Geological evolution of the intermountain Rieti basin (Central Apennines)

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ABSTRACT

The distribution was mapped of essentially Quaternary continental deposits found in the Rieti basin and neighbouring areas (Central Italy). These deposits were correlated on the basis of the reinterpretation of a multidisciplinary database, produced following more than ten years of research conducted by the authors and others.
A vast amount of geomorphic, stratigraphic, geophysical, palaeoclimatic, pedological, archaeological, historical and palaeoseismological data was collected and compared in order to constrain the Quaternary drainage network evolution for a sector of the Central Apennines (Italy). This database includes detailed field mapping and airphoto interpretation, high-resolution stratigraphic data from continuous boreholes and exploratory trenches, absolute dating using different techniques ($^{39}Ar/^{40}Ar$, U/Th, ^{14}C), soil chronosequences, and analyses of excavations across Holocene fault scarps. The choice of a regional scale for the map was motivated by the need for an integrated approach at the basin scale. This approach provides basic information for the reconstruction of the major steps in the evolution of the local landscape and for an assessment of the role played by different morphogenetic processes in the inter-Apennine basin studies, with a resolution that progressively increases as age decreases. It is the authors' opinion that the same approach could be successfully used for other young, seismically-active mountain chains worldwide. These results have important consequences in the field of applied and environmental geology, because they enable the delineation of i) the next-future scenarios in the event of quasi-stationarity of the current processes (for instance, the maximum potential earthquake expected in 10^2 yr, that is, the lifetime of nuclear power plants and high-risk facilities); ii) the long-term scenarios (10^3-10^4 yr) expected after significant changes in the magnitude of major morphogenetic factors, such as climate and/or tectonics (for instance, long-term stability of sites designed for radioactive waste disposal).

AIMS

This map correlates continental deposits on the basis of an integrated database including field mapping, geomorphic investigations, stratigraphies from continuous boreholes, detailed 2D stratigraphies, archeological and historical data, in order to:
1) define the major earth surface processes active in the area;
2) compare Holocene and Quaternary s.l. landscape features;
3) delineate the expected future scenarios.

KEYWORDS

Environment geology, Quaternary deposits, intermountain basin, extensional tectonics, drainage network, Quaternary palaeoclimates, Central Apennines.

RIASSUNTO

E' stata rappresentata in carta la distribuzione dei depositi continentali presenti nel bacino di Rieti e aree adiacenti (Italia Centrale), essenzialmente di età quaternaria. Questi depositi sono stati correlati sulla base della reinterpretazione di una banca dati multidisciplinare, risultato di oltre dieci anni di ricerche condotte dagli autori e da altri studiosi.
Sono disponibili una gran quantità di dati geomorfologici, stratigrafici, geofisici, paleoclimatici, podologici, archeologici, storici e paleosismologici. Tutte queste informazioni sono state confrontate al fine di poter ricostruire l'evoluzione quaternaria del reticolo idrografico per un settore degli Appennini Centrali (Italia). La banca dati citata è il risultato di rilevamenti, fotointerpretazione, stratigrafie dettagliate da sondaggi a carotaggio continuo e da trincee esplorative, datazioni assoluti mediante tecniche diverse ($^{39}Ar/^{40}Ar$, U/Th, ^{14}C), cronosequenze di suoli e analisi di scavi attraverso scarpate di faglia oloceniche. La scelta di una scala regionale è dovuta alla necessità di un approccio integrato alla scala del bacino. Questo approccio fornisce le informazioni base per la ricostruzione delle fasi principali dell'evoluzione locale del paesaggio e per La valutazione del ruolo giocato dai differenti processi morfogenetici nel bacino intrappenninico studiato, con una risoluzione che decresce progressivamente con l'età. E' opinione degli autori che lo stesso approccio potrebbe essere utilizzato con successo in area di catena giovane e sismicamente attiva. Questi risultati hanno importanti conseguenze nel campo della geologia applicata ed ambientale, in quanto consentono di delineare i) gli scenari del prossimo futuro nell'ipotesi di quasi-stazionarietà dei processi attuali (per esempio il terremoto massimo potenziale atteso nei prossimi 10^2 anni, che è il tempo di vita delle centrali nucleari e degli impianti ad alto rischio); ii) gli scenari di lungo periodo (10^3-10^4 anni) a seguito di cambiamenti significativi nella magnitudo dei fattori morfogenetici, quali il clima e/o la tettonica (per esempio la stabilità nel lungo periodo di siti dedicati allo smaltimento di depositi radioattivi).

GEOLOGICAL MAP OF CONTINENTAL DEPOSITS IN THE RIETI BASIN (CENTRAL APENNINES)

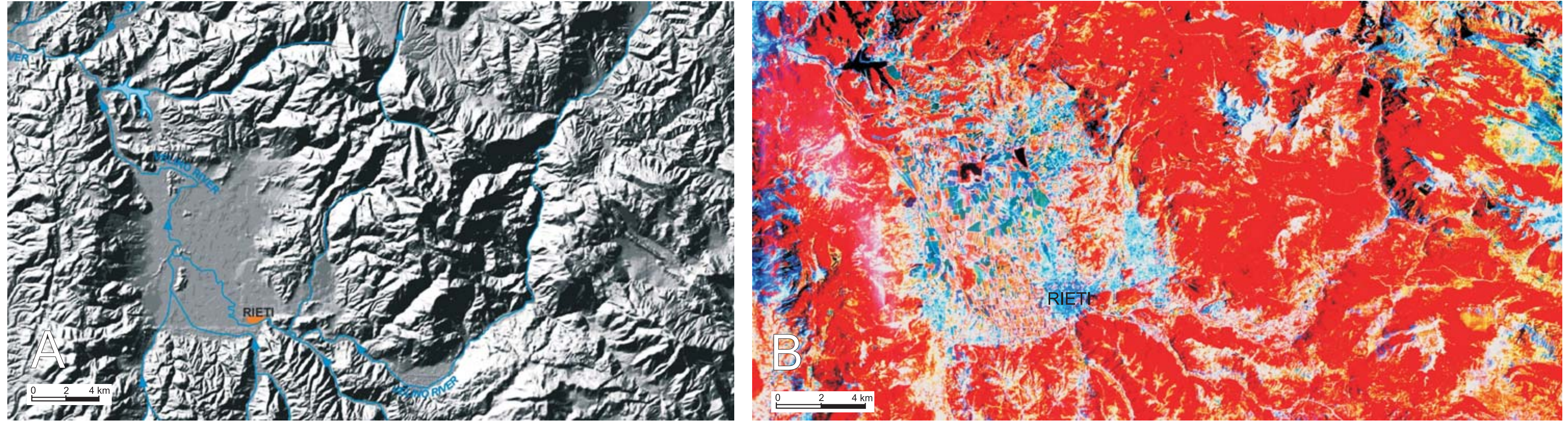


Fig. 2 - *The Rieti basin and surroundings as displayed by (A) a Digital Elevation Model (resolution 20 m) and (B) satellite image (courtesy by Chevron).*

GEOLOGIC SETTING

The Apennines are a NW-SE-trending Neogene and Quaternary fold and thrust belt. Since the late Pliocene, following the opening of the Tyrrhenian sea, extensional tectonics progressively shifting to the East has determined a number of deep tectonic basins, hosting mainly marine deposits and volcanics on the Tyrrhenian side. In the inner sectors of Central Apennines (see Figure 3) normal-fault-bounded intermountain depressions have developed, typically as northwesterly elongated half and full graben. They are up to several tens of kilometres long, bounded by steep limestone faults-generated-mountain front, and hosting a thick Quaternary continental sedimentation.

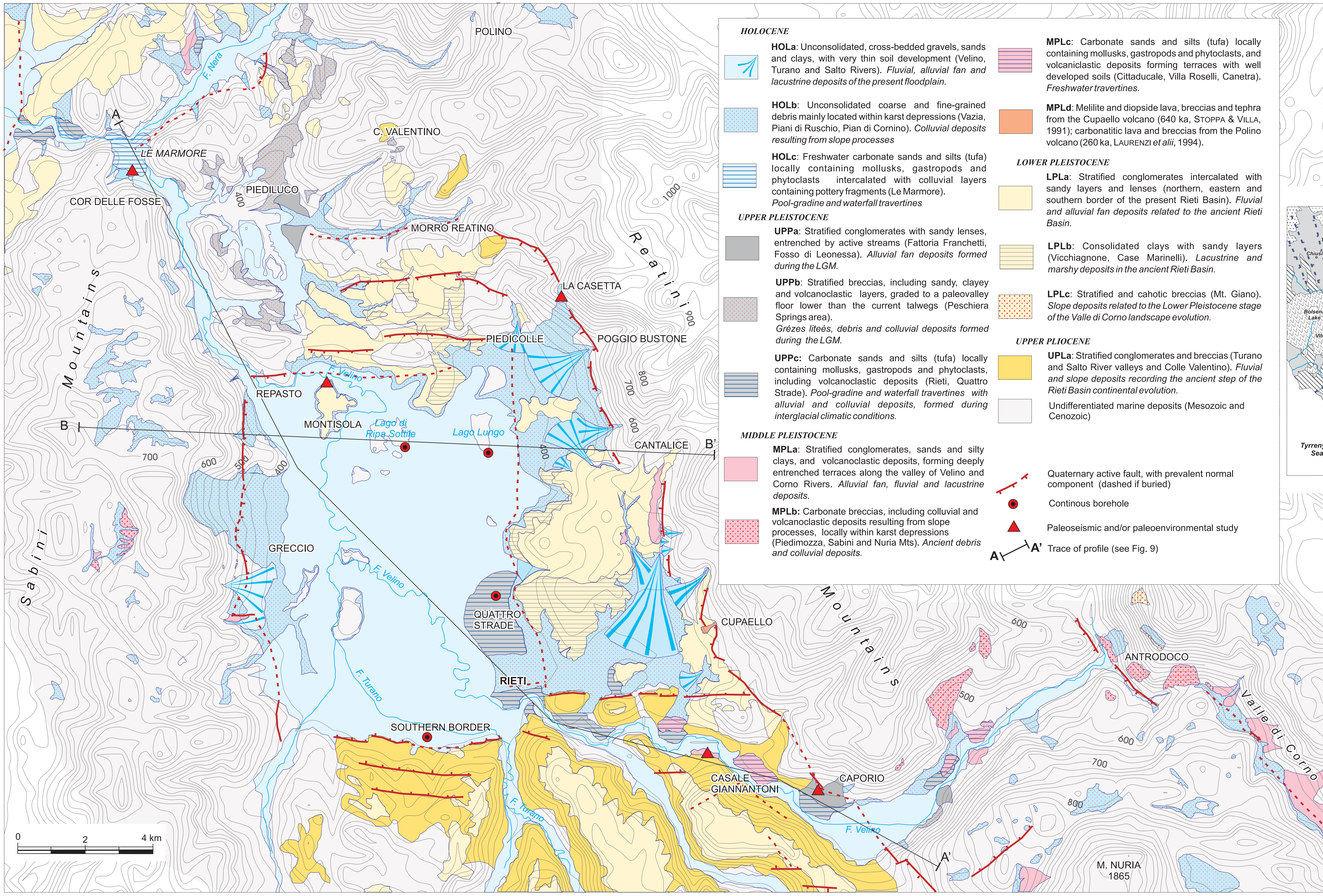


Fig. 1 - *Geological map of continental deposits in the Rieti Basin and surrounding areas (Central Apennines, Italy).*

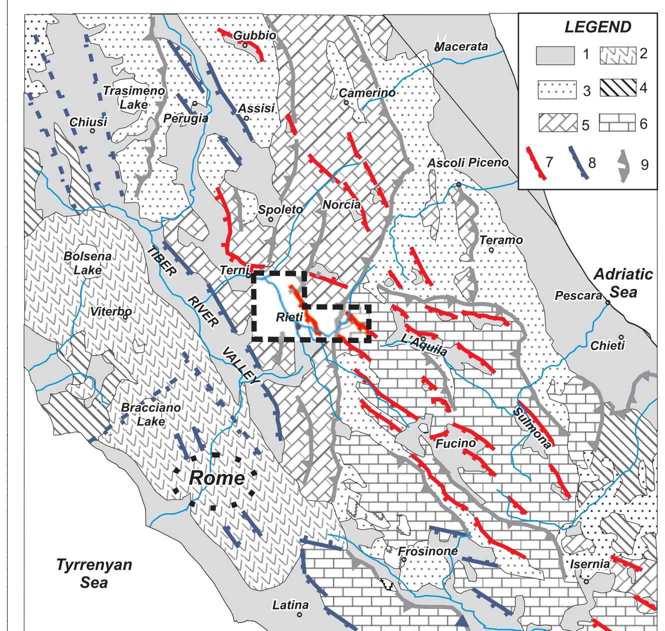


Fig. 3 - *Geological and structural setting of Central Apennines.*
1. Continental deposits (Pliocene to Holocene);
2. Volcanic deposits related to perithyrrenian volcanic districts (Quaternary);
3. Synorogenic deposits (Miocene-Pliocene);
4. Hemipelagites and pelagites, Argille Scagliose (Cenozoic);
5. Umbria-Marche pelagic and transitional limestones and marls (Mesozoic-Cenozoic);
6. Latium-Abruzzi neritic limestones (Mesozoic-Cenozoic);
7. Normal fault in the central sector of the Apenninic chain, capable to produce strong surface faulting earthquakes (Me>6.0);
8. Normal fault in the Tyrrhenian sector of the Apenninic belt, without evidences of coseismic surface faulting;
9. Thrust.

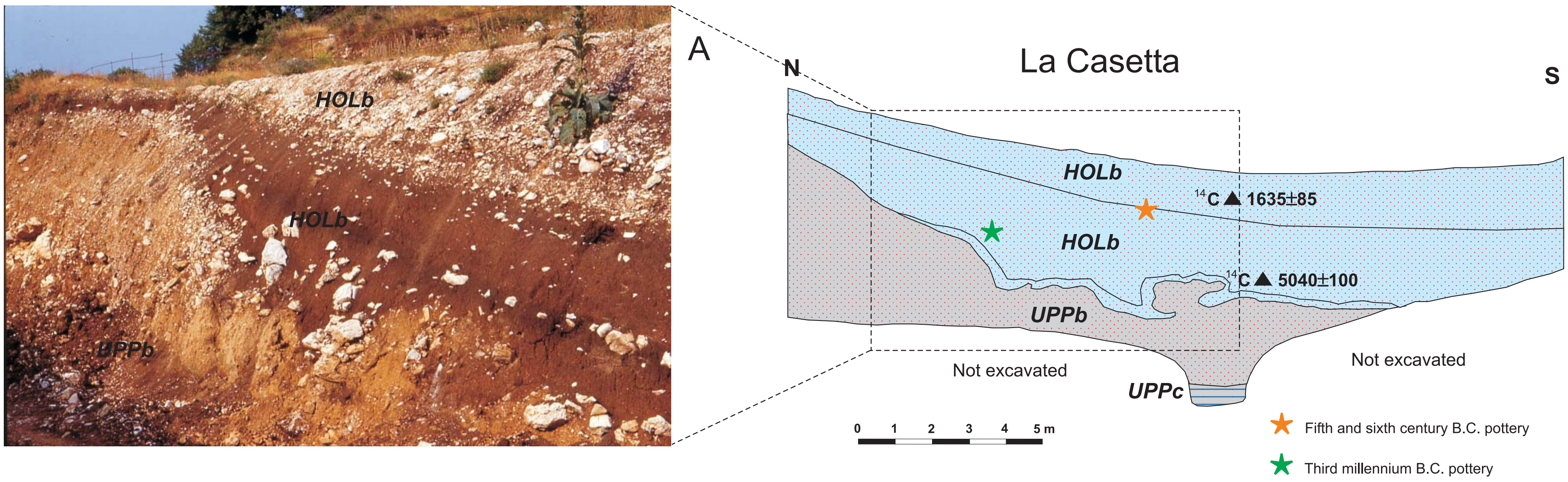


Fig. 4 - *Examples of stratigraphic sections in Late Quaternary deposits, classified and termed as in the legend of the geological map.*

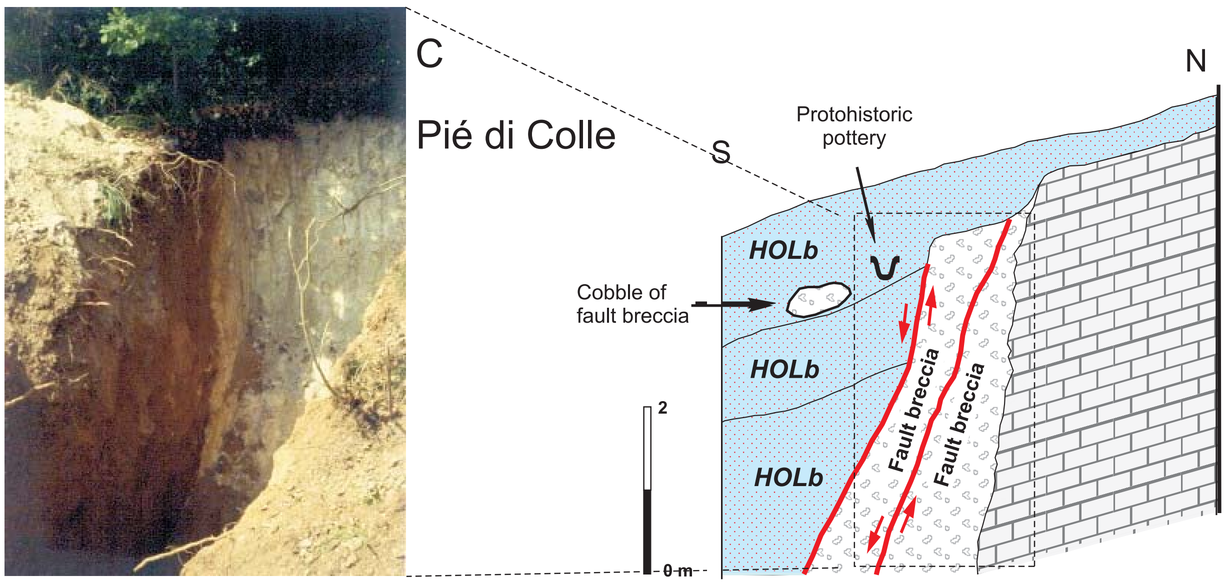
A) *La Casetta, Poggio Bustone: stratigraphic section in debris colluvial deposits;*

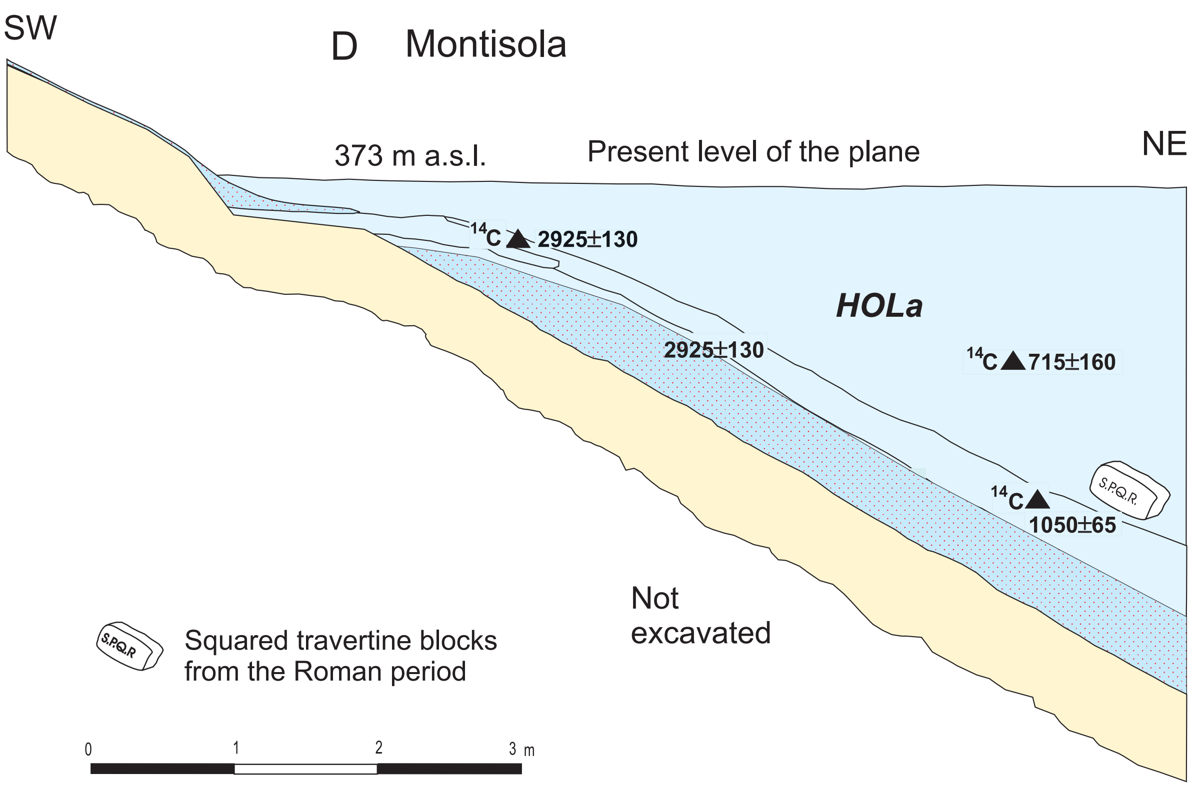
B) *Caporio, gravity graben within Late Quaternary talus deposits: this feature is an evidence of recent coseismic surface faulting;*

C) *Pié di Colle: structural and stratigraphic characteristics provide the evidences for Holocene strong earthquakes, capable to produce surface faulting;*

D) *Montisola: this stratigraphic section provides the historical aggradation rate of fluvial and lacustrine deposits of the Rieti plain from radiocarbon and archeological dating.*

References for dating: (A) MICHETTI et alii, *1995;* (D) FERRELI et alii, *1993.*





INTRODUCTION

The map (Fig. 1) illustrates the distribution of the sequence of essentially Quaternary continental deposits found in the Rieti basin and neighbouring areas (Fig. 2) of the Central Apennines (see Fig. 3 for a geological scheme). These deposits are correlated on the basis of the reinterpretation of a multidisciplinary database, produced following more than ten years of research conducted by the authors and others. This database includes detailed field mapping, geomorphological analyses, high-resolution stratigraphic data from continuous boreholes and natural or artificial exposures (Figs. 4 and 5), geophysical investigations, soil profiles, and archaeological and historical data.

Consistently with the scale of the map, a special effort was made to organize the legend in a few units, in order to put together deposits representing same steps in the continental evolution of the basin.

This was made possible thanks to the availability of a large set of radiometric and relative dating (Ar/Ar, 4 samples; U/Th, 26 samples; soil chronosequences, 15 profiles; radiocarbon, 62 samples; archaeological analyses, 35 samples; tephrachronology, 12 samples; and a relatively complete historical record of the last 25 centuries), and of a wealth of stratigraphic information, which allowed reliable facies analyses and palaeoenvironmental modelling to be carried out.

Therefore, for each time-window of the period studied (from the Late Pliocene to the Late Holocene), the deposits included in a same unit should be regarded as synchronous, taking into account the obvious uncertainty inherent in the pertinent time-window.

In this way, the authors intend to promote an integrated approach at the basin scale. This approach provides basic information for the reconstruction of the major steps in the evolution of the local landscape and for an assessment of the role played by different morphogenetic processes in the inter-Apennine basin studied, with a resolution that progressively increases as age decreases.

It is the authors' opinion that the same approach could be successfully used for other young, seismically-active mountain chains worldwide. These results have important consequences in the field of applied and environmental geology, because they enable the delineation of i) the next-future scenarios in the event of quasi-stationarity of the current processes (for instance, the maximum potential earthquake expected in 10^2 yr, that is, the lifetime of nuclear power plants and high-risk facilities); ii) the long-term scenarios (10^3-10^4 yr) expected after significant changes in the magnitude of major morphogenetic factors, such as climate and/or tectonics (for instance, long-term stability of sites designed for radioactive waste disposal).

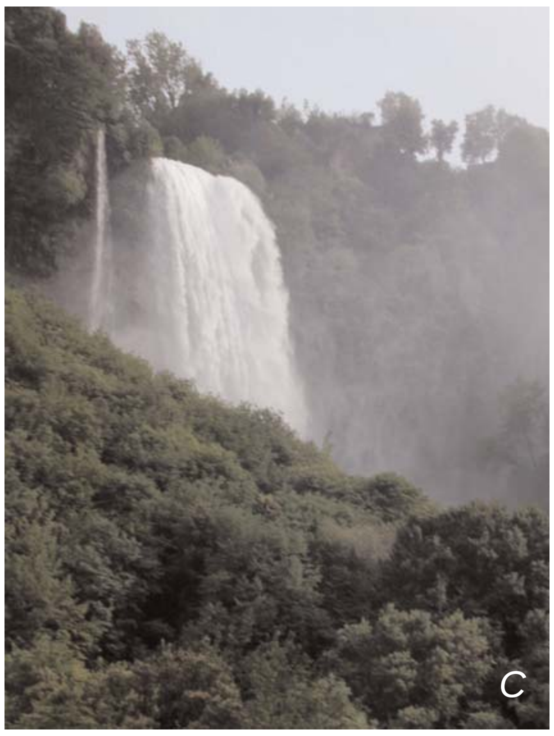
LANDSCAPE EVOLUTION OF THE STUDY AREA

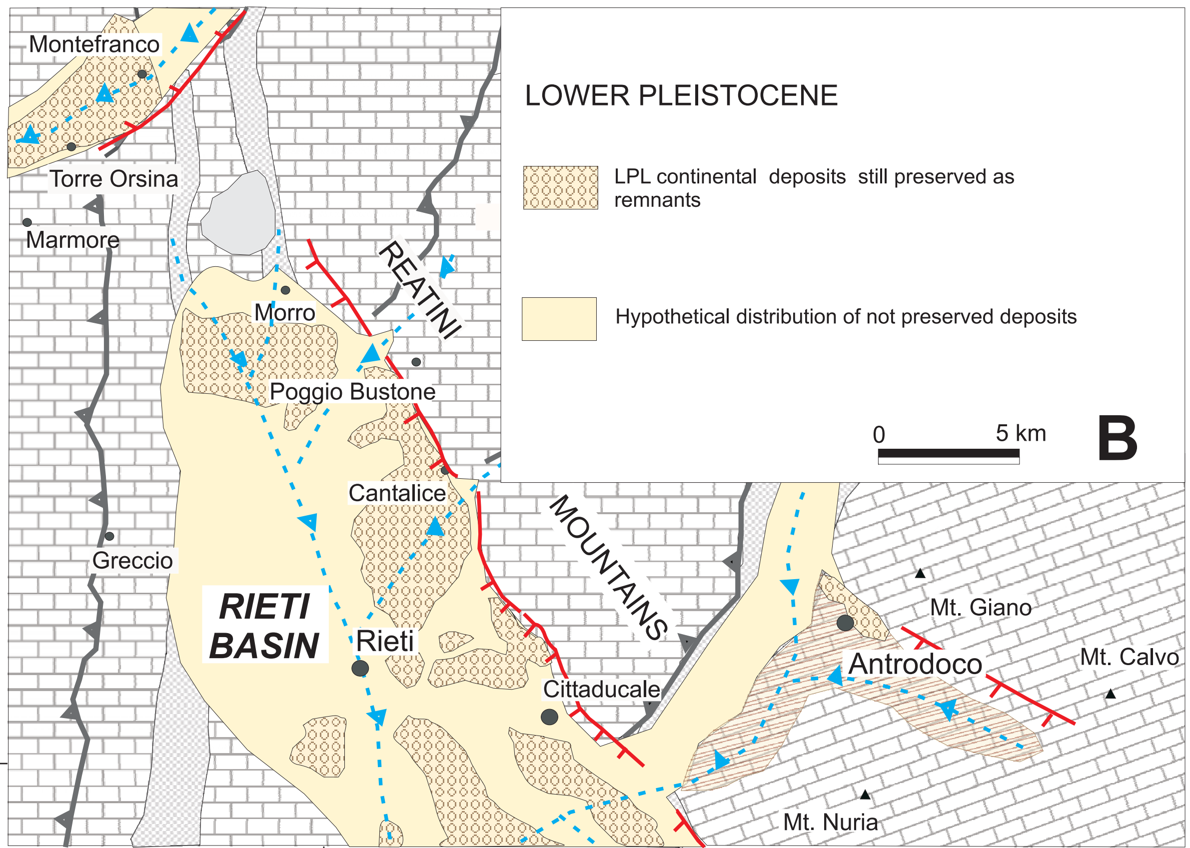
The area studied is currently included within the Velino-Nera drainage system, that is a tributary of the Tevere River. The Plio-Quaternary evolution of the area is strictly related to the post-collisional extensional tectonics that has strongly affected this sector of the Apennines (Fig. 3). The ancient, Late Pliocene to Early Pleistocene Rieti basin was a half-Graben developed in the hangingwall of the SW-dipping, NW-trending Rieti normal fault. This basin filled up with fluvial, alluvial fan and lacustrine sediments, going to form two main depositional units (UPL and LPL). The unconformity between these units is clear at the borders of the basin, but in the central part the younger unit conformably overlies the older one. Geomorphic and stratigraphic evidence (distribution of ancient fluvial deposits, erosional surfaces and wind gaps) clearly supports the hypothesis of two different steps in the Late Pliocene - Early Pleistocene period:

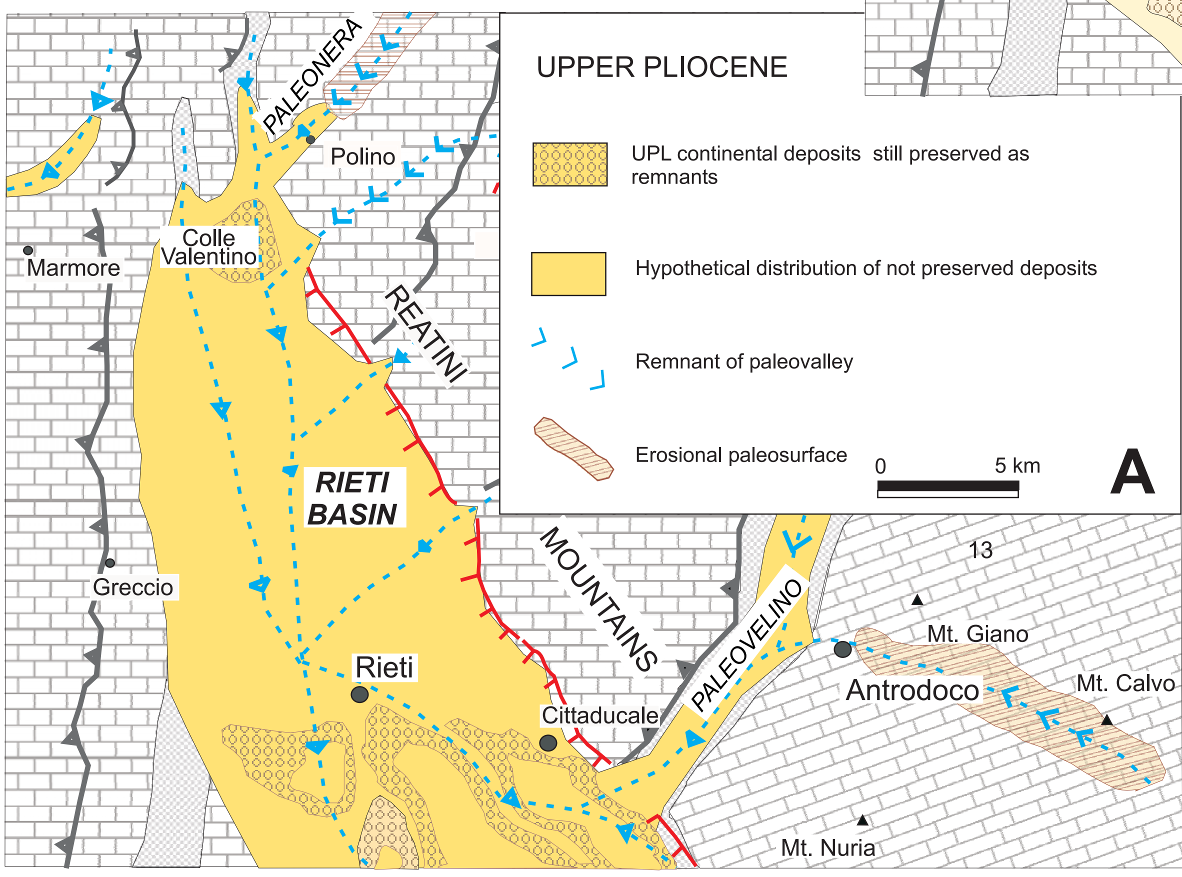
1) one single drainage network directed to the SSE (palaeo Nera - palaeo Velino system; UPL deposits, Fig. 6A); and 2) the palaeo Nera was captured and migrated to the WNW, while the palaeo Velino system was still draining to the SSE (LPL deposits, Fig. 6B).

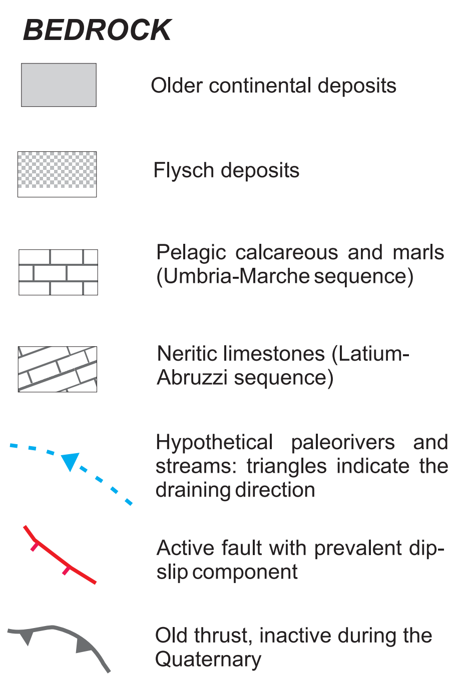
During the Middle Pleistocene (Fig. 6C), the Rieti tectonic structure evolved into a full Graben, and new N-S and E-W-trending normal faults developed, reshaping the ancient Rieti basin. The hangingwall was dissected into several blocks, the lowest of which hosted the present Rieti plain. Small volcanoes were generated, as shown, for instance, by the Cupaello ultrabasic lava flow located along the master normal fault of the basin. Together with the regional uplift, extensional tectonics

Fig. 5 - The Holocene alluvial deposition in the Rieti basin was controlled by the travertine sill located at Cor delle Fosse (A and B) near Le Marmore Falls (C).

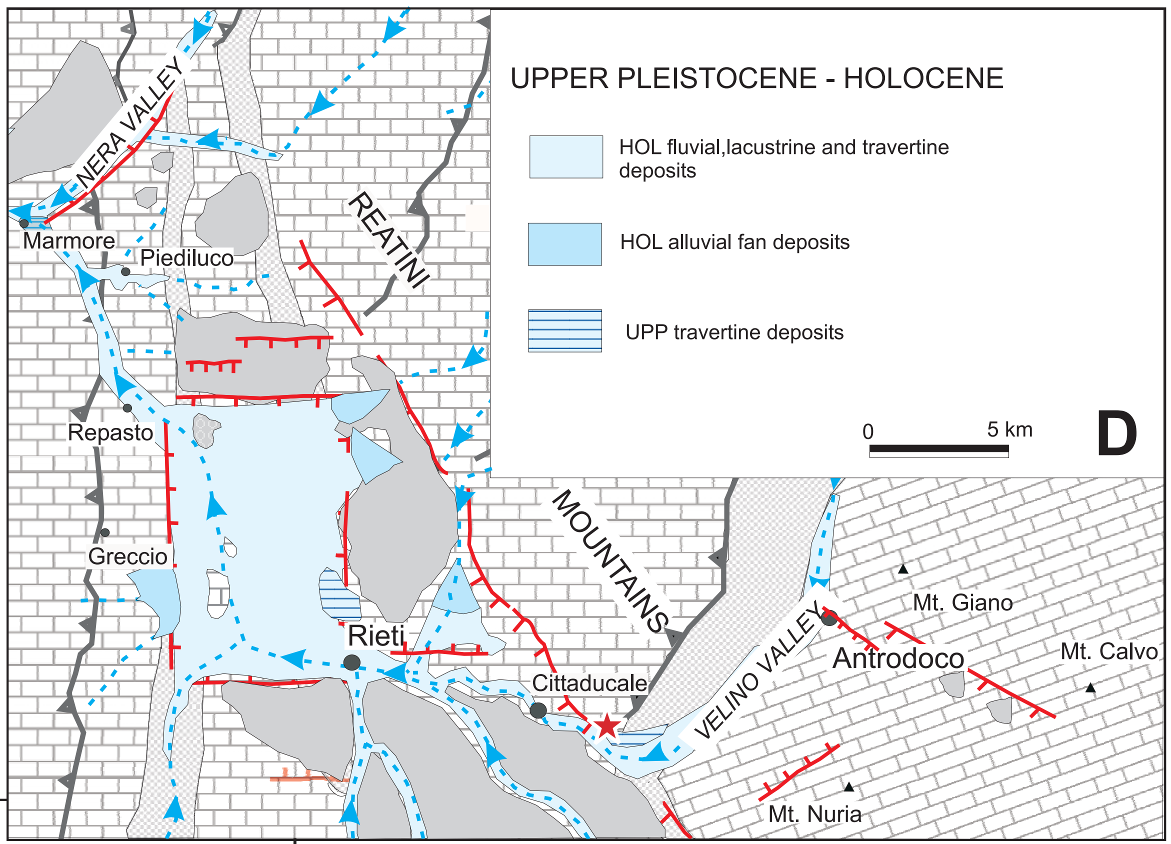








fostered huge downcutting rates in the main rivers (Fig. 7C), as displayed by the longitudinal profile along the lower part of the Velino Valley (Figs. 8 and 9A). The combined action of active tectonics and erosional processes generated a major capture in the palaeo Velino drainage system, which turned NNW inducing dramatic changes in the topography and stratigraphy of the area, including a sequence of beheaded valleys. The hydrogeology of the area was influenced by this new tectonic and volcanic setting.
The Middle Pleistocene climate fluctuations, combined with active extensional tectonics, triggered the formation of thick sequences of travertine deposits along the Velino River. Climatic conditions controlled the rates of travertine growth and downcutting, and, consequently, the sedimentary processes upstream. At least two orders of Middle to Late Pleistocene fluvial and lake terraces have been controlled by travertine platforms associated to warm and humid conditions, completely damming the Velino River near Cittaducale and Rieti (MPL and UPP units, Fig. 6D). Moreover, the Marmore platform (Fig. 5) dammed the Holocene Velino fluvial system (HOL unit) until the excavation of the artificial channel first dug during the Roman Empire. Cold and arid conditions were generally represented by grézes liteés deposition on the slopes and by lack of sedimentation or erosion in the floodplains.
The magnitude of recent aggradation rates was assessed by drilling continuous boreholes in the Holocene lacustrine sediments near the depocenter of the present Rieti plain. Sedimentation rates in the past ca 10 ka are of the order of 3-6 mm/yr (Fig. 8).
Moreover, the highly variable thickness of the HOL unit is in agreement with the hypothesis of a Late Pleistocene palaeotopography shaped by deep valleys connected to the last low-stand of the Marmore threshold. Palaeoseismological investigations, coupled with stratigraphic, geomorphic and geophysical analyses, provide the long-term (Quaternary) and short-term (Holocene) slip rates along major capable faults located at the borders of the basin (examples are shown in Fig. 4); these values are of the same order (0.5 - 1.0 mm/yr), but are at least ten times lower than maximum aggradation rates.



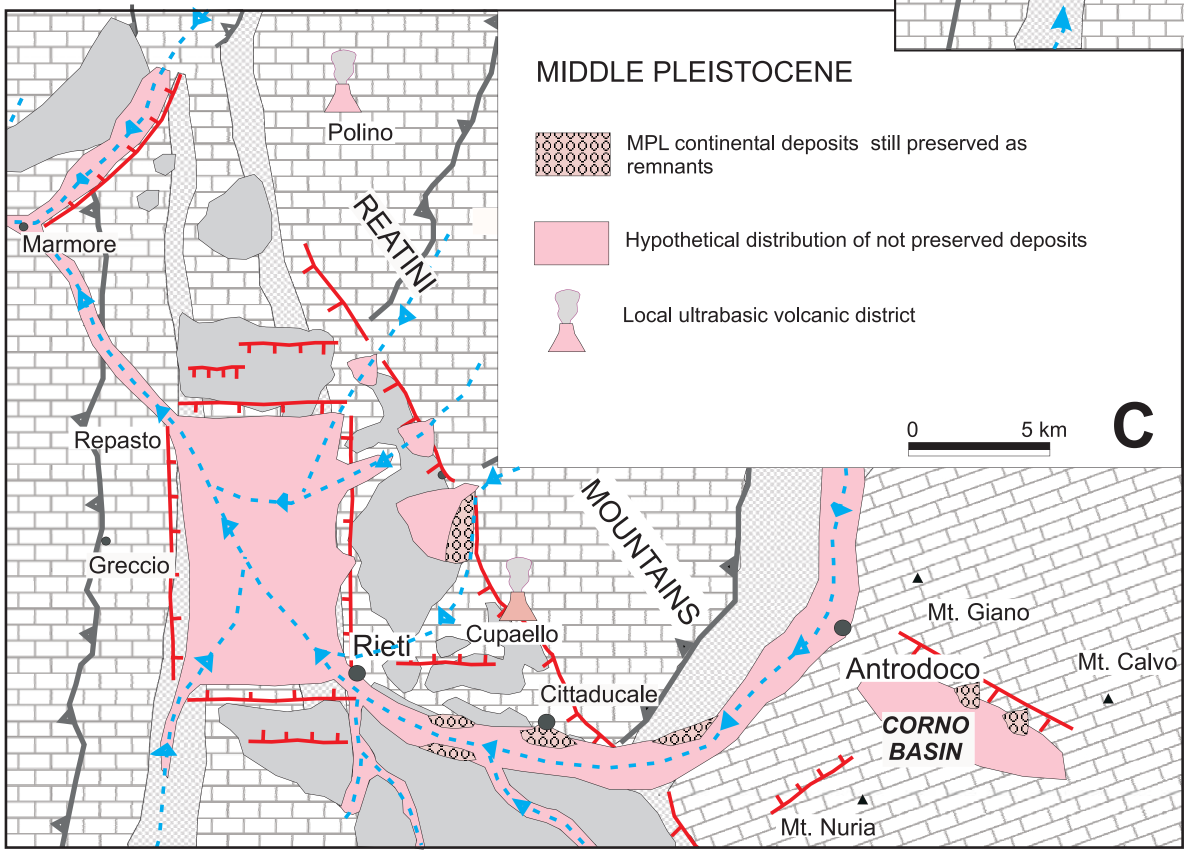


Fig. 6 - *Schematic sketch illustrating in four scenarios the major steps of the continental evolution of the studied area (see text for details). Since Late Pliocene to Early Pleistocene the Rieti basin was a half-Graben. The distribution of ancient fluvial deposits, erosional surfaces and wind gaps clearly support the hypothesis of two steps: i) one single drainage network directed to the SSE (palaeo Nera-palaeo Velino system, Fig. 6A) ii) the palaeo Nera migrated to WSW and the Palaeo Velino system was still draining to SSE (Fig. 6B). Then the Rieti tectonic structure evolved into a full Graben (Middle Pleistocene, Fig. 6C), and new N-S and E-W trending normal faults developed, reshaping the ancient Rieti basin. The palaeo Velino turned to NNW inducing dramatic changes in the topography and stratigraphy of the area, including a sequence of beheaded valleys. Since the Middle Pleistocene, at least two orders of fluvial and lake terraces have been controlled by travertine platforms associated to warm and humid conditions, completely damming the Velino River near Cittaducale and Rieti (Fig. 6D). The Marmore platform dammed the Holocene Velino fluvial system until the excavation of the historical artificial channel.*

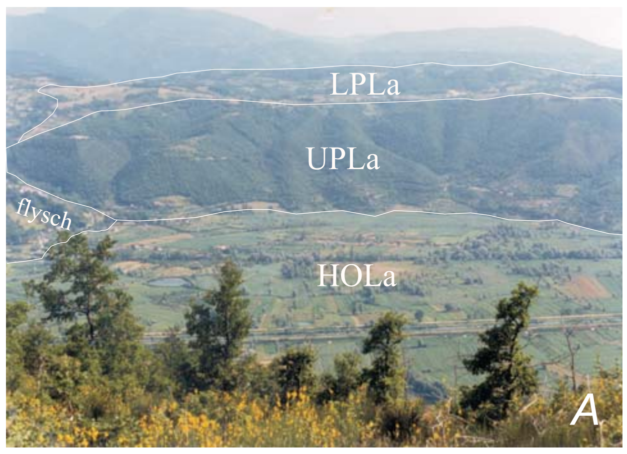
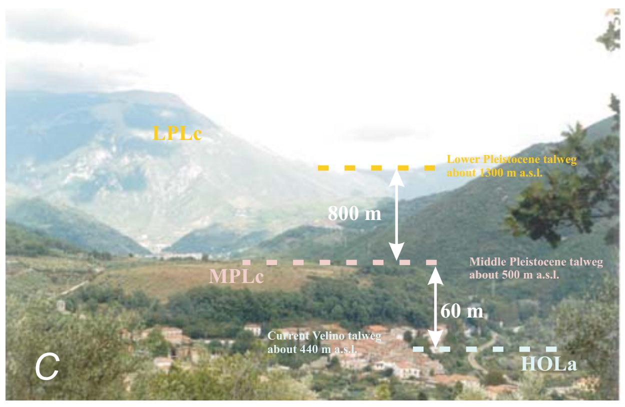


Fig. 7 - *The geomorphological and stratigraphic context of the studied area.*
A) The Calcariola ridge (southern border of the San Vittorino Plain), mainly made up with conglomerates and sands, records a long period of fluvial and alluvial fan aggradation, Lower Pleistocene in age. In this sector LPL *unit overlains* UPL *deposits;*
*B) Fluvial deposits located at the eastern border of the Rieti basin (*LPLa*);*
C) The progressive talweg lowering in the Middle Velino Valley since the Lower Pleistocene, under the interactions between climatic variations and tectonics, as suggested by the distribution of continental deposits and associated erosional surfaces.



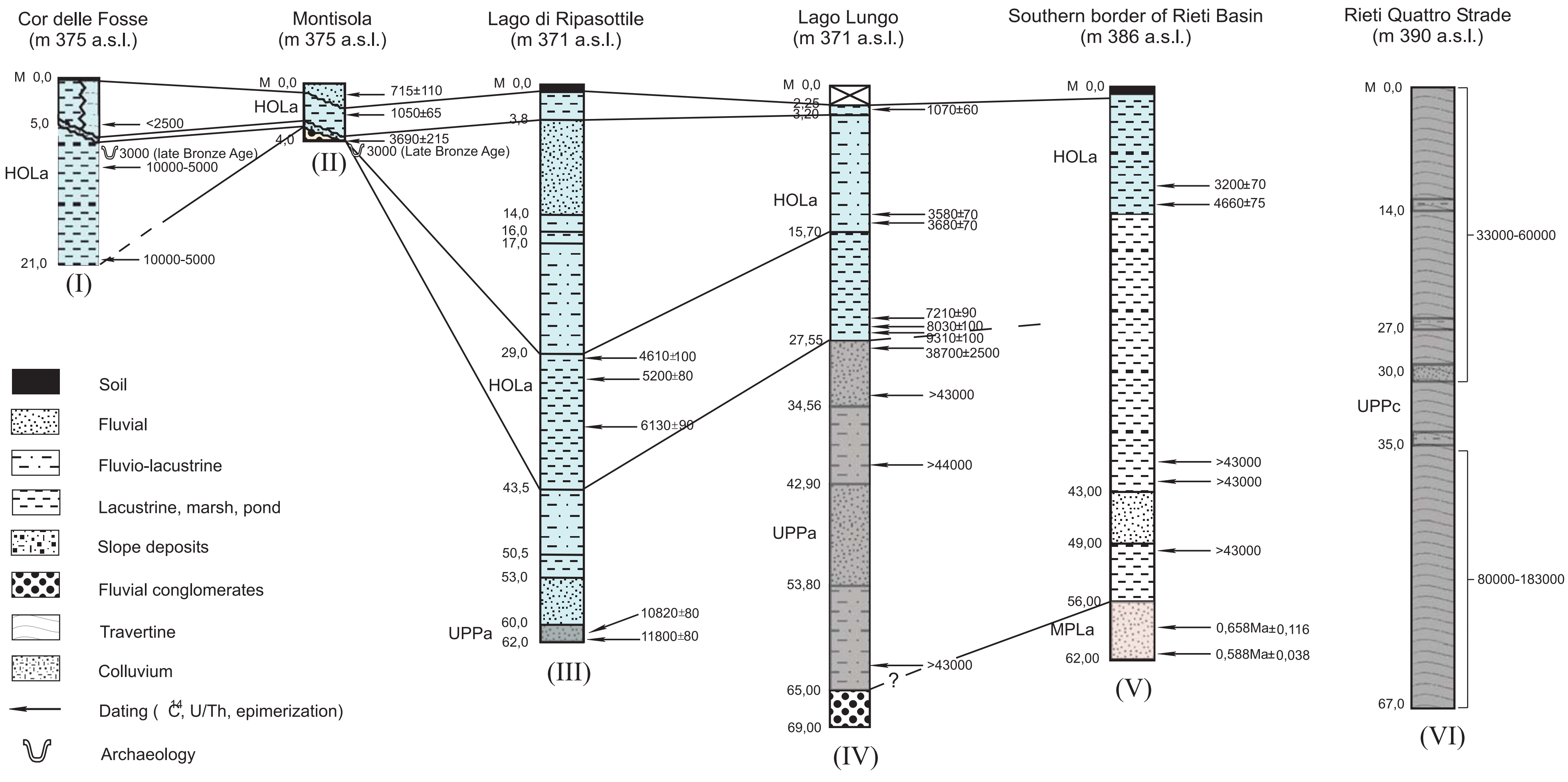
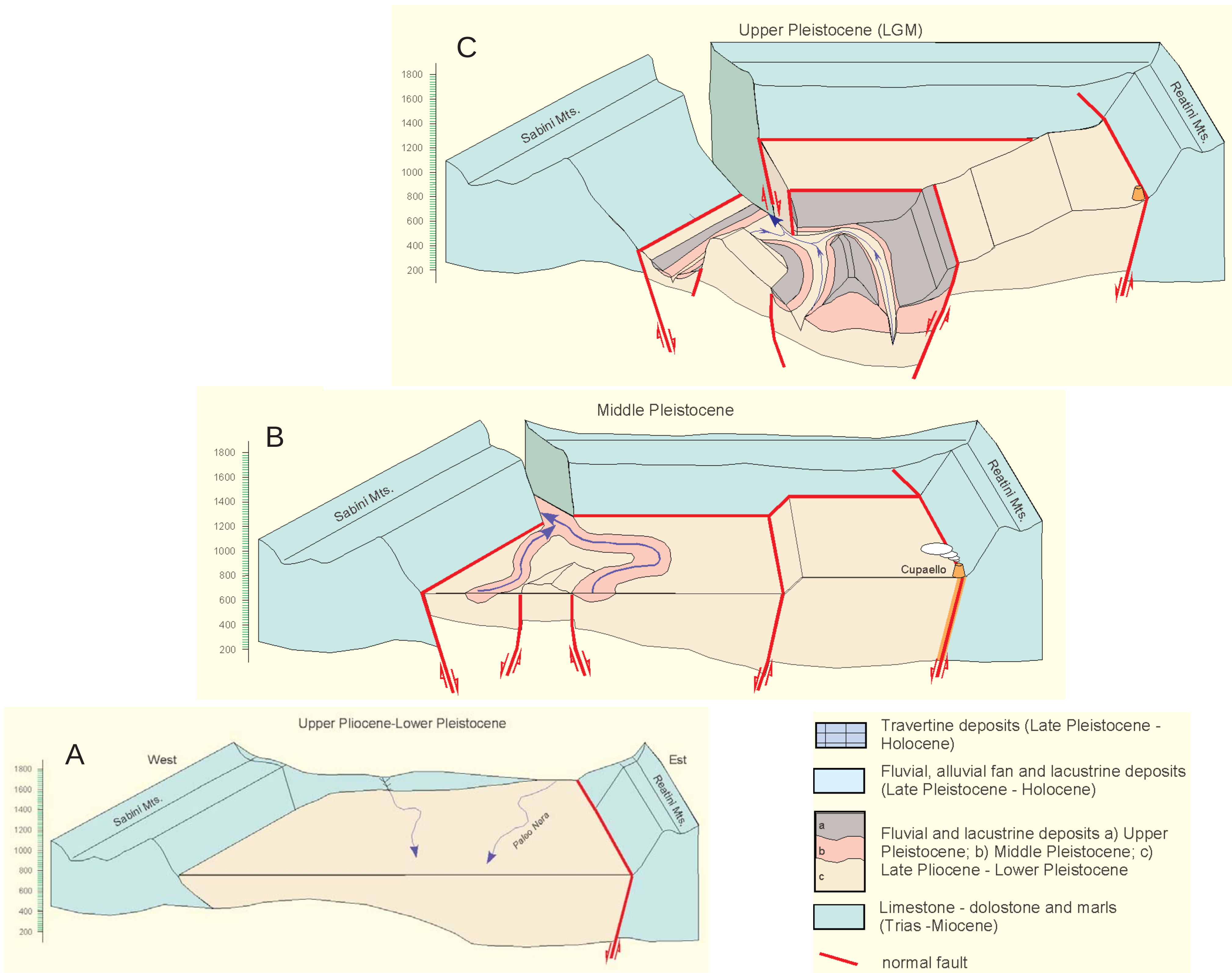
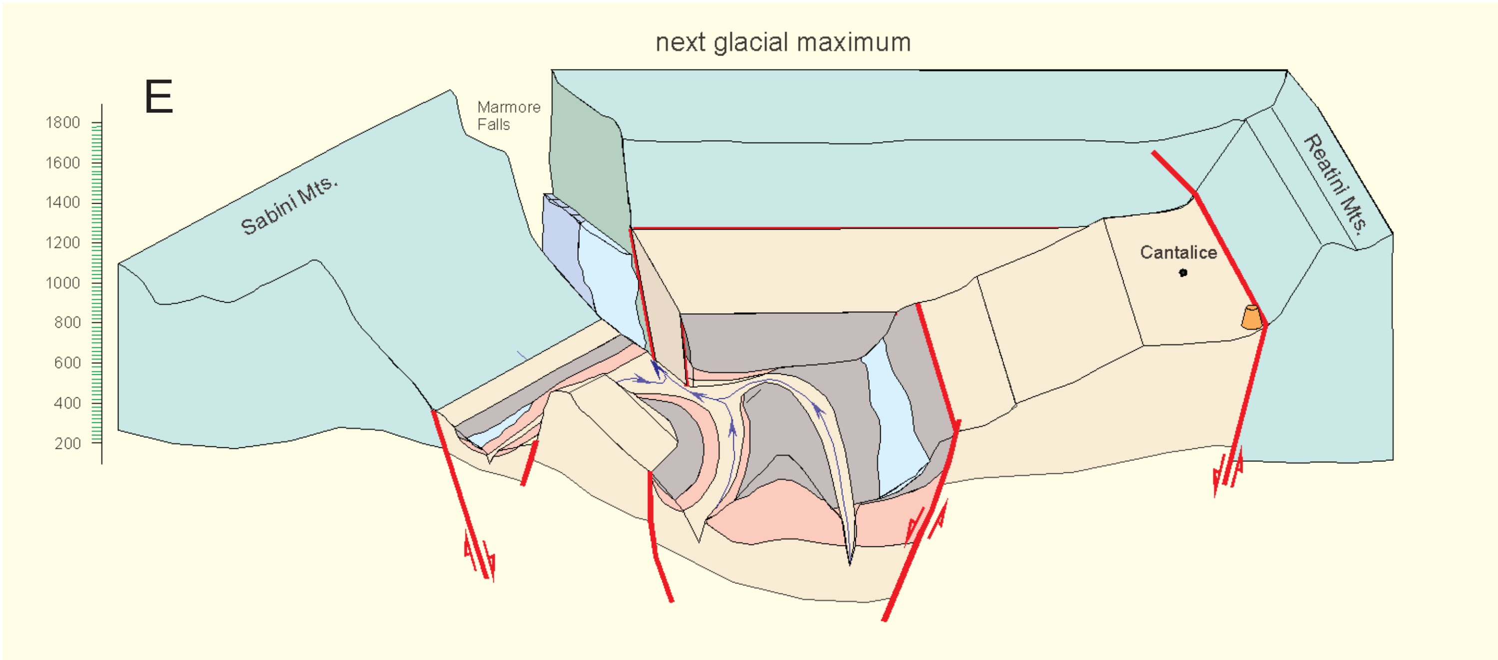


Fig. 8 - *Quantitative information on Late Quaternary rates of sedimentation, erosion and deformation from high-resolution stratigraphies. The deposits are colored as in the geological map.*

References for dating: I) CARRARA et alii*, 1995; II)* FERRELI et alii*, 1993; III)* RICCI LUCCHI et alii*, 2000; IV)* CALDERONI et alii*, 1995; V)* CALDERINI et alii*, 1998; VI)* CARRARA et alii*, 1993.*





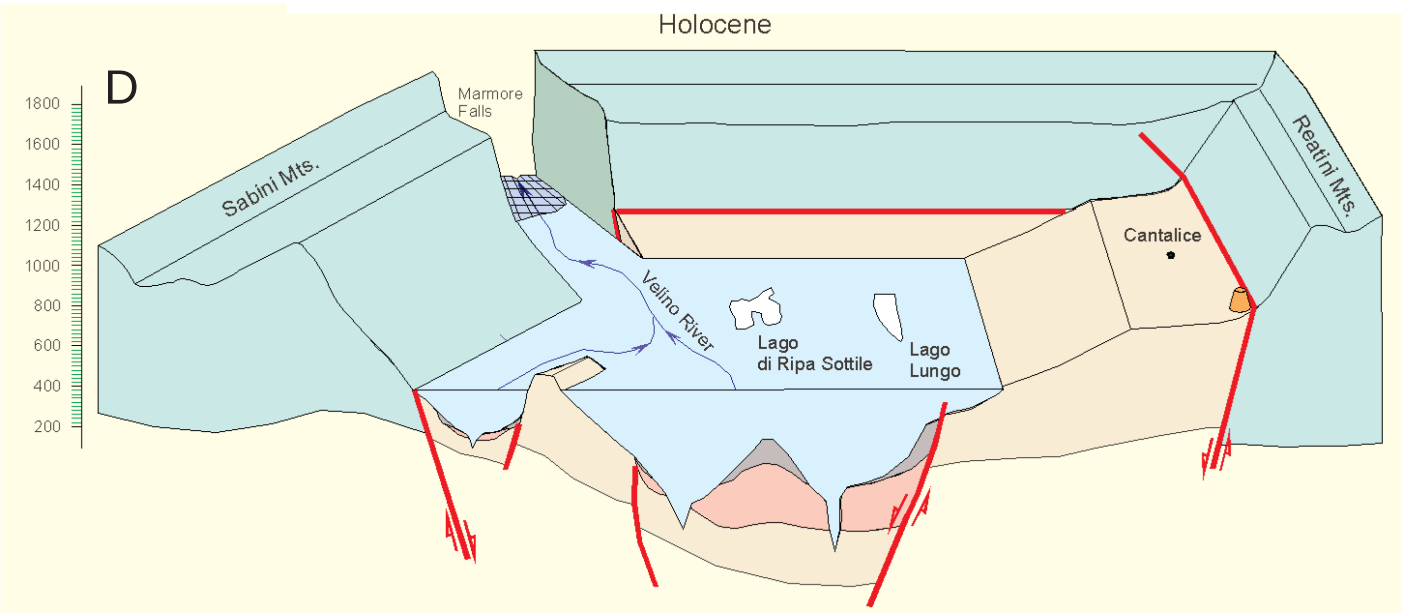
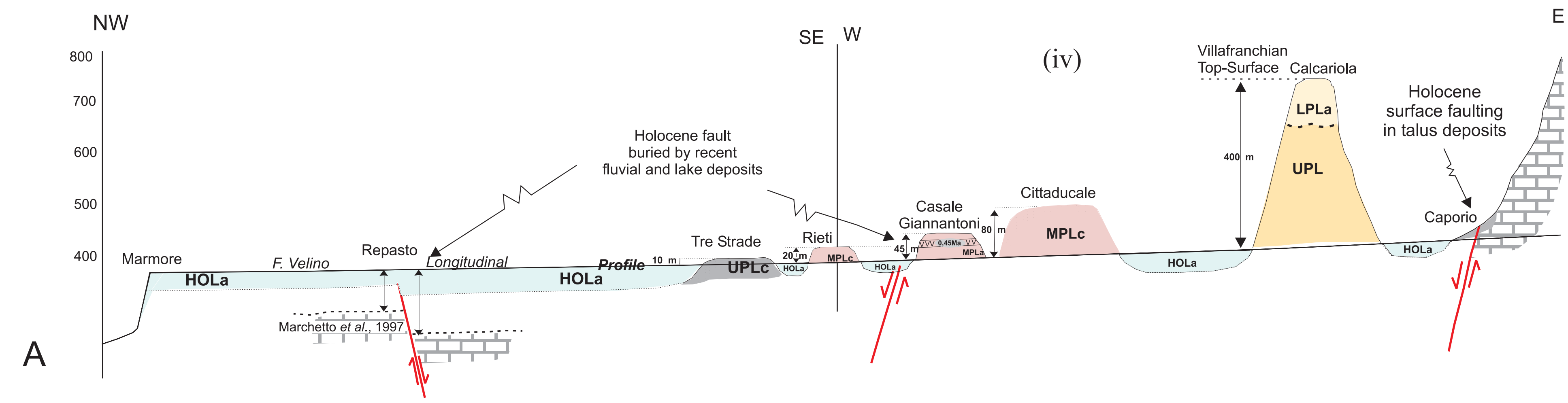


Fig. 10 - *Ancient, recent and future 3D scenarios in the Rieti basin.*
The Late Pliocene drainage network followed the orientation of the Apennine orogenic belt (A). During the Quaternary it changed its feature many times (B and C) as illustrated previously.
At present (D) it is much more complicated and irregular, reflecting and recording a long geological history. The present climatic conditions are promoting the growth of the Marmore travertine sill and consequently huge aggradation processes upstream, in the order of 3-5 mm/yr. According to these data, the last scenario (E) illustrates the expected landscape evolution, induced by the next low-stand of the Marmore travertine sill, under cold and dry climatic conditions characterised by new valleys and canyons able to entrench and terrace the alluvial deposits on the present floodplains.



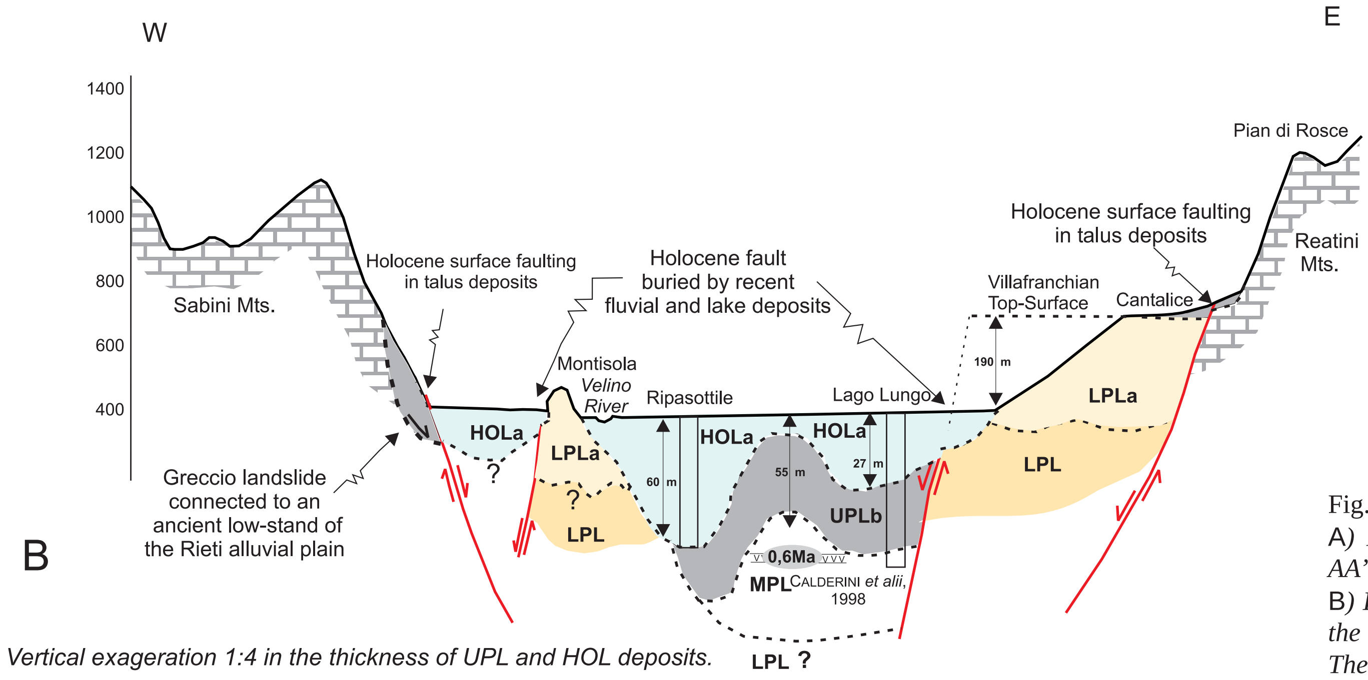


Fig. 9 -
A) Longitudinal profile along the Velino Valley (trace AA' in the map).
B) E-W cross-profile along the Rieti basin (trace BB' in the map).
The deposits are colored as in the geological map.

ANCIENT, RECENT AND FUTURE SCENARIOS

A first result of the combined interpretation of geological, geomorphological and palaeoseismological data is a good level of correlation between fault-generated Holocene and Quaternary landscape features. Geological and geomorphic structures connected to the last steps of the landscape's evolution (changes in facies, unconformities, erosional landforms and fault scarps), shown by high-resolution analyses over restricted time-scales (Fig. 9), if cumulated in time explain major topographic characters (i.e., growth of new fault-controlled escarpment, changes in the basin floor geometry and drainage network modifications) due to the interaction between climate and active extensional tectonics (and strong seismicity) over an extended time-window.

It is evident that climatic variations regulated the local topography, at least in the Late Quaternary, controlling the magnitude of erosional and sedimentary processes that prevailed on the effects of coseismic deformations, although large earthquakes (M about 6.5) repeatedly occurred over this period, as revealed by palaeoseismic evidence.

Thus, present climatic conditions are promoting the growth of the Marmore travertine platform - the hydrological threshold of the Velino River catchment area - and consequently huge aggradation processes upstream of the order of 3-5 mm/yr (Fig. 9). Earthquake surface faulting along tectonic structures, characterised over the same time interval by vertical slip-rates of the order of 0.5 to 1 mm/yr, cannot compete with climatically-controlled surface processes.

This natural evolutionary trend is currently contrasted by the presence of artificial channels and dams that drain areas prone to flooding, also inducing significantly increased subsidence effects in several areas of the Rieti plain.

The reconstruction obtained of the main steps of the Quaternary landscape's evolution enables the elaboration of future scenarios resulting from significant changes in climatic conditions and the differentiation of different sectors of the area according to their level of long-term stability.

The last sketch in Fig. 10 illustrates the evolution in the landscape expected to be induced by the next low-stand of the Marmore travertine threshold under the cold and dry climatic conditions of the Next Glacial Maximum.

New valleys, canyons, and fluvial downcutting, capable of entrenching and terracing the alluvial deposits of the present floodplains, and, as a consequence, of increasing the occurrence of gravitational phenomena along the mountain slopes, will characterise this future geomorphic setting.

ACKNOWLEDGMENTS

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