconformity and the SCF are uplifted and gently folded with a N80°E (eastern hill) to N100°E (western hill) striking axis (Cross-sections; Appendix Figure 8). This originates the opposite dips of the SAF, SCF, and of the interposed Gelasian Unconformity (Cross-sections; Figure 2). The Pleistocene alluvial Synthems (CPS and INS) sit both on top and at the sides of the hill. The CPS bedding dips SW in the highest and lowermost morphological sectors of the San Colombano hill (Main Map), while it lays sub-horizontal on the plain north of the relief, where the unit is downthrown of more than 50 m compared to its hilltop outcrops, along a N110E-striking scarp (Cross-section AA'). Hence, the Middle-Late Pleistocene angular unconformity (Figure 2) is displaced and gently tilted by faulting. Both across the N60E-trending altimetric divide which separates the high (H1) and low sectors of the hill (H2, H3; Geomorphological Scheme), and at the hill margins, the Miocene-Pleistocene stratigraphy is offset and downthrown of tens of metres away from the hilltop (Main Map). CPS and INS are dissected and locally tilted by a dense network of sub-vertical fractures and normal faults with N30E, N60E, N110E strikes (Figure 4), often coupled in conjugate systems. These orientations reflect the main directions of the steepest slopes bounding the hill as well as of other morpho-tectonic indicators (Figure 5).

4.2. Morphological elements

The morphological sectors of the hill and of the surrounding terraced plain (H1–4 and P1–3, respectively) are shown in the Geomorphological Scheme (Main Map).

The San Colombano hill is asymmetric and characterized by a flat-top surface 140–146 m a.s.l. (H1 sector). The northern N110E-directed and the eastern N150E-directed slopes consist of straight, steep and 40–50 m high triangular-trapezoidal facets (Figure 5 (A)); their height progressively decreases toward the western border of the structure, where a rather smooth

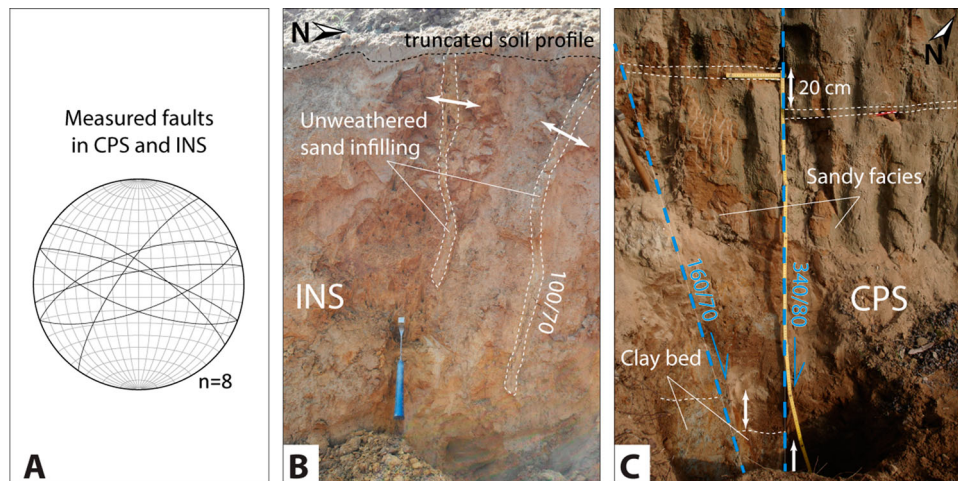


Figure 4. (A–C) Extension-related structures crossing the continental succession of the San Colombano hill. (A) Stereonet plot (Schmidt, lower hemisphere) of meso-fault planes affecting CPS and INS (Cascina Parina Synthem and Invernino Synthem, Late Pleistocene); (B) Infilled tensional fractures through INS, near Invernino village; (C) conjugate normal faults (dashed blue lines) through CPS near Miradolo village.

transition to the surrounding plain occurs. Differently, the southern slopes show curved escarpments, the widest being a 4 km-wide, southward-concave shape which cuts the SW sectors (H2, H4) of the hill. This concave bend hosts the alluvial terrace of the PSS, representing an abandoned paleo-Po meander. The drainage network of the hill (Figure 5(B)) was drawn from the 1:10,000 Lombardy CTR topographic map, Google Earth® images and field survey. All the I–IV order streams (Strahler, 1957) were rectified where traceable without relevant changes of direction relative to their length to compute the azimuth of each segment. Rose diagrams and azimuthal cumulative curves permit comparisons with the structural measurements (Figure 5(B); Figure 6). Drainage anomalies (i.e. valley diversions, piracy) are frequent and occur in correspondence to the straight boundaries of the higher sectors (H1 and H2; Figure 5). Some hanging valleys standing above WNW–ESE-striking, 30 m high scarps, underline the boundary between the H1–H2 and H3 sectors (e.g. near C.na Visola, or near C.na Valbissera, Geomorphological Scheme). A few aligned saddles punctuate the northern border of the H1 sector.

The morphology of the terraced plain flanking the hill (sectors P1 to P3, Geomorphological Scheme) changes from North to South. At the transition between the westernmost sector of the hill (H4) and the plain the P1 ground surface dips 10° NW, opposite to the regional SE dip. Across the same boundary, two of the N–S-directed valleys bent or lose their physical continuity (Figure 6). Furthermore, detailed mapping of dip directions of the P1–P3 topographic surfaces, combined with the classification and ranking of erosional scarps and terrace rims revealed km-wide, elongated, sub-planar morphologies (P2 sector), minor scattered humps (<5 m high), linear ridges and concave-upward curved shapes (Geomorphological Scheme).

Some back-tilted surfaces, compared to the local and regional dips, have been mapped both in the H3 and P2 sectors East of Miradolo. The Lower Terrace sector (P3) comprises different orders of terraced surfaces bounded by 5–15 m high escarpments cutting the plain. Among them, the youngest characterizes the riverbeds of Lambro, Southern Lambro and Po rivers.

5. Discussion and conclusions

In Figure 6(D) we summarize the constraints we obtained from surface mapping to contribute to delineate the Quaternary deformation history at the origin of the San Colombano tectonic relief and landforms.

During Messinian–Gelasian N and NE propagation of the buried N–Apennine thrusts (stage I, Figure 6 (D)) caused uplift increments along the San Colombano arc and folding of the pre-Gelasian marine stratigraphy along WNW–ESE-striking anticlines. The pre-Calabrian unconformities described in the Po Plain subsurface (Regione Emilia-Romagna & Eni-AGIP, 1998; Regione Lombardia & Eni Divisione Agip, 2001; Intra-Zanclean and Gelasian regional unconformities, Ghielmi et al., 2013) merge in the San Colombano Hill outcrops. This Tortonian–Calabrian hiatus, which encompasses the Gelasian Unconformity (Figure 2), has been furthermore constrained by the new micropaleontological data. During this time span the complex tectonic evolution of the Tertiary Epiligurian and Piedmont Basin successions occurred, as well as the deposition of the Messinian-to-Early Pleistocene successions at the N–Apennine fringe (Figure 1; Barbero et al., 2017; Di Dio et al., 2005; Vercesi et al., 2015 and references therein).

Although a gradual decrease of N–Apennine thrusting is documented since Lower Pleistocene (Ghielmi et al., 2013), a Calabrian-to-Late Pleistocene

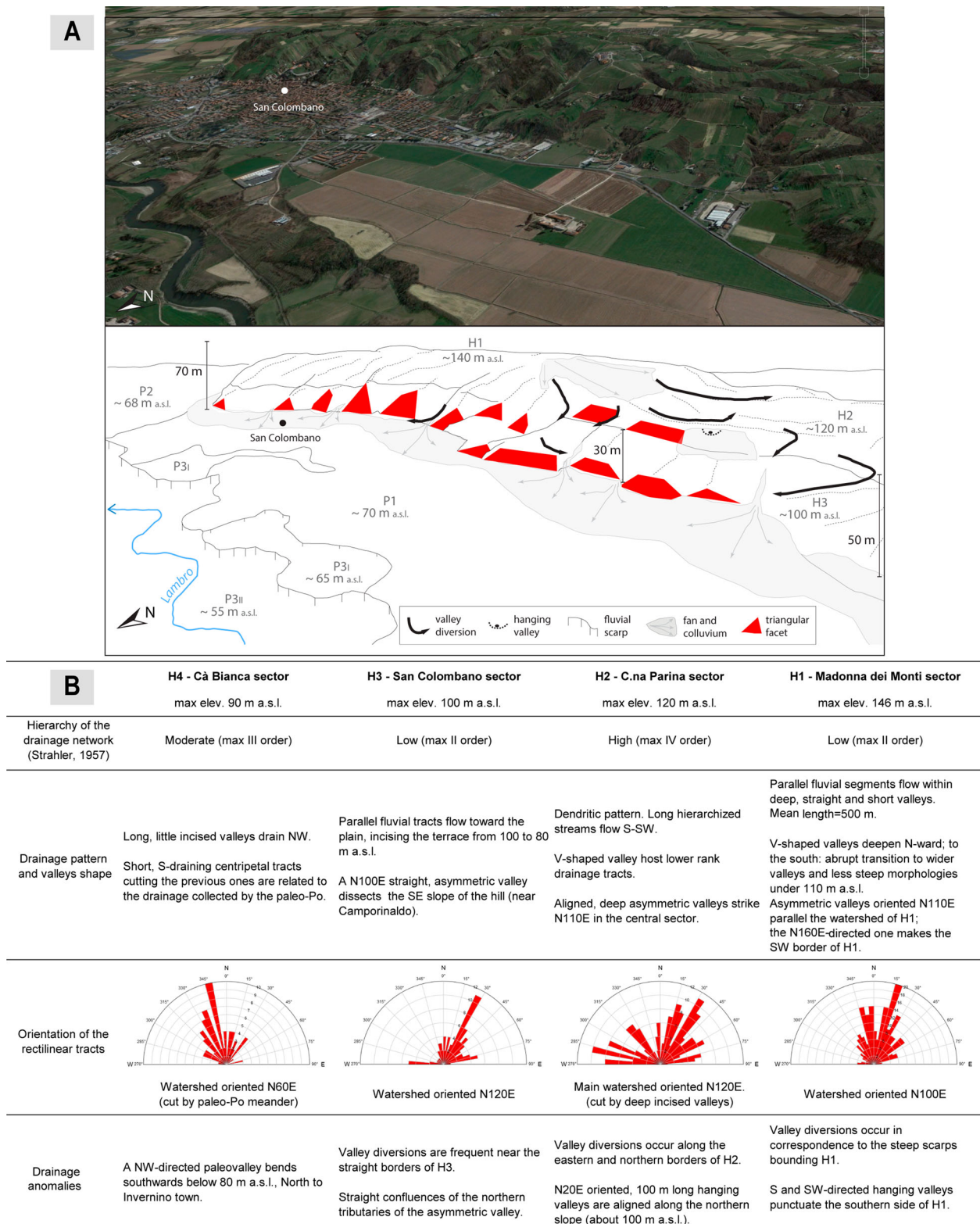


Figure 5. Morpho-structural elements of the San Colombano hill. (A) Two arrays of triangular and trapezoidal facets characterize the steep, northern slope of the San Colombano hill; above: satellite view from Google Earth, below: line-drawing from field surveys. (B) Features of the drainage network and alluvial landforms of the hill morphological sectors. H1 to H3: morphological sectors of the San Colombano hill. P1 to P3: morphological sectors and sub-sectors of the terraced plain (see also the [Main Map](#) – Geomorphological Scheme).

thrust-related folding and uplift is recorded at the SCS (stage II, [Figure 6\(D\)](#)). It is revealed by folding of the Gelasian Unconformity and SCF which determines the post-Calabrian Middle-Late Pleistocene angular unconformity ([Figure 2](#)). This Middle-Late Pleistocene

lacuna on the hill encompasses the regional regressive sedimentary cycles recorded in the subsurface of the Central Po foreland basin ([Ghielmi et al., 2013](#); [Muttoni et al., 2003](#); [Regione Emilia-Romagna & Eni-AGIP, 1998](#); [Regione Lombardia & Eni Divisione Agip, 2001](#)).

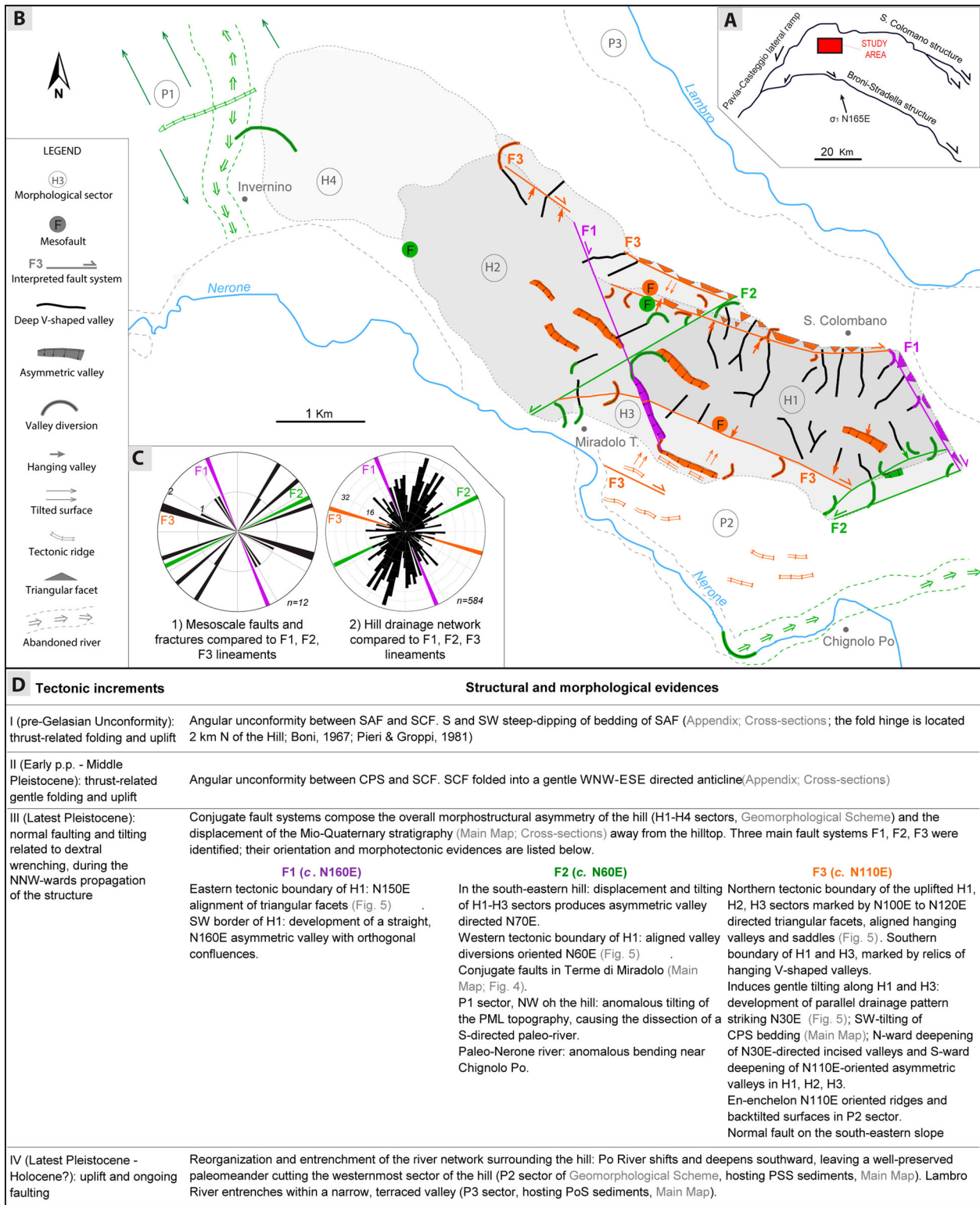


Figure 6. (A) Tectonic framework of the study area along the N-verging Emilian Arc of the Apennines (after Benedetti et al., 2003; Bigi et al., 1990). Arrows show the kinematic interpretation of quaternary active structures after Benedetti et al. (2003). (B) Simplified morpho-structural scheme of the San Colombano hill. F1 (purple), F2 (green), F3 (orange) are the interpreted Late Quaternary fault systems. Key to symbols in the left column; F (mesoscale faults as in Main Map) and morpho-structural elements have the same colours as the correlative interpreted fault systems. Shading of the hill morphological sectors as in Main Map, Geomorphological Scheme; white: plain morphological sectors. (C) 1 – Comparison between the measured orientations of mesoscale structures and the interpreted fault systems (F1, F2, F3); 2 – comparison between the rectilinear segments composing the drainage network and the interpreted fault systems (F1, F2, F3). Note that the large number of NNE-SSW segments corresponds to rectilinear valleys orthogonal to the main watersheds which parallel F3 fault system. They are mostly developed along the eastern morphological sector of the hill. (D) The proposed Quaternary evolution of the San Colombano structure.

Furthermore, gentle folding of the Middle-Late Pleistocene unconformity (Figure 2), and the lateral variations in thickness and facies of the unconformable CPS and INS synthems (Main Maps; Cross-sections), suggest Late Pleistocene syndepositional tectonics. Evidences of Late Pleistocene thrusting reactivation were suggested for the Broni-Stradella fault (Figure 1; Benedetti et al., 2003) outcropping 20 km south of the hill, and for the related PCLR, that bounds the SCS to the west (Figure 1; Figure 6(A)).

The stratigraphic, morphological and structural constraints from surface surveys suggest that the San Colombano ramp anticline underwent dissection since the latest Pleistocene (stage III, Figure 6(D)), along N110E, N60E, N160E trending fault systems (Figure 6(B,C)). Constraints to timing and kinematics of this late tectonic activity are provided by the offset of the base CPS and base INS in correspondence of the triangular/trapezoidal facets which shape the hillslopes with a left-stepping configuration and by the associated mesoscale normal faults (Main Map; Figure 6(B,C)). Considering the current regional schemes for the Quaternary evolution of the Apennine Emilian Arc (Benedetti et al., 2003 and references therein), a right-lateral transtension linked with ongoing N-wards movement driven by the PCLR can be conservatively suggested at the present state of the art (Figure 6(A)).

The latest Pleistocene-to-Holocene reorganization and entrenchment of the river network (P3 sector, Geomorphological scheme) eventually suggests a latest phase of uplift of the San Colombano hill and adjacent areas (stage IV, Figure 6(D)).

In summary, the detailed mapping let the editing of the present geological map, leading to the following improvements:

- (1) elaboration of a new stratigraphic scheme of the Quaternary succession of the San Colombano hill, which includes Late Pleistocene alluvial synthems unconformably overlying the Calabrian shallow marine formation. The new micropaleontological constraints document the Tortonian-Calabrian hiatus on the hill.
- (2) The surface geological data (Figure 6(B)) provide new constraints to interpret the Quaternary tectonic evolution of this key-sector at the N-Apennine-Po Plain hinge. These data permit to recognize the Mid-Late Pleistocene uplift and folding, and the latest Pleistocene dissection of the San Colombano ramp anticline, describing their effects on the stratigraphic record.
- (3) The set-up of a hierarchic Geo-Database collecting new and historical data provides a consistent support for handling multidisciplinary data. The geological dataset is ready for the integration of surface and subsurface data in the 3-D (4-D?) geological model which represents the progressing research.

Software

The compilation of the geological map was performed using the Esri ArcGIS® 10.2.1. Quantitative geomorphological analyses were carried out using ArcGIS Tools, and compared with the field observations. Outcrop descriptions (facies associations, weathering profiles, structures) and subsurface available data were classified and normalized to populate GIS-based geodatabases. Final editing was managed with Adobe Illustrator®.

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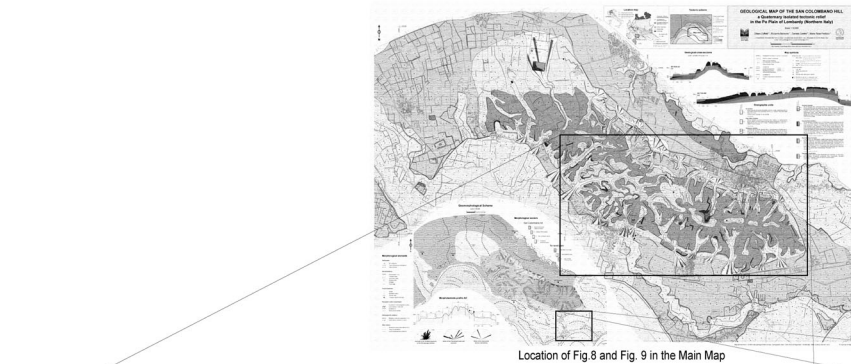
Appendix

APPENDIX - DATA MANAGEMENT AND STRUCTURE OF THE DATABASE

Fig. 7

Existing data	Data	Data analysis and GIS processing	Products
Raster CTR Regional Technical Map, 1:10.000 scale Regional DTM 5x5 Aerial photos	Vector drainage network (GIS digitization)	Qualitative morphological analysis Slope and aspect maps on the San Colombano hill Azimuthal analysis of the drainage network	Geo-database of topographic and hydrographic data Drainage network and drainage pattern maps and plots
Geological maps 1:100.000 scale (Boni, 1967; Anfossi et al., 1971) Marine exposures at present disappeared on the hill Structural elements (Bigi et al., 1990; Fantoni et al., 2004)	Geological field mapping: Soil textures and colours Petrography of surface gravel samples Sedimentological, pedological, structural outcrop description Mesofaults measurements	Micro-paleontological analyses on marine samples, petrographic and pedological analyses GIS-based digitization, normalization and classification of the geological field descriptions Data correlation	Geo-Database of historical and new surface geology and structural data Map of the historical and new surveyed outcrops of marine substratum Geological map, 1:10.000 scale Geological cross-sections
Geomorphological Map 1:250.000 scale (Castiglioni & Pellegrini, 2003) Geomorphological studies on San Colombano relief (Benedetti et al., 2003; Pellegrini et al., 2003)	Geomorphological field mapping: Dip-directions of surface topography Sub-horizontal surfaces Erosional scarps and terrace rims Valley shape	GIS-based digitization, classification and ranking of each geomorphological element Morphostructural analysis	Geo-Database of geomorphological data Geomorphological and morpho-tectonic maps, 1:10.000 scale Morphotectonic profiles

Fig. 7 - Structure of the Geo-Db and methods for data collection and data management adopted to obtain the geological elaborations presented in this work.



Location of Fig. 8 and Fig. 9 in the Main Map

Fig. 8

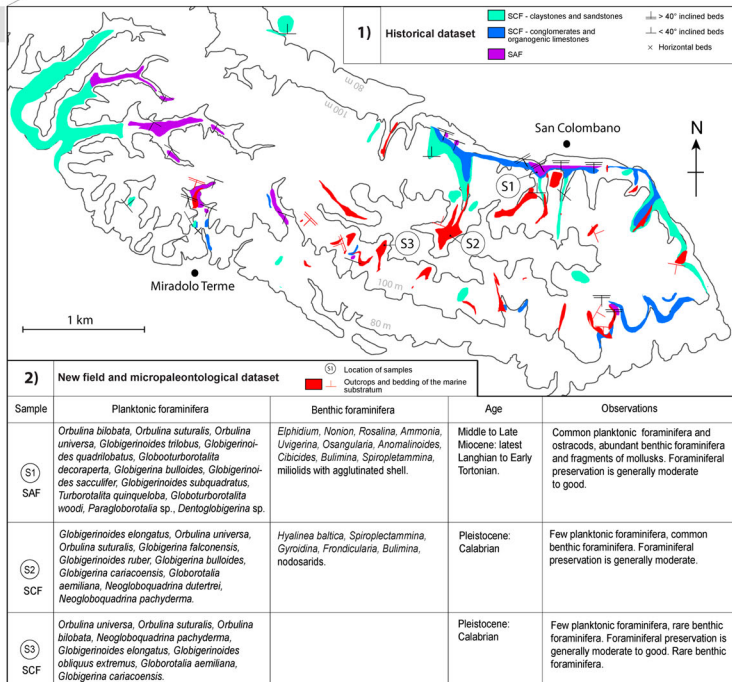


Fig. 8 - The marine exposures of the San Colombano hill. 1) Exposures and dip of bedding of the marine substratum. Historical dataset: location of disappeared outcrops after Airaghi (1897), Fiorani Gallotta (1921), Porro and Anelli (1928), Coggi and Di Napoli Alliata (1950), Farioli (1954), Boni (1967), Anfossi et al. (1971), Anfossi and Brambilla (1981), Soldan (2007) 2) The original dataset. Foraminiferal assemblage of three selected most significant samples of marine formations. SAF: Sant'Agata Fossili Marls; SCF: San Colombano Formation.

Fig. 9

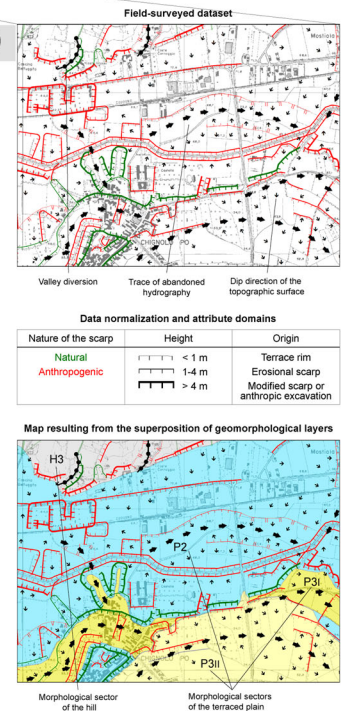


Fig. 9 - Example of GIS-management of the thematic layers to obtain the geomorphological map. Note how GIS symbology is useful to rapidly distinguish natural morphologies (green) from anthropic modifications of the landscape (red). H3, P2, P3: geomorphological sectors (labels as in Main Map - Geomorphological Scheme).

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