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UPLIFT AND LOCAL TECTONIC SUBSIDENCE IN THE EVOLUTION OF INTRAMONTANE BASINS: THE EXAMPLE OF THE SULMONA BASIN (CENTRAL APENNINES, ITALY).

INDEX

ABSTRACT

The geological evolution of the Apennines thrust belt is related to the deformation of different Mesozoic - Cenozoic paleogeographical domains; the deformation developed during Neogene as a chain-foredeep-foreland system in the margin of the Adria plate. Since Middle(?)-Upper Pliocene the thrust belt went through an extensional tectonics. It made the regional and local tectonic setting more complicated, with strong vertical displacement along NW-SE, E-W and SW-NE normal fault systems, or complex kinematics fault systems.

Major and minor intramontane basins have been developed along the fault systems. These basins give a strong imprint to the physiography of the Central Apennines and are a record of the Quaternary geological and geomorphological evolution; the major are: Norcia, Rieti, Fucino, L'Aquila, Sulmona, Venafro, Isernia, Sora.

This paper reviews the data gathered in the Sulmona basin, focusing on the general evolution, the geometry of the basin and the geodynamic processes that have caused them: regional uplift, local subsidence and sedimentation.

Correlations between the Sulmona basin and the Adriatic area are important for analyzing the relationship between Central Apennines and Adriatic area Quaternary geomorphological evolution.

RIASSUNTO

La catena appenninica è il complesso risultato della sovrapposizione di differenti domini paleogeografici mesocenozoici. Inizialmente durante il Neogene si è venuto formando un thrust belt, sviluppatosi secondo un sistema dinamico catena-avanfossa-avanpaese migrante verso est. Successivamente partire dal Pliocene medio(?)-superiore, la catena ha subito una tettonica essenzialmente di tipo estensionale che ha complicato ulteriormente l'assetto geologico strutturale; in un generale contesto di sollevamento si sono sviluppati forti rigetti e dislocamenti verticali lungo faglie normali, o a cinematica complessa, a direzione NW-SE e SW-NE.

Lungo tali elementi tettonici si sono formati a partire dal Pliocene medio (?)-superiore, e poi sviluppati durante tutto il Quaternario, una serie di bacini intramontani (Norcia, Rieti, Fucino, Aquila, Sulmona, Venafro, Isernia, Sora) che caratterizzano l'assetto fisiografico dell'Appennino centrale.

Nel presente lavoro vengono brevemente sintetizzate le caratteristiche stratigrafiche e tettoniche della Conca di Sulmona, messe in luce nel corso di approfonditi studi multidisciplinari, focalizzando gli aspetti riguardanti l'evoluzione generale del bacino e la sua geometria. In particolare sono state definite cinque successioni sedimentarie, sviluppatesi dal Pleistocene inferiore - medio all'Olocene, in ambienti di conoide e conoide alluvionale (Pleistocene inferiore - medio), in ambiente lacustre (Pleistocene medio), in ambiente fluviale e di conoide alluvionale (Pleistocene medio finale, Pleistocene superiore e Olocene). Dal punto di vista tettonico la conca è caratterizzata da un importante sistema di faglie normali, posto nel suo bordo nord-orientale, con direzione NW-SE: il sistema di faglie del Monte Morrone; questo è costituito da una serie di faglie che interessano il substrato formando importanti scarpate di faglie e che dislocano i depositi continentali quaternari, con rigetti anche elevati, in particolare nei depositi più antichi. I dati di superficie sono stati quindi confrontati con dati geofisici per ricostruire la geometria profonda del bacino.

Le caratteristiche geologiche e geomorfologiche del bacino sono quindi state messe in relazione ai processi che le hanno influenzate: sollevamento regionale, subsidenza tettonica locale e sedimentazione.

Si è infine cercato di individuare le fasi principali dell'evoluzione geomorfologica e geologica della Conca di Sulmona dalla sua formazione ad oggi.

Vengono inoltre messe in luce, in via preliminare, alcune possibili correlazioni con l'evoluzione geologica e geomorfologica dell'area adriatica. Si ritiene, infatti, che la conca di Sulmona costituisca un settore importante nella correlazione tra l'Appennino centrale e l'area adriatica.

KEY WORDS: regional uplift, tectonic subsidence, sedimentation/erosion, geomorphology, Central Apennines.

PAROLE CHIAVE: sollevamento regionale, subsidenza tettonica, sedimentazione/erosione, geomorfologia, Appennino centrale.

1. INTRODUCTION

In this paper we review the geological setting of the Sulmona basin considering the facies distribution of the sintectonic deposits in space and time, the tectonic evolution and the geometry of the basin; then we focus on geological and geometrical indications about the relationships between regional uplift and local tectonic subsidence. In order to do that we review the studies regarding the Sulmona basin carried on in the last decades with different approaches (Beneo, 1942; Catalano, 1964; Leuci & Scorziello, 1972, 1974; Radmilli, 1984; Sylos Labini *et al.*, 1993; Vittori *et al.*, 1995; Di Filippo & Miccadei, 1997; Carrara, 1999; Ciccacci *et al.*, 1999; Miccadei *et al.*,

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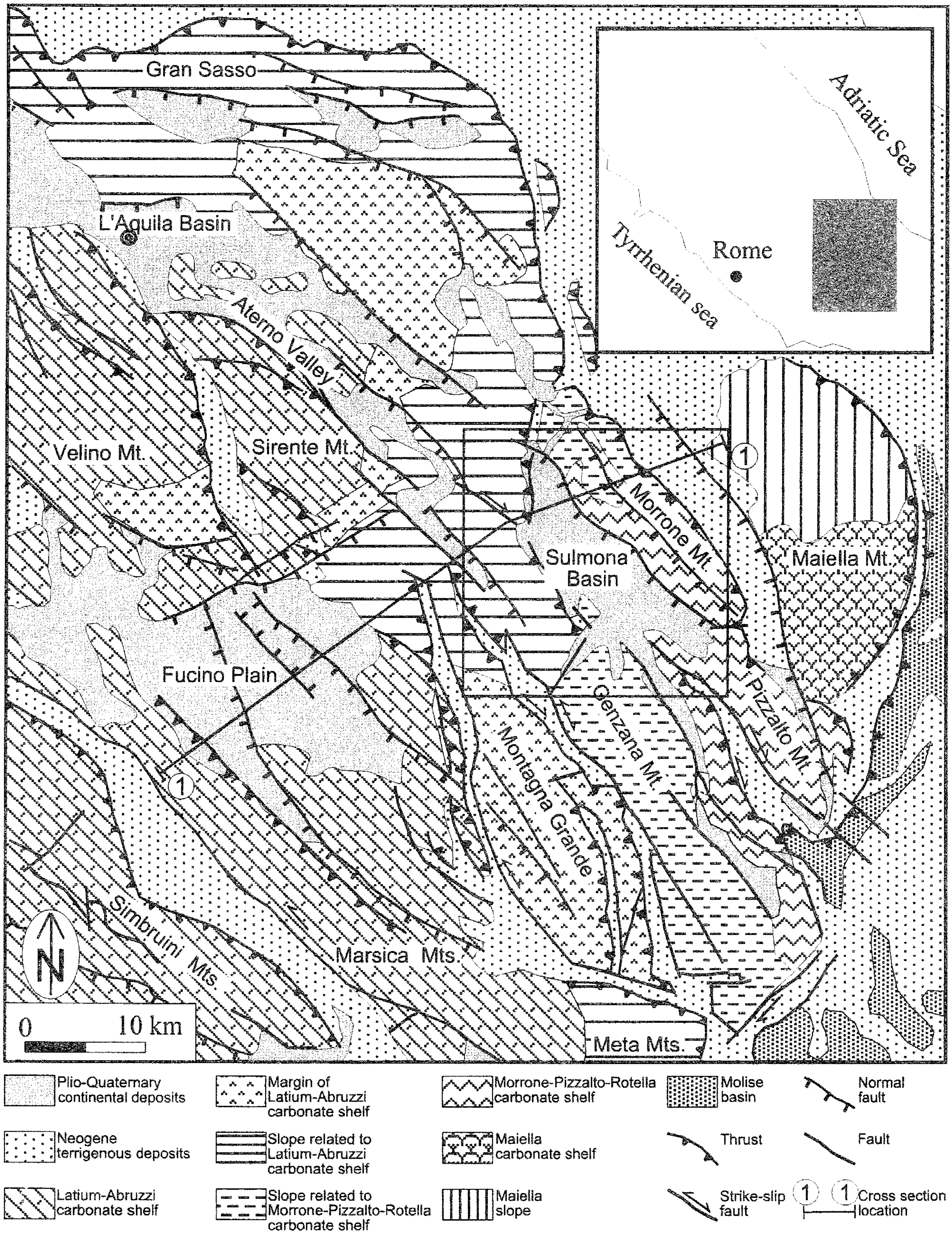

Fig. 1a - Schematic map of the eastern part of Central Apennines thrust belt, showing the relationship between the different paleogeographic domains. The Box indicates the study area.

1999a); we particularly show geometrical elaboration obtained by the analysis of geophysical data compared with field data.

Considering the debate between the authors about the terminology regarding uplift and subsidence processes (ABBOT *et al.*, 1997), here we use the term uplift as the positive displacement (relative to the mean sea level or to the geoid) of a broad area whatever is the geodynamic origin (isostasy or tectonics). Tectonic subsidence is a process related to normal faulting, i.e. the downward displacement relative to surrounding blocks involving portion of the hanging-wall block of major normal fault systems. It is also useful to distinguish that this vertical movements are "crustal" movements due to tectonics and/or isostasy, while "surface" movements (surface subsidence and surface uplift) are those resulting from the interplay of crustal and erosional/depositional phenomena.

In the Apennines during Pliocene and Quaternary different kind of processes are active, regarding the vertical movements. Uplift as a regional crustal process involves the whole chain and the origin of it (tectonics and/or isostasy) is still debated by the authors (AMBROSETTI *et al.*, 1982; DRAMIS, 1993; CINQUE, 1993; BARTOLINI, 1999). Local tectonic subsidence is responsible for the formation of intermontane basins. Minor local tectonic uplift could develop on the foot-wall of major normal faults.

In this context the Quaternary evolution of a basin is strongly related to the climate changes, that influence type and rate of sedimentation, and to the surface movements; the surface subsidence (also called total subsidence) of a basin is equal to the local "crustal" tectonic subsidence minus the regional "crustal" uplift, minus the sedimentary aggradation or plus the erosional degradation; furthermore it is related to the regressive erosion that can modify the evolution and interrupt the stratigraphic record. So the detailed investigation of these depressions provides strong constraints for the comprehension of the geodynamical context and for the interpretation of sin-morphogenetic activity during the Pleistocene-Holocene (BARTOLINI, 1980; BOSI & MESSINA, 1992; BRANCACCIO & CINQUE, 1992; CAVINATO *et al.*, 1994; CARRARO, 1996; CALAMITA *et al.*, 1999; DOGLIONI *et al.* 1998).

The elaboration proposed for the Sulmona basin, regarding the relationship between gemorphological evolution and absolute values of vertical movements, imply a range of approximation for the absence of Plio-Quaternary marine deposits, fundamental for well constrain vertical movements in space and time. In order to do that we are extending geomorphological analysis in the area between the chain and the Adriatic coastal area where Plio-Quaternary marine and transitional deposits are present.

2. GEOLOGICAL SETTING

The Central Apennines thrust belt, as a result of the Europe-Africa incomplete collision, was built up during the Neogene time by juxtaposition of different Meso-Cenozoic palaeogeographic domains: carbonate platforms, their related slope and pelagic basins. They were stacked one over each other and then the geometry of the thrust belt has been strongly modified by the development of strike-slip and extensional tectonics during Pliocene and Pleistocene (Fig. 1a, b).

The present chain topography is made up of a series of ridges and trough oriented from NW-SE to N-S, interrupted by wide planes and basins. This topographic setting is due to a complex morphogenetic evolution started in Pliocene time, after the emergence of the thrust-belt still in formation. The morphogenetic evolution is influenced by the distribution of the lithologic domains, the structural setting of the thrust-belt, its tectonic evolution, the regional uplift and climate changes (DEMANGEOT, 1965; CINQUE, 1993; DRAMIS, 1993; HOVIUS & LEEDER, 1998; BARTOLINI, 1999; BURBANK & PINTER, 1999).

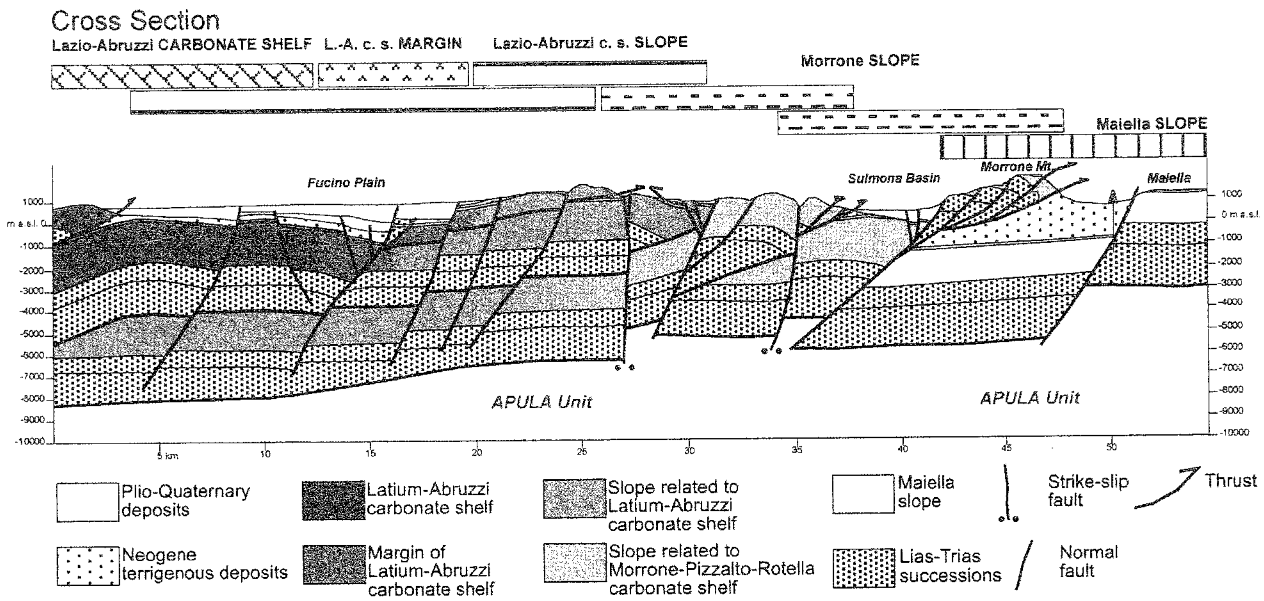

Fig. 1b - Cross section of the eastern part of Central Apennines thrust belt, showing the relationship between the different paleogeographic domains. Location in Fig. 1a.

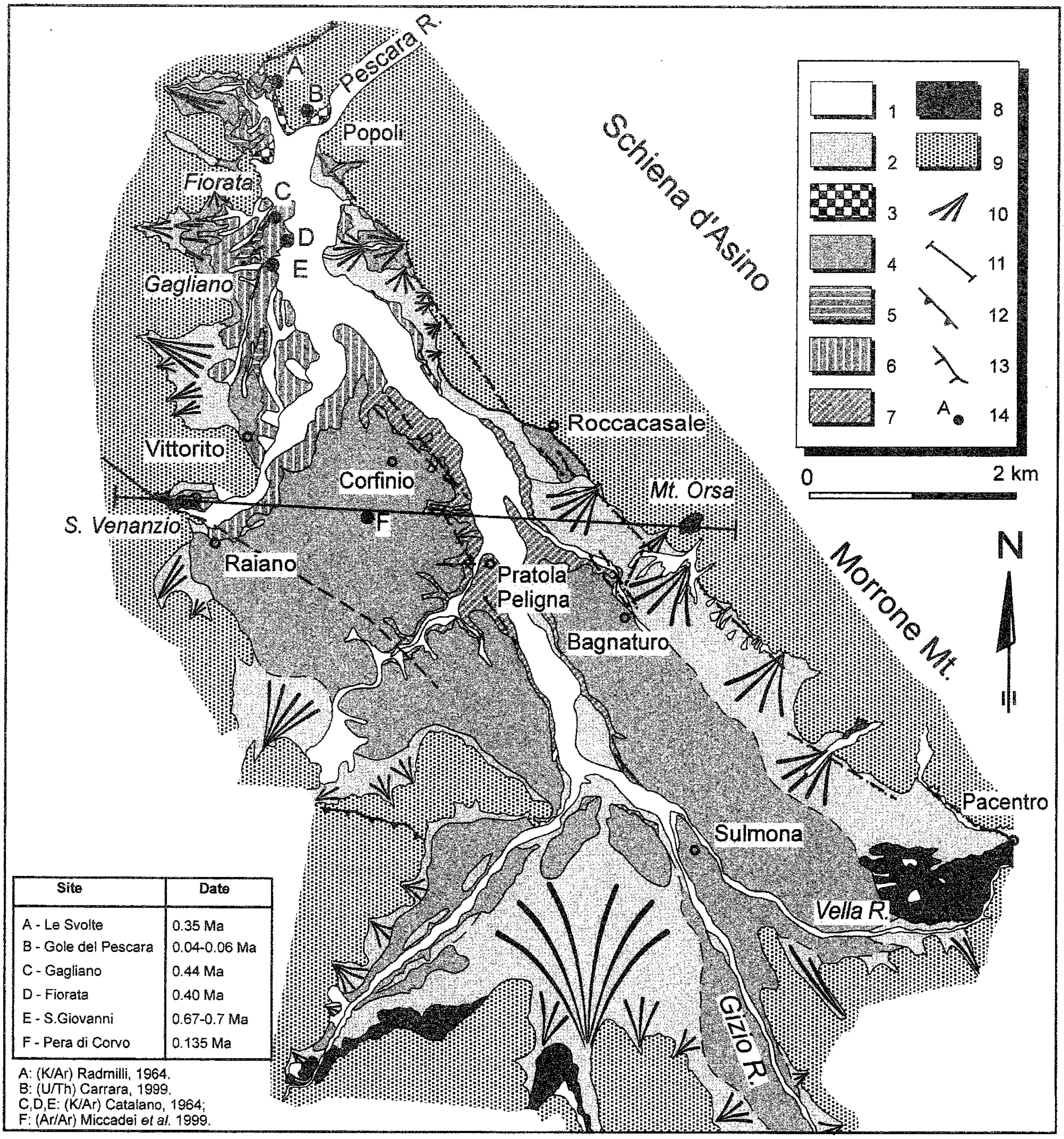

Fig. 2 - Geological scheme of the continental deposits of the Sulmona basin (from MICCADEI *et al.*, 1999a, modified).
Legend: 1) Holocene deposits; 2) Upper Pleistocene deposits; 3) Upper Pleistocene travertine deposits; 4) late Middle Pleistocene fluvial and alluvial fan deposits (Sulmona Unit); 5) Middle Pleistocene lacustrine deposits (Fiorata Unit); 6) Middle Pleistocene lacustrine deposits (Gagliano Unit); 7) Middle Pleistocene marshy deposits (Pratola Peligna Unit); 8) Lower (?) to Middle Pleistocene alluvial fan sediments (S.Venanzio e M.Orsa Unit) and Pacentro paleo-landslide; 9) carbonate bedrock; 10) alluvial fans; 11) cross section location (see Fig. 7); 12) thrust; 13) main normal faults; 14) radiometric dates location.

In Central Apennines the ridges are formed by carbonate thrust sheets and syntectonic terrigenous deposits outcrop in the trough; planes and basins, related to Plio-Quaternary extension tectonics, are filled with clastic continental deposits (ACCORDI & CARBONE, 1988).

In this context the basins are "traps" for the Quaternary continental sediments and possibly represent a record of geomorphologic and tectonic evolution (LEEDER & GAWTHORPHE, 1987; LEEDER *et al.*, 1998).

The major intramontane basins in Central Apennines are Norcia, Rieti, Fucino, L'Aquila, Sulmona, Venafro, Isernia and Sora (BOSI & BERTINI, 1970; BAGNAIA *et al.*, 1989; BERTINI *et al.*, 1989; BOSI & MESSINA, 1992; BLUMETTI & DRAMIS, 1993; CALAMITA & PIZZI, 1993; CAVINATO, 1993; BARBERI & CAVINATO, 1993; CAVINATO *et al.*, 1994; BOSI *et al.*, 1995; CARRARA *et al.*, 1995; COLTORTI & FARABOLLINI, 1995; GIRAUDI, 1995; BLUMETTI *et al.*, 1996; MICCADEI *et al.*, 1999a; BRANCACCIO *et al.*, 2001).

The Sulmona area is important for the comprehension of structural setting and Quaternary evolution of the eastern part of Central Apennines. Here many different structural units converge (Sirente Mt. Unit, Montagna Grande Unit, Gran Sasso Unit, Genzana Mt. Unit, Morrone Mt. Unit) and their relationships are very complex for the development of important N-S, NNW-SSE and NW-SW tectonic lines (Fig. 1) and are debated by the authors. Here the extensional tectonics, along major NW-SE features and secondary E-W and NE-SW faults, has been definitely important in the definition of geological setting and morphologic structures (BIGI *et al.*, 1992; PATACCA *et al.*, 1992; MICCADEI, 1993; D'AGOSTINO *et al.*, 1994, 1998; CIPOLLARI *et al.*, 1997; BIGI *et al.*, 1997; VEZZANI & GHISETTI, 1998, MICCADEI *et al.*, 1999b; MICCADEI & PAROTTO, 1999).

Furthermore the Sulmona basin shows a peculiar physiographic setting: the lowest mean topographic height (300 m) in Central Apennines intramontane basins, a strong relief (1750 m) up to the eastern ridge (Mt.Morrone) and an anomalous triangular shape. Here a complex fluvial drainage system converges. The Aterno river from NW, the Sagittario river from SW and S, the Gizio river from S, the Vella river and Velletta river from SE enter the basin and flow together in the Pescara river. It runs through the Popoli gorge and then straight towards NE down to the Adriatic sea, perpendicular to the coast line, as well as other Adriatic rivers.

In the last decade the Sulmona basin has been object of accurate studies with different approaches driven also by the good exposition of the Quaternary deposits: field surveys on the continental deposits, field surveys on the carbonate bedrock sourrounding the basin, biostratigraphic and paleoecological analyses, facies analyses, dating of vulcanoclastic levels, log analyses and geophysical prospecting (VITTORI *et al.*, 1995; DI FILIPPO & MICCADEI, 1997; MICCADEI *et al.*, 1999a; CICCACCI *et al.*, 1999).

Like other intramontane basins, the Sulmona basin is partially filled with continental Quaternary deposits. The stratigraphic data have allowed us to distinguish five continental depositional sequences that differ in age and are separated by important erosional surfaces (Fig. 2 and Fig. 3a; see MICCADEI *et al.*, 1999a for details). These surfaces are directly outcropping (paleosoil levels) or pointed out by deposits geometry or geomorphologic evidence (i.e. terraced fluvial deposits) (Fig. 3b).

From a structural point of view the superficial tectonic setting of Sulmona basin is characterized by a NW-SE fault system, located alongside the eastern margin of the basin, the Monte Morrone fault zone. This fault system is similar to those of other intramontane basins and has a complex kinematic history (SALVINI, 1992; VITTORI *et al.*, 1995).

The sedimentary evolution of the Sulmona basin is characterized by a series of depositional and erosional pulses (MICCADEI *et al.*, 1999a).

The most ancient continental deposits have Lower to Middle Pleistocene age. They are remnants of proximal gravel fans in isolated and scattered outcrops distributed close to the basin margins both West (Fig. 4; San Venanzio Unit, 8 in Fig. 2 and Fig. 3) and East (Monte Orsa Unit, 8

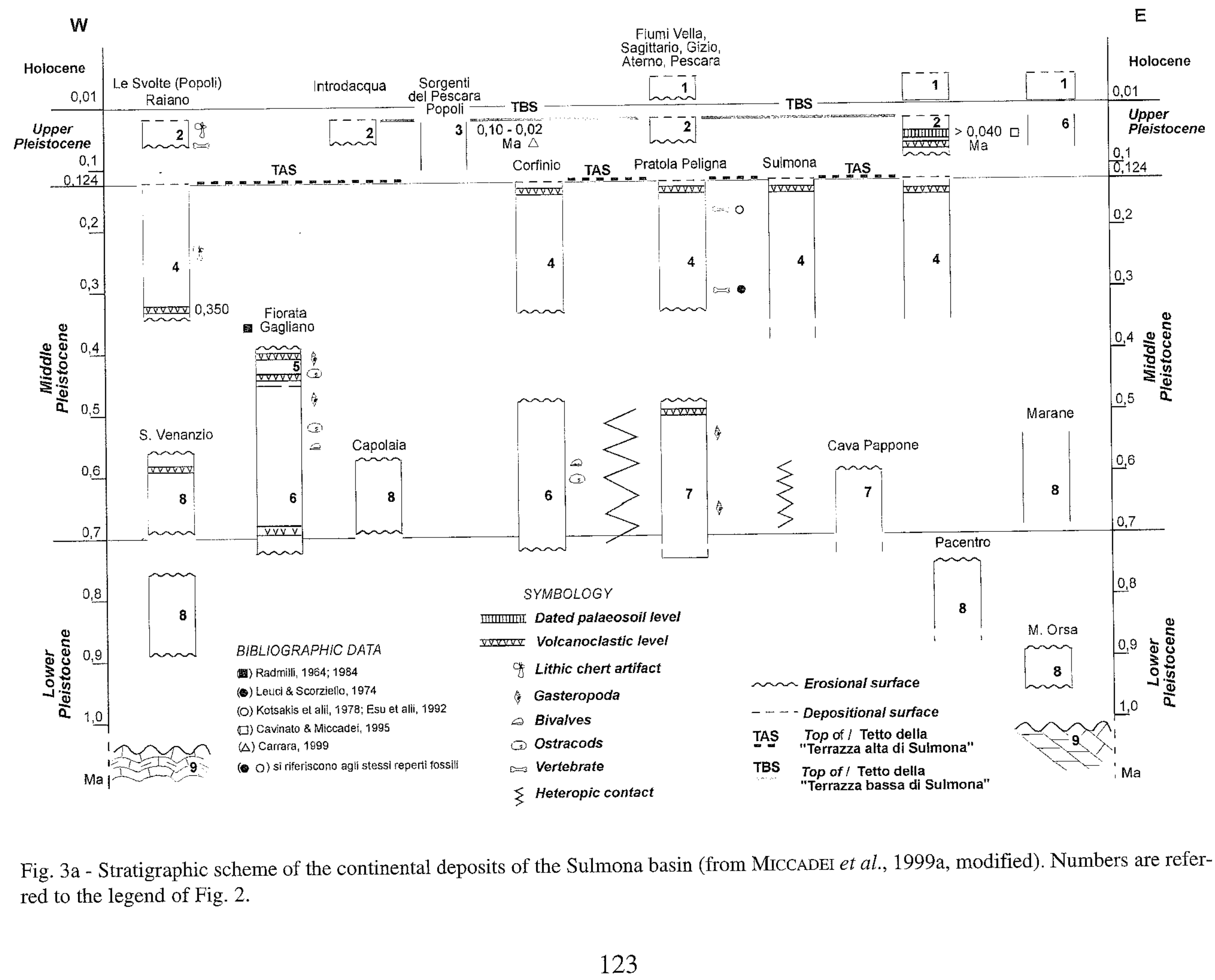

Fig. 3a - Stratigraphic scheme of the continental deposits of the Sulmona basin (from MICCADEI *et al.*, 1999a, modified). Numbers are referred to the legend of Fig. 2.

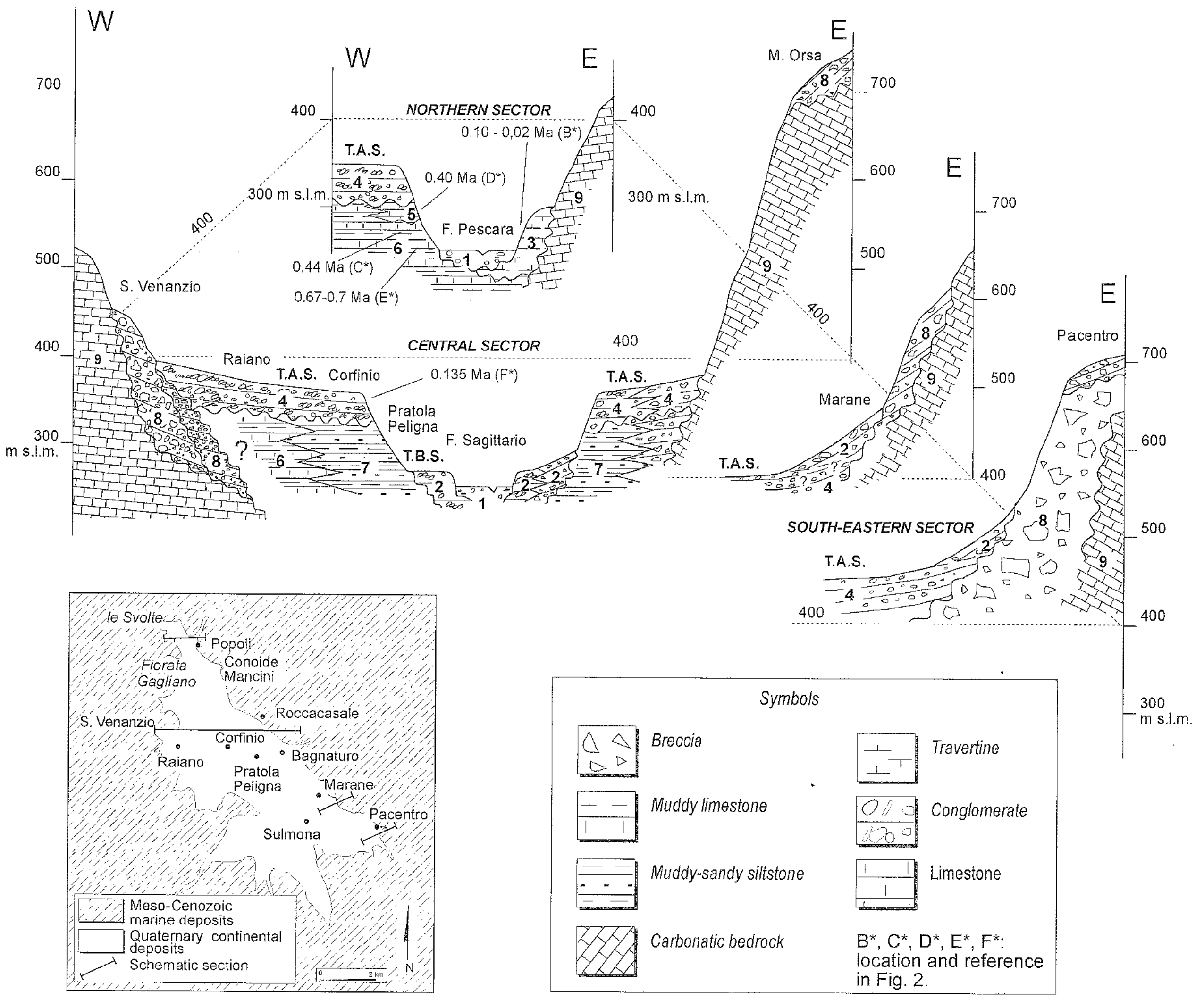

Fig. 3b - Morpho-lithostratigraphic scheme of the continental deposits of the Sulmona basin (from MICCADEI *et al.*, 1999a, modified). Numbers are referred to the legend of Fig. 2. The height above sea level is pointed out on the vertical scale. The dotted line marks the height of 400 m a.s.l.. T.A.S.= Sulmona Surface ("Terrazza Alta di Sulmona", *sensu* BENEO, 1942); T.B.S.= 2° order terrace ("Terrazza Bassa di Sulmona", *sensu* BENEO, 1942).

in Fig. 2 and Fig. 3). The lack of any element witch can date directly these sequences, and the lack of continuous geomorphologic evidence, do not allow a correlation of these units, from the field data. However these deposits should predate 0.7 Myr b.p. (Fig. 3). In the western border of the basin (San Venanzio) an unconformity separates clearly the lower part of the San Venanzio Unit from the upper part (Fig. 4); in the upper part of the unit lacustrine limestone are interbedded, but should be older than the lacustrine units (see below), because the San Venanzio Unit is 5°-10° tilted unlike the lacustrine units that are horizontal (Fig. 3). So at least the lower part of the San Venanzio Unit, but probably the all unit, predate 0.7 Myr b.p. (MICCADEI *et al.*, 1999a).

Sedimentation in lacustrine and swampy environments occurred in the basin during the Middle Pleistocene. A sequence of clay (Pratola Peligna Unit and Gagliano Unit, 7 and 6 in Fig. 2 and Fig. 3) and limestone (Fiorata Unit, 5 in Fig. 2 and Fig. 3) was deposited; volcanoclastic levels are frequent and give Middle Pleistocene radiometric dates (from 0.7 Myr b.p. to 0.4 Myr b.p.; Fig. 2 and Fig. 3). The formation of a threshold in the basin emissary and the consequent lacustrine environment were related to the activity of the Monte Morrone fault system. The basin emissary was already an old Pescara River that run close to the present path.

Then strong regressive erosion cut the Popoli gorge down and eroded the lacustrine deposits in the Sulmona basin defining an irregular erosional surface.

In the late Middle Pleistocene sedimentation in fluvial environment occurred; it caused conglomerate deposition in the basin and alluvial fan deposition along its margins; the older erosional surface was completely filled. This depositional event is possibly related to the "Riss"[1] glacial stage (Oxygen Isotopic Stage 6) as pointed out by COLTORTI & DRAMIS (1988) for the Umbria – Marche Apennine. The late Middle Pleistocene conglomerate deposits form the "Sulmona Unit" (4 in Fig. 2 and Fig. 3). Its upper flat depositional surface is called "Sulmona surface"; it is evident in the central and southern part of the basin, while in the northern part it is in remnants (T.A.S. in Fig 3). A vulcanoclastic level sampled close to the unit top gives a date of 0.135 Myr b.p. (Fig 2 and Fig. 3).

During Upper Pleistocene the travertine sedimentation

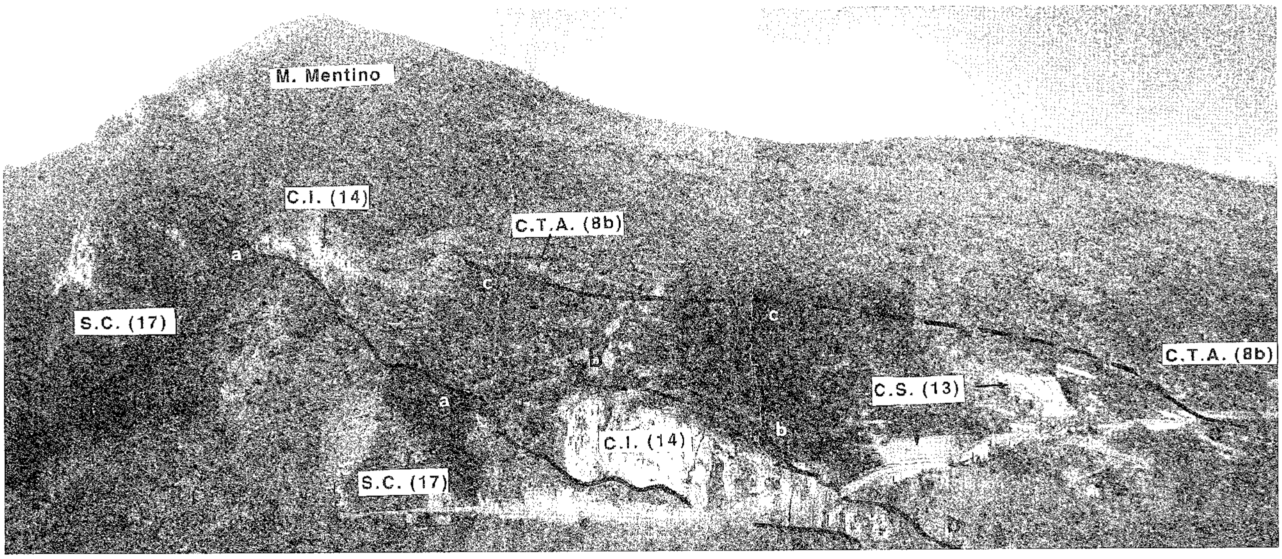

Fig. 4 - View from south of the San Venanzio alluvial fan deposits. SC) Carbonatic bedrock; C.I.) lower San Venanzio alluvial fan deposits; C.S) upper San Venanzio alluvial fan deposits; C.T.A.) alluvial fan deposits of the "Terrazza alta di Sulmona"; a) contact surface (angular unconformity) on the carbonatic bedrock; b) contact surface (angular unconformity) between lower alluvial fan deposits (C.I.) and upper alluvial fan (C.S.); c) lower limit of the fluvial deposits of the "Terrazza alta di Sulmona" (F.T.A.). (From Miccadei *et al.*, 1999a)

in the Pescara valley NE of Popoli (3 in Fig. 2 and Fig. 3) influenced the basin evolution in the northern sector; it was possibly related to the climate changes during the last interglacial (OIS 5) and the last glacial stage (OIS 4 and 2) (Carrara, 1999; Lombardo *et al.*, 1999). A new regressive erosion pulse caused downcutting into the older deposits and formation of the first order of fluvial terraces; this pulse was due to climatic change and sea level change, related to the "Würm"[1] glacial stage (OIS 4) and to regional uplift too.

Then the deposition of a new generation of alluvial fans occurred along the basin margins; the Upper Pleistocene alluvial fan (2 in Fig. 2 and Fig. 3) are better developed along the Monte Morrone slope and in the southern part of the basin. At the same time fluvial sediments were deposited embanked along the incisions in the basin; a new erosional pulse formed a second order of fluvial terraces (T.B.S. in Fig. 3).

In the Holocene, deposition of fluvial sediments occurred.

The tectonic setting of the Sulmona basin is defined by a major NW-SE fault system along the north-eastern margin of the basin, the Monte Morrone fault zone (Fig. 5), well known since late 30's (Beneo, 1939; Demangeot, 1965), and by a series of minor NW-SE, NE-SW and E-W faults, more frequent in the eastern part of the basin. The deposits show horizontal attitude (or normal sedimentary clinostratification) everywhere the basin but close to secondary faults along the Sagittario river and in the S. Venanzio Unit alluvial fan (Lower-Middle Pleistocene); in the latter lacustrine limestone interbedded in conglomerates show a 5-10° NE dip towards the centre of the basin (Fig. 4). The field structural data have allowed us to recognize normal and oblique movements along the quaternary fault planes of the Monte Morrone fault zone, with more ancient strike-slip movements (Fig. 6) (Vittori *et al.*, 1995).

[1] Traditional term used by the authors but obsolescent following recent advance in glaciology.

Tectonic activity affected the area from Lower Pleistocene to present times; Upper Pliocene tectonics is possible, as initial stage of the basin, but unlikely for the lack of filling units of this age. In the eastern part of the basin normal faults cut all the sedimentary successions, but the Holocene sediments that seal the faults. In the central and western part the faults are sealed by the Sulmona unit (late Middle Pleistocene). It demonstrates fault activity in the Sulmona Basin up to the Upper Pleistocene, but there is no clear field evidence for activity along these faults during the Holocene too. However a strong historical seismicity (Postpischl, 1985; Camassi & Stucchi, 1997) indicates a present active tectonics.

From structural and stratigraphic data is possible to interpret the Sulmona basin as a half-graben tectonic depression (Leeder & Gawthorphe, 1987), with a NW-SE

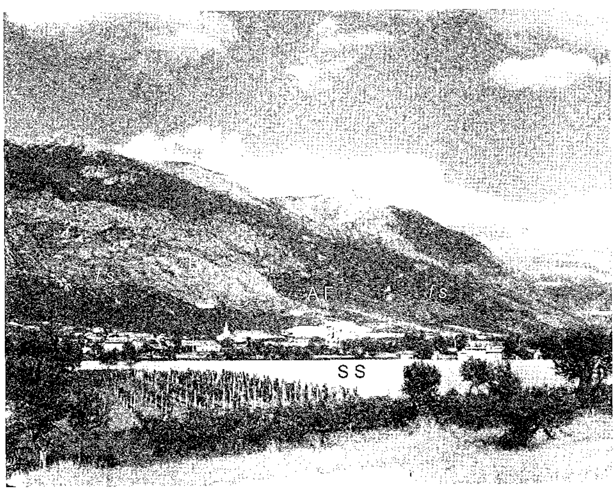

Fig. 5 - Panoramic view of the Monte Morrone slope. The flat area in the foreground corresponds to the "Sulmona Surface" (S S); in the background the main fault scarp of the Monte Morrone fault zone (*f s*) that is the contact between carbonate bedrock (B) and late Middle and Upper Pleistocene alluvial fan (A F).

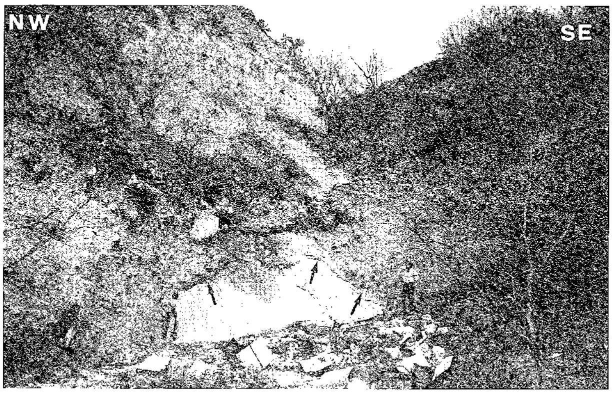

Fig. 6 - Close up of the Morrone Mt. fault zone near Roccacasale: the arrows mark the contact between the alluvial fan deposits of the "Sulmona Unit" and the carbonatic bedrock along a N145-55SW fault plane.

master fault forming its eastern boundary along the Mt. Morrone slope, the Monte Morrone fault zone (MICCADEI *et al.*, 1999a).

The *cut and fill* evolution, pointed out by sedimentary and geomorphologic features (Fig. 3), is related to climate changes, to tectonic activity and to regional uplift. In the next paragraphs we try to evaluate the influence of this factors in the geological evolution of the basin and the relationship between each of them.

This sequence of events is also recorded in other areas of the Apennine. It is very similar in minor basins close to the Sulmona basin (Aterno valley, BOSI & BERTINI, 1970; BERTINI & BOSI, 1976; BAGNAIA *et al.*, 1989; BERTINI *et al.*, 1989; Tirino valley, GIULIANI & SPOSATO, 1995; Subequano basin, MICCADEI *et al.*, 1997) and also in other basins in Northern and Southern Apennines (COLTORTI & DRAMIS, 1988; BRANCACCIO & CINQUE, 1992) unless for the starting of the evolution and sometime for the kind of deposits (Gubbio, MENICHETTI, 1993; Norcia, BLUMETTI & DRAMIS 1993; L'Aquila, BLUMETTI *et al.* 1996; Rieti, CAVINATO, 1993; BARBERI & CAVINATO, 1993; Fucino, ZARLENGA, 1987, BOSI *et al.*, 1995, 1996, CAVINATO *et al.*, in press; Sora, CARRARA *et al.*, 1995; Isernia, CORRADO *et al.*, 1997; BRANCACCIO *et al.*, 2001).

3. SURFACE AND BURIED GEOMETRY

The interpretation of commercial seismic lines, reprocessed to highlight geometry and stratigraphy of clastic continental deposits, allow Sus to give strong constraints to the buried geometry of basin and sediments.

It also clarifies the geometry of the faults cutting continental deposits, observed in the field surveys, and their relationship with bedrock faults. So it has been possible to analyze the sedimentation development in the basin and the relationships with regional uplift and local tectonic subsidence; the tectonic subsidence is related to the slip rate along the Mt.Morrone fault zone, master fault of the basin.

Figure 7 shows a geological cross section in the central part of the basin: Fig 7a is based on field data (location in Fig. 2), Fig 7b shows seismic data acquired in the same area (but not precisely corresponding to the Fig. 7a location) and Fig 7c is an interpretation of the buried geometry of the basin based on the correlation of field and seismic data.

The general geometry of the basin is referable to a half graben model as inferred also from field data (MICCADEI *et al.*, 1999a) and gravimetric data (DI FILIPPO & MICCADEI, 1997). The quaternary deposits form a wedge with irregular bottom and the basin depocentre is located close to the Monte Morrone fault. The master fault of the basin is actually related to the Monte Morrone fault that indeed shows a planar trend unlike the general trend shown by normal faults particularly in seismic lines.

The basin is also asymmetric along its NW-SE axis and shows a general increase of the deposits thickness towards north. It is possibly due to the carbonate bedrock geometry and particularly to the interference between thrusts geometry and normal faults geometry (VEZZANI & GHISETTI, 1997; MICCADEI *et al.*, 1999b)

The bedrock top under the basin is irregular and is displaced by a major normal fault SW dipping in the central part of the basin possibly related to the NW-SW Aterno valley fault. It shows field evidence in the Aterno valley (S. Venanzio gorge western part of the basin) as a bedrock fault, but no clear field evidence for displacement in Quaternary deposits apart from the presence of little fault planes in the S. Venanzio Unit alluvial fans and the lacking of similar deposits on the right side of the gorge (hanging wall of the bedrock fault) (Fig. 2; Fig 4). The Sulmona Unit fluvial deposits seals this fault and show neither tectonic, nor morphologic, nor seismic evidence for faulting.

In the eastern part of the basin secondary faults cut from the bedrock top up to the Sulmona Unit deposits. These faults show clear field evidence (NW-SE and NE-SW trend, VITTORI *et al.*, 1995; MICCADEI *et al.*, 1999a) and are also evident in the seismic data that indicate a general vertical trend. The development of the secondary faults is strictly related to the Monte Morrone fault of witch they are antithetic and synthetic faults.

Furthermore seismic data allow us to define the buried geometry of the Quaternary deposits and suggest a possible correlation across the basin.

Clear seismic reflectors (Fig 7b) above the top of the bedrock suggest a possible correlation across the basin of the oldest deposits, S.Venanzio Unit and Monte Orsa Unit (8 in Fig. 2).

The height of these deposits, and related seismic reflectors, in footwall (600-800 m a.s.l.) and hanging wall (-100/-200 m a.s.l.) of the Monte Morrone fault lead us to evaluate a possible slip rate for this fault (Fig. 7c). Considering a possible age of the deposits around 0.7-0.8 Myr and a vertical displacement of 700-800 m or more, the vertical slip rate could be up to ' 1 mm/a.

This strong tectonic subsidence is responsible for the lowering of the old continental deposits down below the present sea level (Fig. 7c). In the Morrone ridge is possible but not proofed a little tectonic uplift (footwall tectonic uplift in normal fault is a debated topic between the authors); along the slope the oldest alluvial fan (Monte Orsa Unit) are between two major faults (at the base and in the middle of the slope), so they could be little or no lowered by tectonic subsidence.

The tectonic subsidence decreases towards the west-

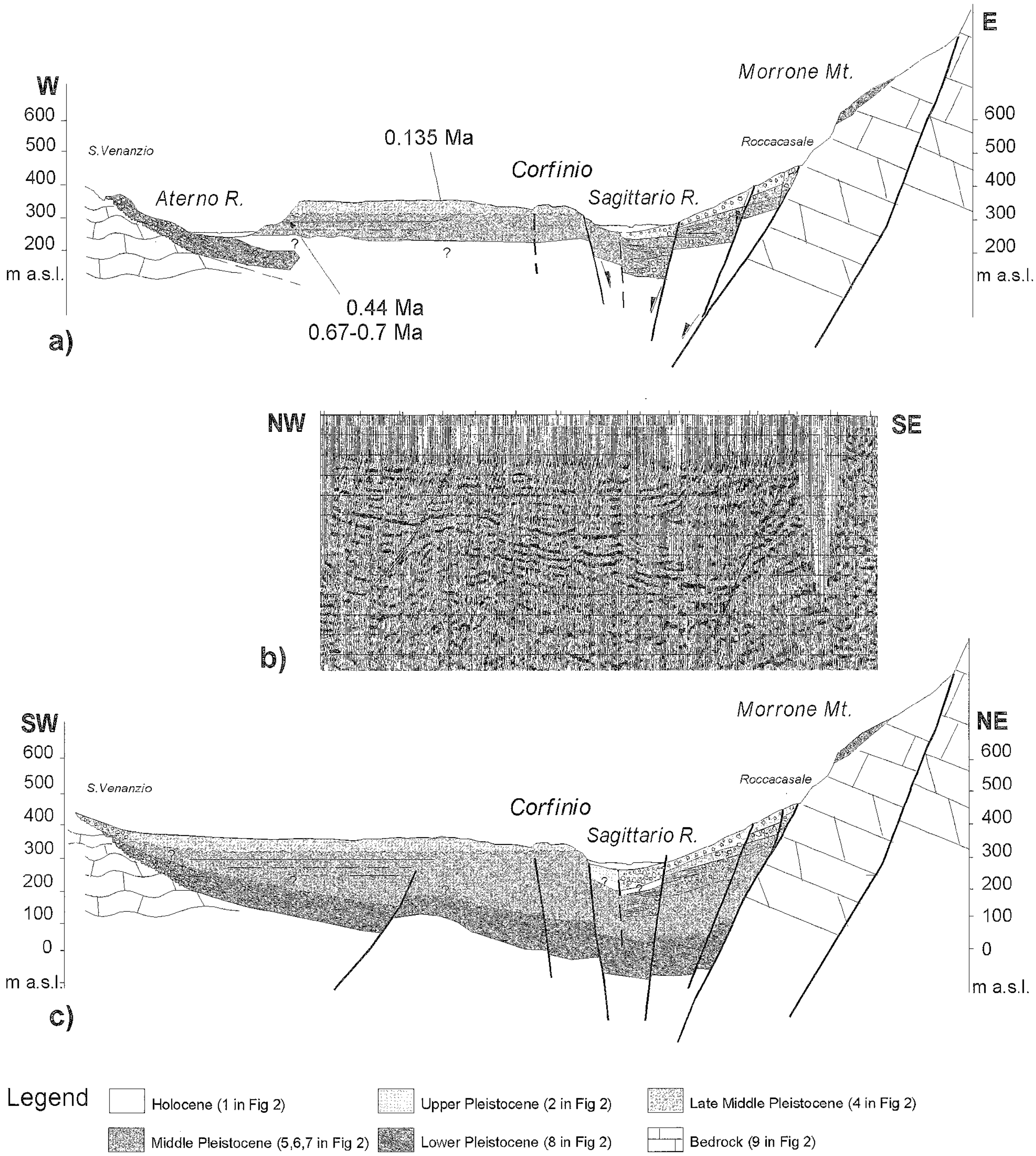

Fig. 7 - Cross section of the Sulmona basin: a) geological section from field data in the central part of the basin (from MICCADEI *et al.*, 1999a modified, location in Fig. 2); b) commercial seismic line located close to the section in a); c) interpreted geological section based on field data and seismic data, showing the buried geometry of the basin.
Numbers are referred to the legend of Fig. 2.

ern part of the basin, where the bedrock top is less and less deep. A secondary increase of tectonic subsidence in the western part of the basin is due to the Middle Pleistocene activity of the buried part of the Aterno valley fault. It has produced a variable thickness in the Middle Pleistocene lacustrine deposits, at his top in the eastern part of the basin (more than 200 m) and decreasing irregularly towards the west.

On the other side the Sulmona Unit (Fig. 7) has a regular thickness and is generally neither tilted nor influenced by syntectonic faults, except in the north-eastern area along the Sagittario river, where Monte Morrone fault and secondary faults cut the Sulmona Unit itself with tens of meter displacements (MICCADEI *et al.*, 1999a). So it is little involved or it is not involved at all in tectonic subsidence. More recent deposits are embanked along the fluvial incisions of the basin.

4. UPLIFT AND TECTONIC SUBSIDENCE: GEOMORPHOLOGICAL EVOLUTION

The analysis of the Quaternary evolution of the Sulmona basin, the geometry, distribution and height of deposits and morphologic surfaces and, finally, the comparison of present elevation and original elevation (at the beginning of the basin formation) both of the topographic surface and of the bottom of the sedimentary sequence let us point out some considerations about the relationship between *regional uplift*, *local tectonic subsidence* and *sedimentary aggradation*. In A, B, C we attempt to define the present balance between *regional uplift* (RU), *local tectonic subsidence* (TS) and (SA) developed in different subdomain of the basin (Fig. 8); in this attempt we use as a reference the present sea level. In this case note that the whole sequence is a continental one, so the elevation in the basin has never been below 0 m a.s.l.

So the balance between Tectonic Subsidence and Regional Uplift, stand for the absolute value of downward "crustal" vertical movement of the bottom of the sedimentary filling, i.e. the bedrock of the basin; Tectonic subsidence - Regional Uplift - Sedimentary Aggradation is the downward "surface" vertical movement of the depositional surface.

Western part of the basin: far from the Morrone fault zone.

The bottom of the continental deposits is above the present sea level at about 50-100 m a.s.l. and the top of the continental deposits is above the present sea level at 350-400 m a.s.l.; so we can deduce that:

Tectonic subsidence - Regional Uplift < Original Elevation

Tectonic subsidence - Regional Uplift - Sedimentary Aggradation < Original Elevation

Eastern part of the basin: close to the Morrone fault zone.

The bottom of the continental deposits is below the present sea level at about 100-200 m b.s.l. and the top of the continental deposits is above the present sea level at 300-350 m a.s.l. (a total deposit thickness of about 500 m); in this domain the tectonic subsidence is equal to the vertical slip along the MFZ; so we can deduce that:

Tectonic subsidence - Regional Uplift > Original Elevation

Tectonic subsidence - Regional Uplift - Sedimentary Aggradation < Original Elevation

Monte Morrone slope.

The bottom of the continental deposits, as well as the top, is obviously above the present sea level, at 600-800 m a.s.l. (the total deposit thickness is some tens of meters); in this domain the tectonic subsidence could near zero or negative (i.e. footwall tectonic uplift of the normal faults); so we can deduce that:

Tectonic subsidence - Regional Uplift < Original Elevation

Tectonic subsidence - Regional Uplift - Sedimentary Aggradation < Original Elevation

In this case furthermore the value of "Tectonic subsidence - Regional Uplift" should be negative indicating a real uplift of the Monte Morrone ridge.

These hypotheses will be constrained, in order to obtain absolute value of the vertical movements, extending our work to the east down to the coast, along the Pescara river and in the Maiella area, and to the west up to the Fucino area and along the Aterno river. We think indeed that the Sulmona area is a key area for correlating the Quaternary evolution of Central Apennines area and Adriatic area.

At the moment we can only try some correlation with the Adriatic area, based on general and specific works in Abruzzo and Marche (DRAMIS, 1993; NESCI *et al.*, 1993; FANUCCI *et al.*, 1996; BIGI *et al.*, 1997; CALAMITA *et al.*, 1999).

The "Sulmona surface", on the top of the Sulmona Unit, is now 350 m a.s.l., 100 m above the present talweg (Fig. 3, 7). It is cut by faults (with little displacement) related to the Monte Morrone fault, but is no lowered at all by tectonic subsidence; it shows, indeed, a possible correlation with others depositional surfaces at the same height in the Tirino valley on the footwall of Monte Morrone fault (GIULIANI & SPOSATO, 1995; CARRARA, 1999) and at about 320-360 m a.s.l. out of the Popoli gorge (Castiglione a Casauria and Tocco da Casauria area; CARRARA, 1999). These unit could be possibly related to the terraced alluvial deposits along the Pescara valley out of the chain front (Castiglione a Casauria, known as 1° order terrace, DEMANGEOT, 1965) that are about 120-150 m above the present talweg, similarly to other Adriatic rivers (Marche area; FANUCCI *et al.*, 1996). So the drop between Sulmona surface and present talweg seems to be regular and continuous along the Pescara valley, no or little influenced by local tectonic subsidence, and could be related to regional uplift (Fig. 8).

The relicts of the oldest alluvial fans in the basin are now 600-800 m a.s.l. on the Monte Morrone slope (Monte Orsa Unit) and, trying to reconstruct their original geometry down to the basin, they could be projected to about 500 m a.s.l. at the slope base; it is 250 m above the present talweg (Fig. 3, 7). In the western margin of the basin proximal alluvial fan (S. Venanzio Unit) are 400 m a.s.l. but are faulted, tilted towards the basin and lowered by tectonic subsidence. The height of Monte Orsa Unit could be related to regional uplift too, assumed to be little or no influenced at all by tectonic subsidence in the Monte Morrone fault zone, whereas in the basin the regional uplift is contrasted by tectonic subsidence (Fig. 8).

Following this two points we can evaluate about 100-120 m of regional uplift from late Middle Pleistocene and at least 200-300 m from the Lower(?)-Middle Pleistocene (Fig. 8); the latter value is doubtful, considering the assumption given and it could be up to 500 as suggested by the distribution of the marine and transitional deposits of this age, closing the marine Plio-Pleistocene sequences of the Abruzzo and Marche area (MANFREDINI, 1970; BIGI *et al.*, 1997).

The Sulmona basin evolution related to the regional uplift is explained in the five step of Figure 8. The initial stage is possibly referable to an Upper Pliocene – Lower Pleistocene age. The area of the present Sulmona basin was

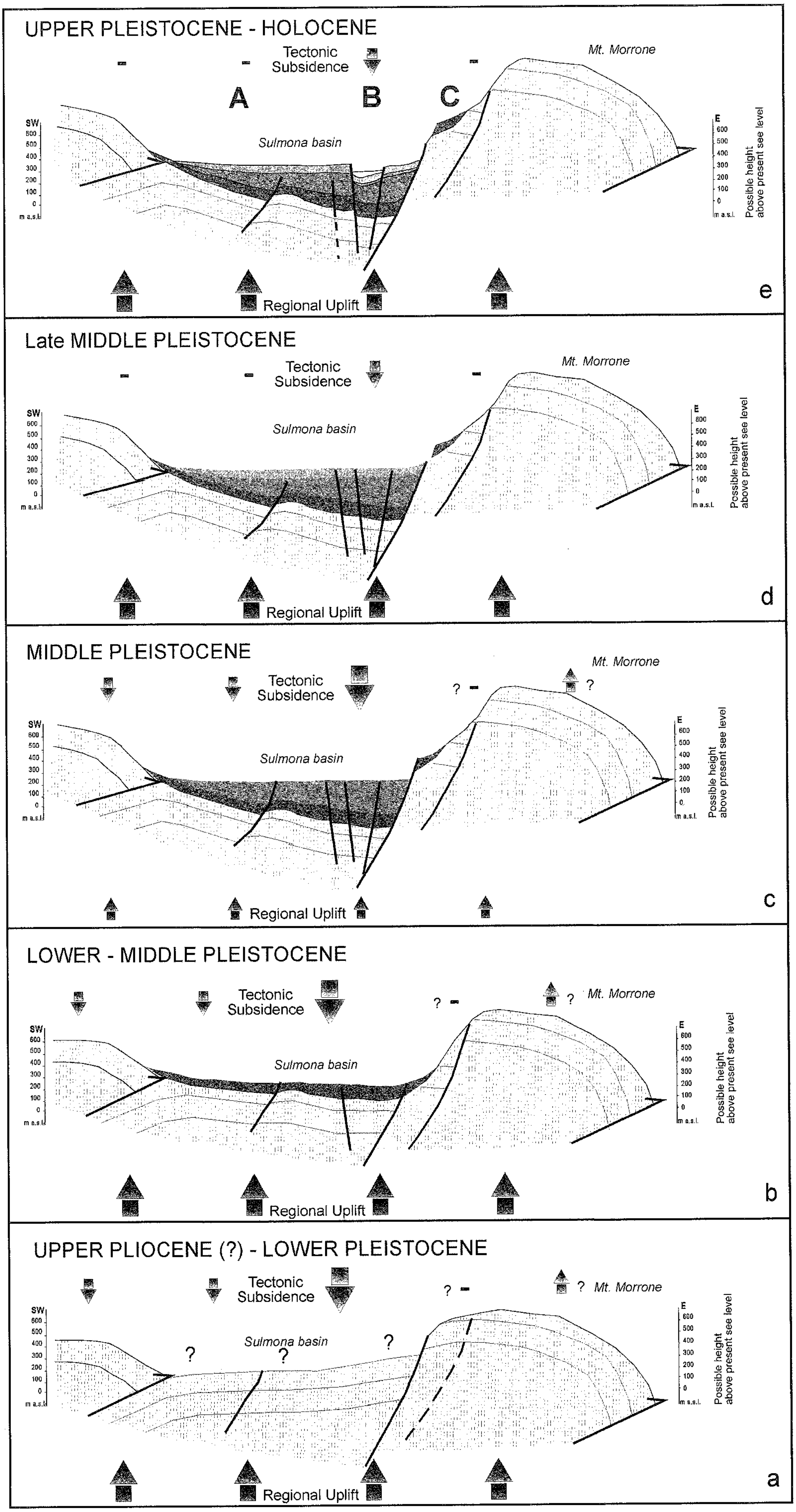

Fig. 8 - Sulmona basin geological evolution and possible correlation to the regional uplift vs. tectonic subsidence and sedimentation evolution from Upper Pliocene (?) - Lower Pleistocene to present. The arrows indicate uplift and tectonic subsidence and the dimension indicates the possible intensity of the process ("–" indicates no or little vertical movement).

between two non coaxial thrust sheet stacked during Upper Miocene (Messinian) – Lower Pleistocene (Prezza – Monte Mentino thrust, to the west; Monte Morrone thrust, to the east; VEZZANI & GHISETTI, 1998; MICCADEI *et al.*, 1999b). This area went through extensional tectonics and the formation of the Sulmona basin started (Fig. 8a).

This stage runs in a strong regional uplift testified by the coeval marine and transitional regressive sequences of Abruzzi coastal area (DRAMIS, 1993).

During Lower – Middle Pleistocene the basin acquired a defined physiography and the sedimentation in it is well testified (Fig. 8b). Deposits referable to this period outcrop in the basin margin slopes whereas in the center of basin they are possibly buried below more recent deposits (Fig. 7). The regional uplift was going on, as is testified by the height of the deposits in the Monte Morrone slope that is no or little influenced by the tectonic subsidence.

This stage is possibly related or right preceding a strong extensional tectonics developed in the Apennines at about 0,7 – 0,8 Myr as suggested by correlation with volcanic activity along the Thyrrenian area (CAVINATO *et al.*, 1994) and by geomorphological consideration (BRANCACCIO & CINQUE, 1992). It is confirmed by the age of tefra layers in Sulmona basin (Fig. 2, Fig. 3; MICCADEI *et al.*, 1999a).

During Middle Pleistocene the tectonic subsidence due to the strong extensional activity on the Monte Morrone fault determined the formation of a threshold in the present Popoli gorge area (northern part of the basin) and the formation of a lacustrine basin. Lacustrine sequences were deposited in the basin with a strong aggradation; the thickness is variable as shown by seismic data. The lacustrine sequence bottom is now below the present sea level in the north-eastern sector and could be lower in Middle Pleistocene because afterwards the uplift has gone on whereas tectonic subsidence has been not so strong (Fig. 8c).

During late Middle Pleistocene the regional uplift was no longer balanced by tectonic subsidence; the regressive erosion cut the lake threshold in the Popoli gorge down, stopped the lacustrine sedimentation and eroded the upper part of the lacustrine sequences; this process affected other basins in Central and Southern Apennines (BRANCACCIO & CINQUE, 1992). Then an alluvial sedimentary pulse related to climatic changes (OIS 6, "Riss"[1] glacial stage) formed the Sulmona Unit (Fig. 8d). The decrease of tectonic subsidence is testified by no tilting in the Sulmona Surface, apart from local tilting along secondary fault close to Monte Morrone fault zone.

During Upper Pleistocene and Holocene tectonic subsidence is low, the fault displacement in the deposits at most few tens of meters, but the uplift still continues; this process together with climatic changes related to last interglacial and last glacial stages induced new cut and fill pulses and the formation of two order of alluvial terraces (Fig. 8e) and travertine deposits.

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