Available online http://amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Alpine and Mediterranean Quaternary, 32 (2), 2019, 185 - 197 https://doi.org/10.26382/AMQ.2019.13

LATE QUATERNARY GEOMORPHOLOGICAL EVOLUTION AND EVIDENCE OF POST-CAMPANIA IGNIMBRITE (40 KA) FAULT ACTIVITY IN THE INNER SECTOR OF THE SARNO PLAIN (SOUTHERN APENNINES, ITALY)

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ABSTRACT: The Sarno plain corresponds to the southernmost sector of the Campana Plain peri-Tyrrhenian graben, and it is limited towards the northwest by the Somma-Vesuvius volcanic edifice. The Sarno plain corresponds to the depocenter of a Quaternary sedimentary basin which is more than 2000 m thick and is bounded by high angle faults with NE-SW, E-W and NW-SE trends. Our study focussed on the less investigated, inner part of the Sarno plain, and aimed at reconstructing the recent (Late Pleistocene - Holocene) geomorphological and tectonic evolution of the area. The study was based on detailed geomorphological investigation combined with subsurface stratigraphic analyses of around 80 borehole logs.
The geomorphological-stratigraphical approach has allowed the identification of the main geomorphological features of the alluvial plain and adjacent piedmont areas, and the reconstruction of the shallow subsurface setting of the inner Sarno Plain. The results indicate post-Late Pleistocene subsidence of the investigated area and the presence of an articulated fault system at the north-eastern boundary of the investigated area. Surface morphological features and the characteristics of the drainage network are consistent with the subsurface stratigraphy in pointing to the activity of E-W and NW-SE trending fault strands during the late Quaternary. Overall evidence suggests the occurrence of vertical displacements postdating the emplacement of the Campania Ignimbrite regional chronostratigraphical marker, which implies fault activity continuing in the last 40 ka in the inner part of the densely populated Sarno Plain.

Keywords: active faults, Campania Ignimbrite, southern Apennines, Italy.

1. INTRODUCTION

Unravelling recent displacements along the faults at the boundaries of the Campania Plain Quaternary coastal graben, in the southern Apennines, is a challenging task. Difficulty arises mainly from intense urbanization and high-rate sediment accumulation during late Quaternary times. In fact, in the circum-volcanic region of the Campania Plain, several explosive eruptions supplied pyroclastic sediments with repeated and abundant inputs which favoured filling of the basin and forced coastal progradation (Brancaccio et al., 1991; 1995; Santangelo et al., 2017). In the piedmont belts, abundant pyroclastic deposition, possibly in excess of fault slip, eventually masked the near-fault surface evidence of recent displacements along the faults at the boundaries of the plain (Ascione & Cinque, 2003).
In such a scenario, the topographic expression of recent fault offsets is expected to be subdued and the identification of recent fault offsets fundamentally rests on the coupling of detail scale geomorphological analysis with careful interpretation of subsurface stratigraphy data.
We have investigated the Sarno plain, which is part of the major Campania Plain coastal graben, with the aim of reconstructing the Late Quaternary activity of the fault strands at the boundary of the sedimentary basin and constraining the age and the amount of their recent displacements.

In the Campania Plain basin, the interaction between vertical motions and sea-level fluctuations controlled the accumulation of thousands-of-meters thick successions of marine, transitional and continental deposits during the Quaternary (e.g., Santangelo et al., 2017, and reference therein). The marine to continental sediments are interlayered with products emitted, through effusive and explosive eruptions, by several volcanic centres (Santangelo et al., 2017, and reference therein). Major NE-SW to E-W trending and NW-SE trending high angle extensional faults separate different sub-basins within the Campania Plain (e.g., Caiazzo et al., 2006; Cella et al., 2007; Milia &Torrente, 2015), with the Sarno Plain corresponding to the south-easternmost one. Associated with the normal fault systems are features like mineral springs, travertine/tufa deposits and sinkholes. By regional scale evidence from the central and southern Apennines (Santo et al., 2011; Ascione et al., 2014), which indicates that such features cluster along active faults that dissect the topographic surface,

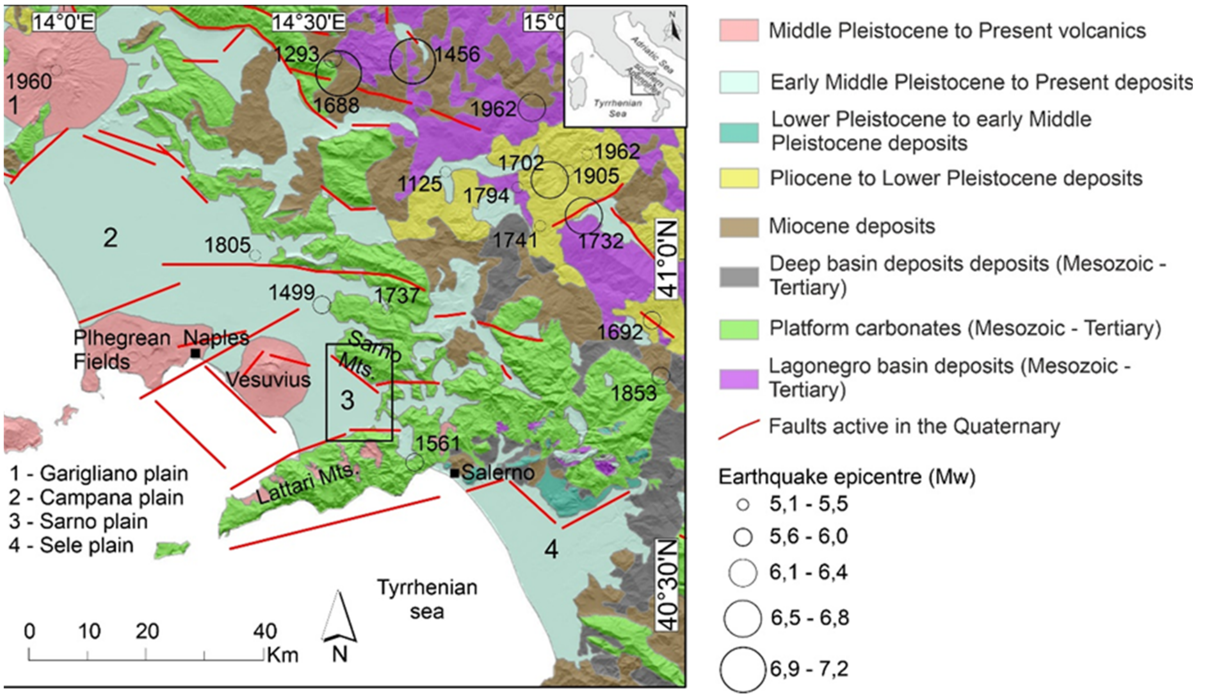

Fig. 1 - Simplified geological map of the southern Apennines (modified from Santo et al., 2019). Black box indicates location of the study area. Earthquakes epicentres are derived from Rovida et al., (2016).

recent activity of the faults at the boundaries of the Campania Plain may be inferred. Indeed, Holocene displacement along the western segment of the normal fault system that bounds the Sarno Plain towards the SE has been inferred from subsurface stratigraphy (Irollo et al., 2005). On the other hand, Late Pleistocene-Holocene activity of the faults at the boundaries of the less investigated inner part of the Sarno Plain, has not been assessed to date (e.g., Cinque et al., 2000).

Our study focuses on the north-eastern part of the Sarno Plain and is based on a detailed geomorphological investigation combined with the analyses of subsurface stratigraphy data from both deep (depth >30 m) and shallow (depth <30 m) boreholes.

2. GEOLOGICAL SETTING

The Sarno plain is located in the Tyrrhenian flank of the southern Apennines fold-and-thrust belt (Mazzoli &Helman, 1994; Cello &Mazzoli, 1999; Turco et al., 2012). Since the Late Miocene, thrust tectonics along the north-eastern side of the chain was accompanied by extensional tectonics along the southwestern flank, where the Tyrrhenian extensional basin was formed (Malinverno & Ryan, 1986; Patacca et al., 1990; Cinque et al., 1993; Doglioni et al., 2004). Since the Early Quaternary (Calabrian), crustal stretching driven by NW-SE oriented extension caused the lowering, for thousands of meters, of the chain units and the formation of large peri-Tyrrhenian grabens named, from the N to the S, the Garigliano Plain, the Campania Plain, the Sele Plain and the Policastro Gulf (e.g., Sartori, 1990, 2003; Caiazzo et al., 2006; Aucelli et al., 2012; Santangelo et al., 2017 and reference therein; Fig. 1). During the Middle Pleistocene, thrust tectonics ceased and extensional tectonics affected the axial portion of the chain causing the formation of large intermontane basins (Russo Ermolli et al., 2010; Amato et al., 2014, 2017; Ascione et al., 2018), whereas the outer flank of the chain experienced surface uplift (Cinque et al., 1993) accompanied by NE shifting of the Apennine divide (Buscher et al., 2017).

In the Campania plain graben, extensional faulting was accompanied by volcanism. During the Quaternary, several volcanic centres located both inland and offshore were active and, since the late part of the Middle Pleistocene, volcanism was active in the Phlegrean Fields area and Somma-Vesuvius volcano (e.g., Rolandi et al., 2003; de Alteriis et al., 2006; Milia et al., 2013; Santangelo et al., 2017; Misuraca et al., 2018). Volcanism climaxed with the catastrophic Campania Ignimbrite eruption, recently dated at 39.85 ±0.14 ka (Giaccio et al., 2017), which caused emplacement of several tens of m thick deposits in a large area spanning over the Campania region (De Vivo et al., 2001; Rolandi et al., 2003), that morphologically corresponds to a widespread plateau.

Based on geophysical data, three main depocenters have been distinguished within the Campania Plain graben (e.g., Cella et al., 2007; Milia &Torrente, 2015), with the south-eastern one corresponding with the Sarno Plain. The southern boundary of the Sarno Plain is defined by a fault system composed of mainly NE-SW and E-W trending segments, located at the toe of the Lattari Mts. slopes (Cinque, 1991; Irollo et al., 2005), while to the northeast the plain is bounded by a NW-SE trending

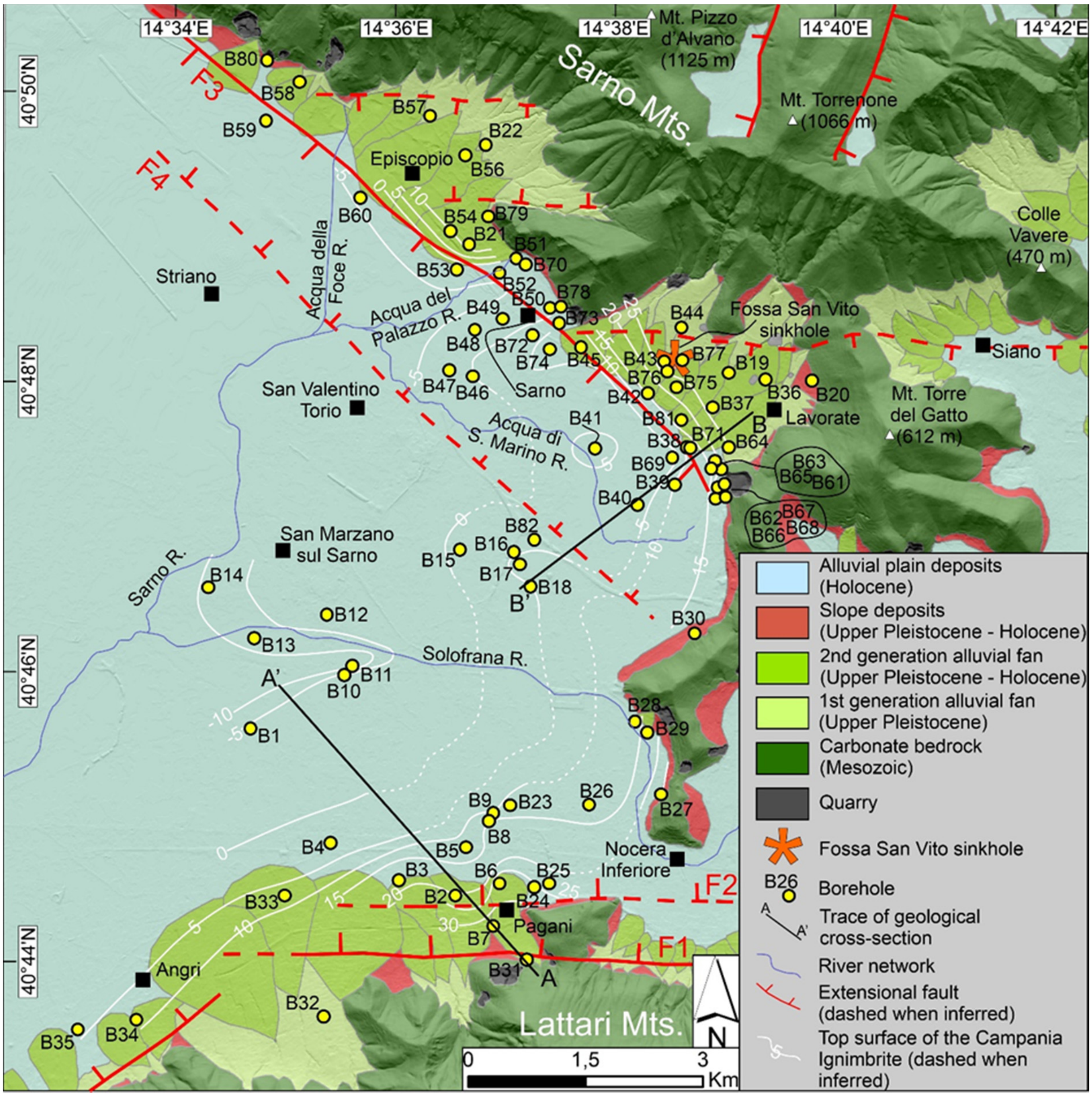

Fig. 2 - Geological map of the inner corner of the Sarno plain. Black boxes indicate main localities listed in the text. White contour lines indicate the top surface of the Campania Ignimbrite (in meters a.s.l.).

fault running at the base of the Monti di Sarno Mts. (Cinque et al., 1987; Cinque, 1991; Fig. 1). The hillslopes of the Lattari Mts. and Monti di Sarno Mts. consist of a carbonate succession of Jurassic to Cretaceous age (Sheet 448-Ercolano, ISPRA, 2014a; Sheet 466-Sorrento, ISPRA, 2014b). Between these major ridges, a downfaulted belt consisting of the upper part of the carbonate succession (Cretaceous; Sheet 448-Ercolano; ISPRA, 2014a) is present. Towards NW, the Sarno Plain is limited by the Somma-Vesuvius volcanic edifice. Thickness of the Quaternary filling of the Sarno Plain is constrained by the Trecase 1 well (Bernasconi et al., 1981; Balducci et al., 1983; Brocchini et al., 2001), which is located in the western sector of the plain, at the base of the Somma-Vesuvius volcano. The well is 2072 m deep and the carbonate bedrock has been found at depth of 1882 m. ^{40}Ar/^{39}Ar and biostratigraphy of the Trecase 1 core suggest a Middle Pleistocene age for the upper ~1000 m part of the basin fill (Brocchini et al., 2001). The 275-290 m-deep fallout deposit of the Trecase 1 well is correlated with the 25 ka Codola eruption (Alessio et al., 1974), which testifies to the onset of the Somma volcanic activity.

The recent (late part of Upper Pleistocene to Holocene) evolution of the western part of the Sarno Plain, and its relationship with relative sea-level fluctuations,

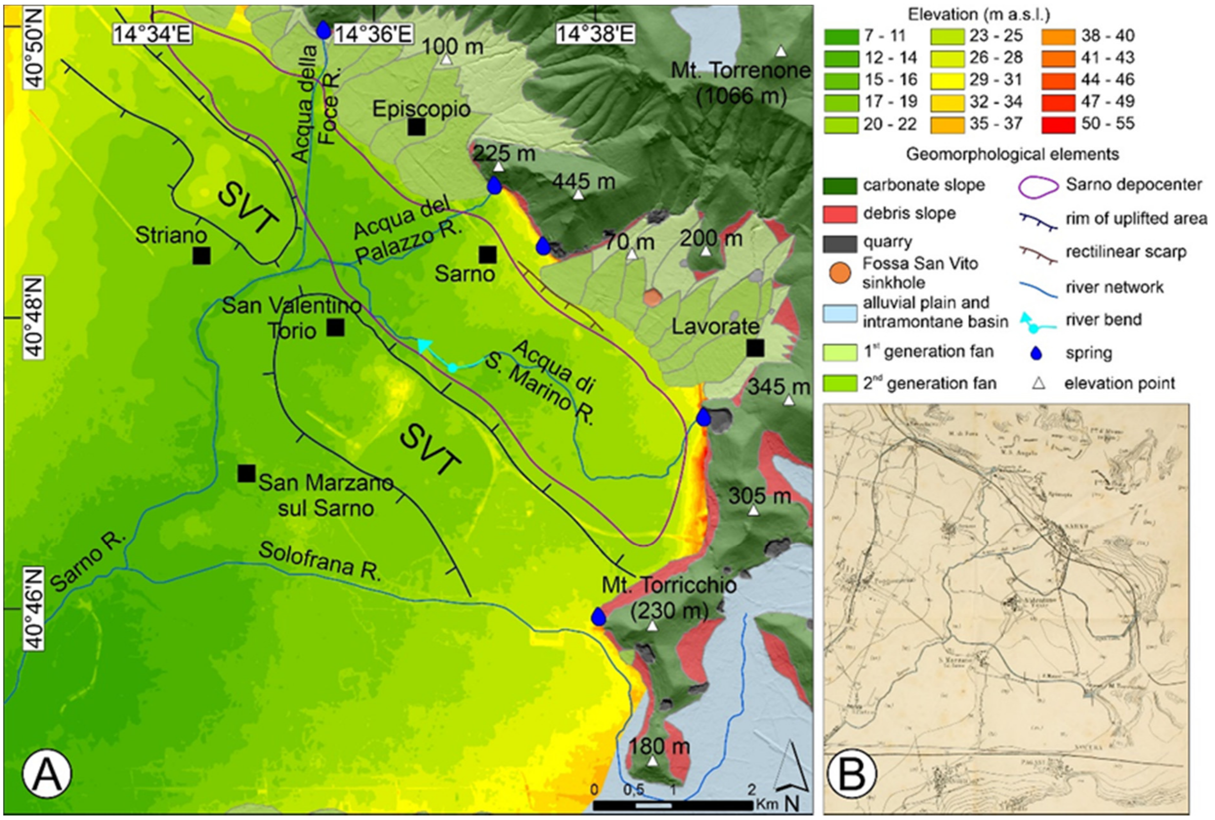

Fig. 3 - A) Geomorphological map of the inner sector of the Sarno Plain. SVT = Striano - San Valentino Torio topographic high. B) Historical topographic map of the inner sector of the Sarno Plain with 10 m spaced contour lines (from Morano, 1882).

has been reconstructed in detail in several works (Cinque & Russo, 1986; Cinque et al., 1987; Barra et al., 1989; Albore Livadie et al., 1990; Cinque, 1991; Cinque & Irollo, 2004). These studies identified the late stages of coastal progradation that followed the maximum Holocene ingression, which reached ~8 km inland of the present-day coastline (Cinque, 1991). In addition, basing on age constraints on the sediments buried at shallow depths, Holocene subsidence-postdating the maximum Holocene ingression-of the southwestern part of the Sarno Plain has been inferred (e.g., Albore Livadie et al., 1990). Less constrained is the subsurface stratigraphical setting and recent evolution of the inner (eastern) part of the Sarno Plain. In the subsurface of that area, marine and transitional deposits have been drilled down to depths >200 m (Nicotera & Civita, 1969) and the presence of several tens of m of buried thick deposits of the Campania Ignimbrite chronostratigraphic marker has been reported (Nicotera & Civita, 1969; Cinque, 1991; Aprile & Toccaceli, 2002).

The recent Late Pleistocene - Holocene activity of the western part of the fault system bounding the Sarno plain towards the south has been inferred from subsurface stratigraphy (Irollo et al., 2005) and current extensional deformation has been identified from faults affecting the Somma-Vesuvius volcanic edifice (Tramparulo et al., 2018). However, besides low-energy earthquakes related with the Vesuvius volcano area (http://www.ov.ingv.it/ov/), the Sarno Plain lacks significant historical seismicity, while low to moderate magnitude earthquakes have affected the surroundings of the plain. The strongest events are represented by the Mw =5.56, 1499 earthquake and the Mw =5.56, 1561 earthquake, whose epicentres are located ~15 km to the NW and SE of the Sarno Plain respectively (Rovida et al., 2016; Fig. 1).

3. METHODS

The work has been based on the combination of field survey, geomorphological analysis of large-scale topographic maps and reinterpretation of stratigraphical data from a total of 80 boreholes, both published and unpublished.

The geomorphological investigation has been based on the analysis of Technical Maps of the Campania Region at scale 1:5000 and a high-resolution Digital Terrain Model (LiDAR DTM, 1x1 m horizontal resolution, which cover the entire study area). The combination of both datasets allowed the identification of the main features of the topographic and hydrographic networks of the investigated area.

Borehole data include 8 boreholes from Guarino & Nisio (2009), 12 boreholes from Nicotera & Civita (1969), 35 boreholes from the ISPRA database (http://sgi2.isprambiente.it/mapviewer/), 25 boreholes from the

Piano Urbanistico Comunale of the Sarno municipality, and one deep borehole from Cinque et al. (1987). Depths of the boreholes range from 15 m to 252 m. Borehole data have been imported in a GIS software (Arcgis 10.7 ©), converted in a point shapefile and a database has been associated to this shapefile. The latter include information about the absolute elevation of the main stratigraphic units that have been distinguished. These data have been then plotted on a hillshade map of the north-eastern corner of the Sarno Plain, that has been derived from the 1x1 m LiDAR DTM. Elevation data from the LiDAR data were used for the construction of two cross-sections representative of the subsurface setting of the Sarno Plain.

4. RESULTS

4.1. Geomorphological features of the inner Sarno plain

The Sarno Plain is an ~50 km^2 large and substantially flat alluvial plain. It is crossed by the Sarno River, which originates from the merging of three streams (namely the Acqua di Palazzo, Acqua di San Marino and Acqua della Foce streams; Fig. 2) fed by springs located along the Monti di Sarno mountain front. Some man-made interventions have partially modified the hydrography of the Sarno Plain, with the construction of the Acqua della Foce artificial, rectilinear canal and the bending of the Solofrana River towards the north, in order to make it flow into a roughly E-W trending stream fed by the spring located at the base of Mt. Torricchio (Morano, 1882; Fig. 3B). Along the Sarno Plain, alluvial terraces are lacking, and the elevation increases to maximum values around 30 m along the adjacent piedmont areas. The analysed area of the Sarno Plain spans between the straight, roughly E-W trending mountain front of the Lattari Mts., in the south, and the slopes of the Monti di Sarno ridge, in the northeast (Fig. 2), where the springs originating the Sarno River are located. In the lowered belt located between the steep scarps of the Lattari and Monti di Sarno Mts., the smooth and low hills of the Mt. Torricchio ridge (maximum elevation around 600 m) form the eastern limit of the Sarno Plain (Fig. 2).

The Lattari Mts. mountain front (Fig. 3A) is characterised by planar slopes and triangular facets formed in the Mesozoic carbonate rocks. The Monti di Sarno ridge has maximum elevation of 1125 m a.s.l. in correspondence of the Pizzo d'Alvano Mt., and an articulated perimeter characterised by two large embayment (namely, the Episcopio and Lavorate embayment; Fig. 2; Fig. 3A), with an overall NW-SE trend. In the piedmont belt of the Lattari Mts. and in the embayment located at the toe of the Monti di Sarno Mts., two generation of coalescent alluvial fans may be distinguished, locally interrupted by debris slopes. Alluvial fans from the Lattari Mts. ridge surround the downfaulted carbonate hill of Pagani (Fig. 2). Alluvial fans of the 1st generation are dissected and are steeper than those of the 2nd generation. The latter ones are wider and gently graded to the adjacent alluvial plain. Deposits of the alluvial fans of the 2nd generation that form the piedmont of the Monti di Sarno Mts. are well exposed in the Lavorate embayment, along the ~ 25 m high walls of a ~ 200 m wide cover collapse sinkhole (Fossa San Vito sinkhole; Santo et al., 2019; Fig. 2; Fig. 3A). They consist of gravels composed of carbonate clasts alternated with pyroclastic layers, that overlie the Campania Ignimbrite (hereinafter, CI), a regional chronostratigraphic marker layer ~40 ka old (Fig. 4). In the outcrops along the walls of the Fossa San Vito sinkhole, the CI is visible for about 7 metres as a greyish tuff, while in the piedmont area of Sarno Mts. it is possible to observe its basal pumices layer (Fig. 4). In the Lavorate area, the boundary between the alluvial fan surfaces and the alluvial plain to the SW is marked by a ~5 m high, NW-SE trending and SW facing scarp that is strikingly rectilinear (Fig. 3A).

Topography of the analysed sector of the Sarno alluvial plain is smooth and low-lying. It rises rather gradually from the SW to the NE, to maximum values around 25-30 m a.s.l. around the Striano and S. Valentino Torio sector (hereinafter, SVT; Fig. 3A). This sector is identified as a NW-SE trending, smooth topographic high rising of about 5-10 m above the alluvial plain, which is incised transversally by the Sarno river (Fig. 3A). The SVT high limits a relatively NW-SE oriented low-lying area, around 2 km in width and 10 km in length (hereinafter named the Sarno depocenter; Fig. 3A), towards the SW. The eastern boundary of the Sarno depocenter is represented by the NW-SE trending and SW facing rectilinear scarp at the toe of the alluvial fans in the Lavorate area (Fig. 3A).

The drainage network upstream of the SVT is characterised by several anomalies, which suggest that the high-and-low topographic setting of the SVT and Sarno depocenter affects the surface water flow. For instance, irrespective of the general NE-SW topographic gradient of the alluvial plain, all the tributaries of the Sarno River that flow from the mountain front merge into the Sarno River upstream of the SVT. Particularly anomalous is the path of the Acqua di San Marino streambed. The Acqua di San Marino streambed is initially characterised by a wandering course while, in the lower part, it bends and gains a NW-SE oriented, straight path that is aligned for about 2 km along the northeastern margin of the SVT high (Fig. 3A and B).

4.2. Shallow subsurface setting of the inner Sarno plain

Borehole data from the Monti di Sarno and Lattari Mts. piedmont indicate that the deposits of the alluvial fan of the 1st generation consist of poorly cemented to cemented calcareous gravels with abundant pyroclastic matrix, interbedded with sandy layers, cineritic layers and thin palaeosoils. The thickness of these deposits varies along the mountain fronts being ~100 m in the Episcopio embayment (borehole B22), ~45 m in the Lavorate embayment (borehole B19), ~70 m near Pagani (borehole B7) and ~150 m near Angri (borehole B32; see Fig. 2 for borehole locations), respectively.

Consistent with evidence from outcrops in the Lavorate embayment, deposits of the alluvial fans of the 2nd generation overlie a well-defined 20-30 m thick unit that consists of pyroclastic deposits/tuff, yellowish or

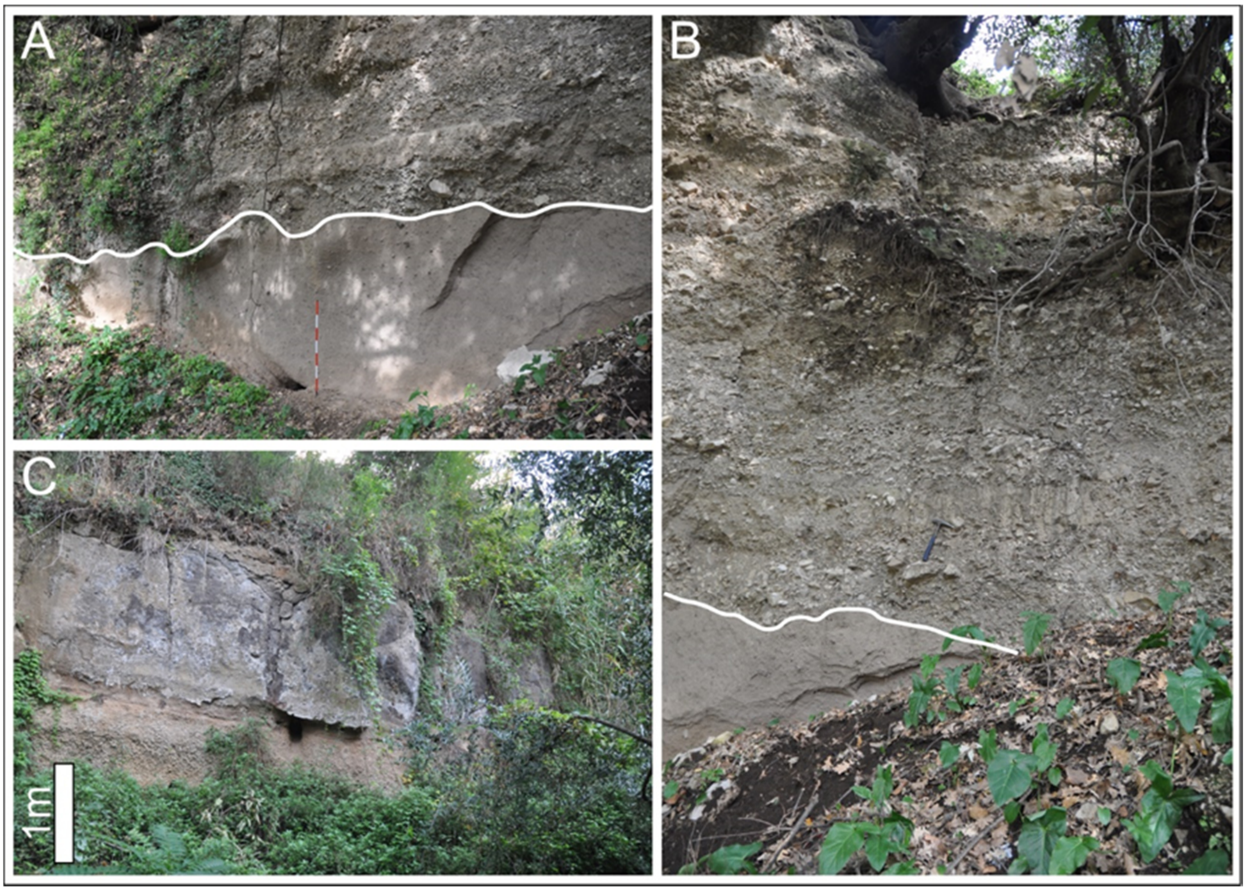

Fig. 4 - Late Quaternary deposits outcropping along the walls of the Fossa San Vito sinkhole (A and B) and in the Monti di Sarno Mts. piedmont (C). In diagrams A and B, white lines mark the stratigraphical contact, between the Campania Ignimbrite (below) and the alluvial and pyroclastics deposits collectively labelled post-C.I. deposits (above). Photograph in C shows an outcrop of the Campania Ignimbrite, with its basal pumice level.

greyish in colour, that in some instances pass downwards to a pumice layer. Based on its features, such a unit can be correlated with the Campania Ignimbrite regional chronostratigraphic marker.

Towards the alluvial plain, the alluvial fan deposits associated with the southern and eastern piedmont areas pass laterally to a succession of deposits composed of alluvial plain to marine sediments alternated with pyroclastic deposits. The upper part of the alluvial plain fill consists of a group of deposits that are composed of poorly cemented sands and gravelly layers and includes an abundant pyroclastic component. Information from several boreholes shows that the above-described group of deposits (hereinafter labelled post-CI deposits) postdates deposition of the Campania Ignimbrite. Data from the area spanning from Episcopio and Lavorate, to the NE, to the SVT high, to the SW, indicate that the post-CI deposits in the SVT essentially consist of pyroclastic deposits, while the adjacent Sarno depocenter is the only sector where the post-CI deposits include fine-grained-lacustrine facies-sediments and peat layers, in the investigated area (Fig. 5). In the Sarno depocenter the post-CI deposits have a maximum thickness of ~20 m around the municipality of Sarno, and also include travertine layers. The spatial distributions of post-CI travertine, peat and lacustrine deposits in the Sarno depocenter are shown in the sketches A to F of Fig. 5.

Borehole data have been used for the reconstruction of the top surface of the Campania Ignimbrite, which is shown in Fig. 2. Although, due to the uneven spatial distribution of data, a variable degree of uncertainty affects the surface that has been reconstructed, as a general feature the map of Fig. 2 shows that the CI top surface declines from the inner margin towards the central part of the Sarno Plain. Such a shape of the CI top surface is substantially consistent with the current morphology of the Sarno Plain also in the northeastern part of it, where both a localised low in the subsurface of the Sarno depocenter, and a slight steepening aligned with the SW-facing scarp located at the NE boundary of that topographic low occur (Fig. 2). The top surface of the buried CI plateau is also characterised by elongated lows that can be interpreted as paleovalleys, one of which originates in correspondence of the Acqua del Palazzo springs and roughly parallels the current path of that stream. Another one, with E-W trend, lies below the Solofrana River course (Fig. 2).

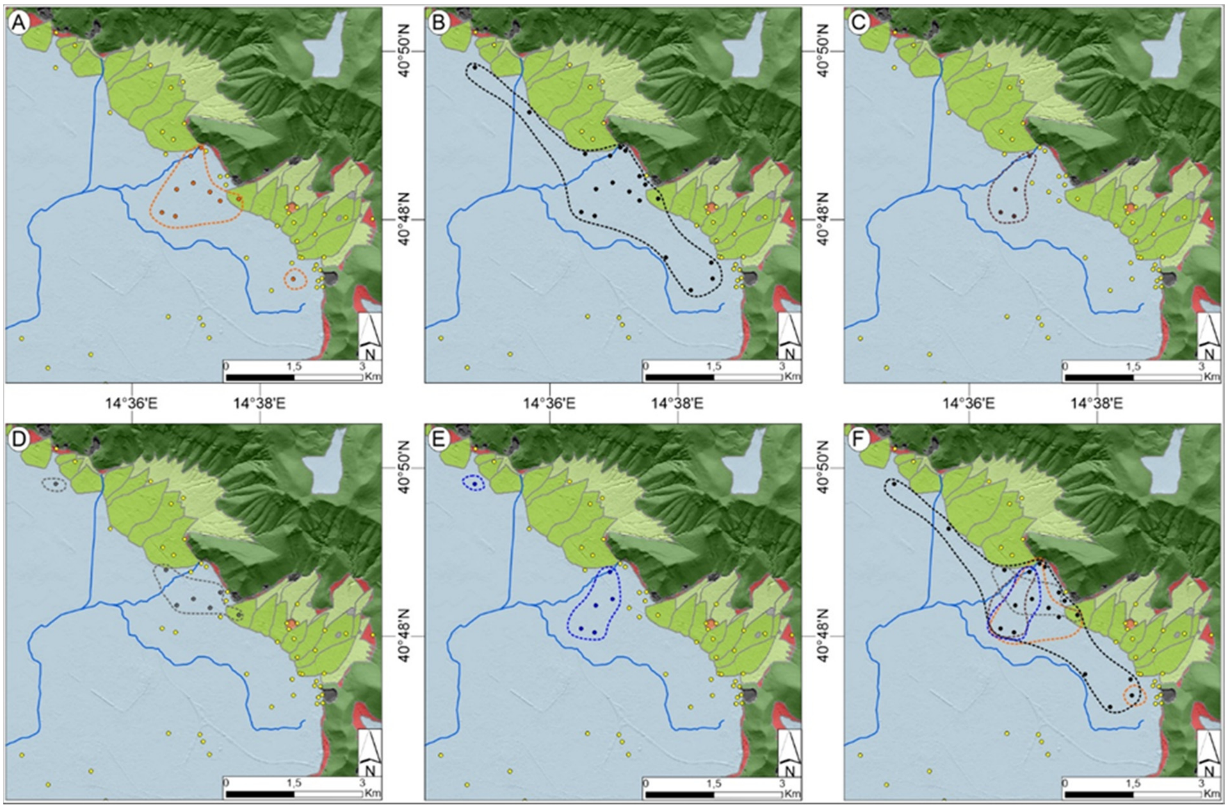

Fig. 5 - Schematic maps showing spatial distributions of areas with stratigraphical evidences of lacustrine/marshy environment postdating the Campania Ignimbrite deposition. A) Dashed orange line limits boreholes with travertine layers at 2-5 m of depth (orange dots). B) Dashed black line limits boreholes with peat layers at 5-10 m of depth (black dots). C) Dashed brown line limits boreholes with travertine layers at 10-12 m of depth (brown dots). D) Dashed grey line limits boreholes with peat layers at 15-18 m of depth (grey dots). E) Dashed blue line limits boreholes with lacustrine layers at 18-20 m of depth (blue dots). F) Superposition of areas sketched in diagrams A to E. Yellow dots in each panel indicate boreholes with no either travertine, or peat or lacustrine layers. Borehole labels are reported in Fig. 2.

The deeper boreholes provide information on the lower part of the basin fill. They show that the CI passes downwards to a group of deposits composed of alternated pyroclastic and sandy-gravelly layers, collectively labelled pre-Campania Ignimbrite (hereinafter pre-CI) deposits, whose maximum thickness locally exceeds 70 m (borehole B3, Fig. 2 for location). Based on their lithological features, an alluvial plain environment can be hypothesised for the pre-CI sediments. Below the pre-CI deposits, an alternation of sand, gravel and silt layers with abundant macrofossils (mostly bivalves), related to marine and transitional environment, occurs. More detailed data from borehole B82 (which corresponds to borehole labelled Pozzo Sarno in Cinque et al., 1987) show that a layer of fluvial-marshy deposits is interposed in the marine deposits at depths from about 45 to 50 m b.s.l. In the piedmont belts, the transitional-marine deposits have been drilled, above the carbonate bedrock, in the subsurface of the Lavorate area, whereas the presence of fossiliferous deposits is not reported in borehole logs from the subsurface of the areas around Pagani and Angri. In the northeastern sector of the investigated area, thickness of the marine-transitional deposits increases abruptly from the Lavorate area towards the subsurface of the Sarno alluvial plain from around 20-30 m up to values exceeding 150 m (borehole B69, Fig. 2 for location).

Information from borehole data has been synthesised in two cross-sections (Fig. 6), which have been constructed through the alluvial plain and adjoining piedmont areas to the south and NE of the investigated area, respectively, using the deeper available boreholes. The cross-sections highlight either significant lateral variation of thickness of single stratigraphic units, or/and vertical separation between correlative stratigraphic horizons, with both features suggesting vertical displacements along faults.

Cross section A-A' strikes from the piedmont area around Pagani to the SE to the Sarno Plain to the NW (location in Fig. 2). The main Quaternary units in this part of the plain include, from the surface: deposits of the alluvial fans of the 2nd generation, which pass laterally into alluvial plain and post-CI pyroclastic deposits; the CI layer; pre-CI deposits with thickness exceeding 70 m; fossiliferous marine-transitional deposits (drilled for at least 40 m towards the end of section A-A', borehole B11, Fig. 6). The lateral distribution of the drilled units suggests that, at depth, the continental environment pre-CI deposits pass towards the NW into transitional-marine deposits. Cross section A-A' shows the abrupt

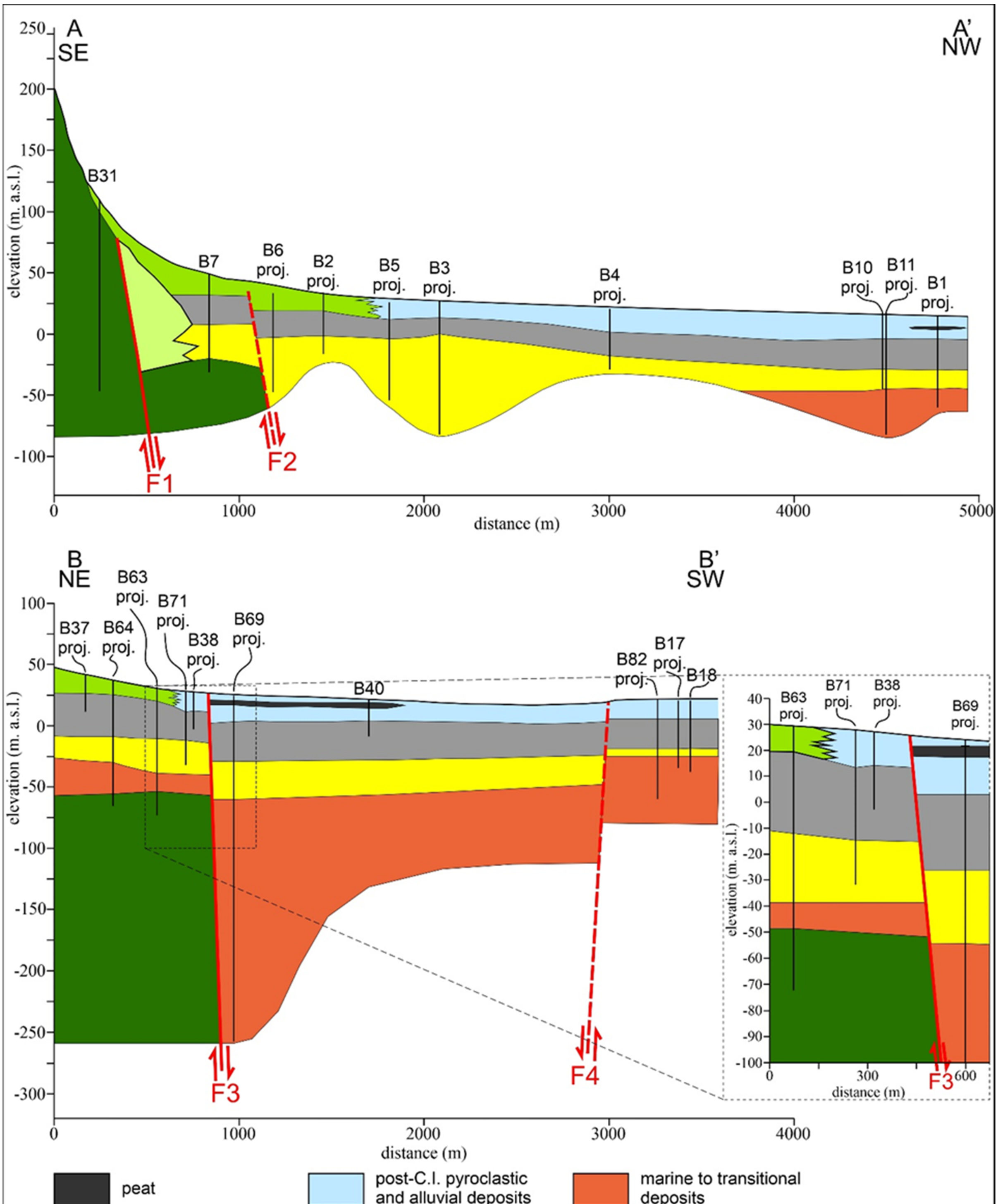

Fig. 6 - Geological cross-sections within the study area. Locations of the cross-section traces are reported in Fig. 2. Dashed box in cross-section B-B' indicates the magnification of the fault zone showed to the right of the cross-section.

deepening of the carbonate bedrock towards NW that occurs at two main steps (Fig. 6). We associate the carbonate rocks drilled by borehole B7 with the lowered carbonate block that includes the Pagani hill (Fig. 2), and the first step of the carbonate bedrock with the fault (labelled F1 in cross section A-A' and Fig. 2) that separates the Lattari Mts. mountain front from the Pagani carbonate hill. To the north of fault F1 trace, the base of the pre-CI deposits is lowered down to ~25 m b.s.l. The second step is located to the north of the Pagani hill, where the carbonate bedrock deepens down to more than 100 m b.s.l. Associated with steps of the carbonate bedrock, are lateral variations of depths of the overlaying, correlative stratigraphic horizons, which suggest displacement along faults. In particular, as the CI layer maintains a substantially constant thickness along the trace of cross section AA', the vertical separation of both bottom and top of that layer suggests displacement along the inferred fault F2 more than erosion of the CI surface. Cross-section B-B' (Fig. 6; location in Fig. 2) strikes from the embayment of Lavorate to the NE to the Sarno Plain to the SW. Section B-B' shows that thicknesses of the sedimentary units that lay both below and over the CI increase abruptly substantially in correspondence of the SW-facing scarp located at the north-eastern boundary of the Sarno depocenter, that we interpret as the surface expression of an extensional fault. In particular, from the subsurface of the piedmont area near Lavorate to the subsurface of the Sarno depocenter, the section shows: (1) deepening of the carbonate bedrock (from ~50 m to >250 m b.s.l.), (2) an increase of marine deposits thickness (from 25-30 m to at least 175 m) and (3) vertical separation of the pre-CI horizon and of both the base and top of the CI. A rise of both the marine and pre-CI units top surfaces occurs in the subsurface of the SVT high, where a slight rise of the CI top also occurs.

5. DISCUSSION

The low-gradient topography of the entire Sarno Plain, onto which only the smooth SVT high rises, corresponds to the undissected surface of an alluvial plain graded to the present-day coastline. The stratigraphical framework of the shallow subsurface of the inner part of the Sarno Plain, which is inferred from inspection and correlation of the borehole logs that we have collected, indicates that the environmental conditions have changed from marine to continental through time. Furthermore, throughout its recent evolution, the investigated area has been affected by repeated pyroclastic inputs, which represent an important component of all the alluvial units buried in the plain and are interlayered with deposits of the alluvial fans that form the piedmont belts of the Monti di Sarno and Lattari Mts. mountain fronts. Crucial to the reconstruction of a chronostratigraphical framework for the investigated area is the distinct marker layer that is represented by the c. 40 ka old Campania Ignimbrite. In the piedmont belts, the presence of the CI underneath coarse grained deposits associated with alluvial fans of the 2nd generation, suggests that the growth of the latter alluvial fans, which can be related to abundant detrital production promoted by frost action, may be correlated, at least in part, with the Last Glacial period (in agreement with attribution of those alluvial fans to the Upper-Middle Wurm by Cinque et al., 1987). As surfaces of the 2nd generation alluvial fans grade to the alluvial plain, we suggest that their deposition continued during the Holocene, coeval with aggradation in the alluvial plain (see below). Based on relative chronology criteria, an older, Middle-Upper Pleistocene age may be inferred for the growth of the thick alluvial fans of the 1st generation. Thicknesses of the latter ones, as inferred from available boreholes, indicate that they deepen in the subsurface down to several tens of metres below the sea level.

The lowest Quaternary unit drilled by the deeper boreholes from the entire investigated area consists of fossiliferous marine-transitional deposits, which have been recovered down to a depth >250 m b.s.l. These deposits testify to a marine/coastal environment that, during periods of positive sea-level fluctuations, occupied the entire Sarno Plain to reach its innermost margin, represented by the Monti di Sarno mountain front. Based on information from the Trecase 1 well (Brocchini et al., 2001), the buried marine-transitional deposits cover the upper part of the Middle Pleistocene. Although age of the top part of the marine unit (that reaches a minimum depth of ~25 m b.s.l.) is not constrained, it can be hypothetically correlated with the Last Interglacial high sea level. Such a correlation is in substantial agreement with attribution to the Eutyrrhenian by Cinque (1991) and Albore-Livadie et al. (1990) of marine deposits recovered in the 30 to 40 m b.s.l. depth interval in the subsurface of the Sarno Plain to the SW of our study area, below a further marine succession (located from ~ 10 to 20 m b.s.l.) constrained to the Holocene sea-level rise by geochronological and geoarcheological data.

In the entire investigated area, the marine-transitional deposits are covered by alluvial sediments, which are interlayered with pyroclastic deposits. Based on chronostratigraphical correlation, within the alluvial deposits, we have distinguished a >40 ka pre-CI unit, and a post-CI unit. Between these units, the CI forms a ~ 20 to 30 m thick, distinctive layer. Deposition of the CI occurred at a time when the sea level was ~80 m lower than at present (e.g. Siddall et al., 2005), and the Sarno Plain was entirely located above the sea level (Milia, 1998; 2000). Cinque & Irollo (2004) related the incision by the Sarno River, in the CI layer, of a valley down to -30 m a.s.l. in the soutwestern part of the Sarno Plain (Pompei area) to the further lowering of the sea level down to -120 m in the Last Glacial Maximum (e.g. Siddall et al., 2005). We correlate to the same LGM incision phase the formation of the valleys that we have identified in the inner part of the Sarno Plain, where they reach depths >5 m b.s.l. (Fig. 2). More in general, we hypothesise that in response to the instantaneous deposition of a 20-30 m thick layer combined with sea level lowering, fluvial dynamics in the study area in the 40-20 ka time span was dominated by fluvial downcutting. Within such a scenario, alluvial deposition was essentially limited to the piedmont belts and coeval aggradation in the quasi-flat plain mostly related to pyroclastic inputs by the Somma-Vesuvius and, to a minor extent, Phlegrean Fields. Most probably, alluvial aggradation in the study area mostly occurred during the late part of the Holocene, when the sea level rise led to a transgression in the southwestern part of the Sarno Plain up to a distance of ~8 km from the present-day coastline (e.g., Albore Livadie et al., 1990; Cinque, 1991).

Overall, detailed chronostratigraphical and geochronological information from the central-coastal area of the Sarno Plain, which highlights the occurrence of the buried Holocene coastal wedge at few tens of metres below the sea level, points to Quaternary subsidence continuing during the Holocene (e.g., Cinque et al., 1987; Barra et al., 1989; Albore Livadie et al., 1990). On the other hand, Holocene coastal progradation and alluvial plain aggradation point to sediment accumulation outpacing coeval subsidence. Based on stratigraphical data, such an unbalance may be explained as the response to the emplacement of abundant pyroclastic products, which has taken place mostly since the Late Pleistocene.

The geomorphological and stratigraphical analyses that we have carried out provides new information on the possible locations of some of the faults which controlled the recent vertical motions of the Sarno Plain, particularly at the southern and northern boundaries of the inner part of the plain. In particular, the geomorphological analysis combined with the subsurface data analysis has allowed identification of features that are consistent with vertical, fault-related, displacement affecting both the topographic surface and underlying buried bodies. Combined evidence has allowed constraining location of the major fault, which bounds the Lattari Mts. mountain front (fault F1 in cross-section AA', which separates carbonates of the Lattari Mts. ridge from those of the Pagani hill block) and suggests possible displacement along a further fault (fault F2) located to the north of it. Worthy to note, late Quaternary subsidence of the sector to the north of the Lattari Mts. mountain front located to the east of the area investigated with our study, i.e. the region which corresponds to the Solofrana River valley and includes the carbonate elevations that rise above the plain, has been inferred by Brancaccio et al. (1994) from subsurface data.

The presence of a fault (fault F3 in Fig. 2 and cross section B-B') at the southwestern border of the Monti di Sarno Mts. ridge is inferred from the presence in the Lavorate area of a ~5 m high, SW-facing scarp, which substantially follows a step in the buried CI top surface. The vertical separation among buried, correlative horizons shown in cross-section B-B' is consistent with interpretation of the NW-SE trending Lavorate scarp as a fault scarp representing the surface expression of fault F3. For both F2 and F3, information from the cross sections in Fig. 6 is consistent with displacement of the pre-CI deposits and underlying marine-transitional deposits, as well as the Campania Ignimbrite layer. The increase of vertical separation from the upper to lower boundaries of the pre-CI unit suggests syn-sedimentary fault activity.

The geomorphological analysis has allowed the identification, to the southwest of the F3 fault scarp, of the Sarno depocenter topographic low, which is limited towards the SW by SVT high. Towards the NE, the SVT is bounded by a straight scarp that can be interpreted as a fault scarp associated with the inferred fault F4, in agreement with Cinque et al. (2000). Consistent with features of topography, the vertical separation that characterises both the CI and underlying Quaternary units across the traces of the inferred faults F3 and F4 is compatible with fault activity causing lowering of the Sarno depocenter. In the Sarno depocenter, Holocene ponding is inferred from the accumulation of travertine, peat and fine-grained deposits in a marshy/lacustrine environment (Fig. 5) that postdates deep incision (related with the LGM sea-level lowering) of the CI. Such a ponding may be related to either tilting or/and lowering of the Sarno depocenter surface during the latest Pleistocene-Holocene. The analysis of the hydrographic network, which is very sensitive to differential motions of the topographic surface (Schumm et al., 2002; Ascione et al., 2007) provides evidence for vertical motions of the SVT based on inconsistency of drainage orientations (e.g. Acqua di San Marino stream) with respect to the large-scale gradient. In addition, merging of streams originating from the Monti di Sarno mountain front upstream of the SVT high suggests that minor streams, with relatively low discharge and stream power, have been substantially incapable of dissecting the morphological high itself. Overall evidence suggests antecedence of the stream network relative to the SVT. A very recent rise of the SVT may also explain the anomalous bending, and straight (NW-SE oriented) path of the Acqua di San Marino stream, which is compatible with displacements along the inferred fault F4 affecting the topographic surface and the sensitive fluvial system.

The geomorphological and geometrical settings that we have reconstructed may be justified by faults slipping at a relatively low rate. In particular, by correlation with the MIS5 of the uppermost marine deposits, a mean vertical motion rate in the last ~125 ka of less than 0.3 mm/yr may be inferred for faults F2, F3 and F4 from the vertical separation of the marine unit top, while a decrease to less than 0.2 mm/yr and even less than 0.1 mm/yr in the last 40 ka for faults F3 and F4, respectively, may be inferred if the Campania Ignimbrite marker is taken as a reference. Geomorphic and stratigraphic evidence from the boundaries of the Sarno depocenter suggests that slip along faults F3 and F4 has continued during the Holocene, while the lack of offset landforms associated with fault F2 at the base of the Lattari Mts. may suggest either substantial quiescence of this fault since the late Holocene, or faulting at a rate slower than that of accumulation of the sediments in the piedmont of the Lattari Mts.

The around 30 m b.s.l. depth of the top of the late Quaternary marine deposits in the footwall block of fault F3 indicates that the Lavorate embayment, as well as the plain in front of it, have been subject to subsidence during the final part of the Late Quaternary. Such evidence implies that a more articulated fault system along the north-eastern boundary of the Sarno Plain has controlled the late Quaternary subsidence of the southeasternmost sector of the Campania Plain as well as the contiguous sector, which includes the Solofrana River valley and adjacent carbonate hills. Lowering of the F3 footwall block could be related to some fault strand possibly represented by the inferred fault with orientation around E-W, located along the northern boundary of the Lavorate area (Fig. 3A), the recent activity of which could not be constrained by our data sets.

6. CONCLUDING REMARKS

The combination of detailed geomorphological analysis and reinterpretation of stratigraphical data from 80 boreholes has allowed to constrain the geomorphological and geological evolution of the inner part of the Sarno Plain, contributing to the reconstruction of the late Quaternary evolution of the southern part of the Campania Plain Quaternary coastal graben.

Our results are consistent with former findings by e.g., Albore Livadie et al. (1990) and Cinque (1991) in the outer, southwestern part of the Sarno Plain, and by Brancaccio et al. (1994) in the Solofrana River valley and adjacent elevations. Collectively, such data point to Quaternary subsidence of the southern part of the Campania Plain continuing after the Late Pleistocene. Within such a scenario, the ultimate evolution from marine to continental environment recorded in the inner part of the Sarno Plain following the Last Interglacial has been essentially controlled by high sedimentation rate, which received a substantial contribution by the emplacement of abundant pyroclastic inputs by both the Phlegrean Fields and Somma-Vesuvius.

Although the perimeter of the subsiding region could not be entirely constrained by our data sets, the evidence that we have provided for recent displacements at the north-eastern boundary of the Sarno Plain supports the hypothesis of active fault strands along the Monti di Sarno Mts. mountain front, inferred by Santo et al. (2011) and Ascione et al. (2014) from the presence of features such as mineral springs, sinkholes and tufa/travertine deposits, which are indicators of leakage of fluids along active fault.

The post-40 ka vertical motion along faults with NW-SE and E-W trends that we have identified at the boundaries of the inner sector of Sarno Plain are consistent with findings by Irollo et al. (2005) of Holocene vertical displacements along the western strands of the fault system at the southern boundary of the Sarno Plain. Overall information suggests that the inferred fault strands F2, F3 and F4 may be considered as active faults. In addition, the values of mean vertical displacement that we have inferred for faults F2, F3 and F4 are comparable with slip rate values of faults that, in the southern Apennines region, show evidence of activity since the Upper Pleistocene (e.g., Cinque et al., 2000, and references therein). Taking into consideration the important implications of our findings on the geological hazard of the densely populated Sarno Plain area, the area that we have investigated appears worthy of further in-depth investigations aimed at constraining the geometry and late activity of the identified faults.

ACKNOWLEDGEMENTS

We wish to thank editor Paolo Mozzi and the two reviewers, Domenico Capolongo and Biagio Giaccio, for thoughtful and constructive criticism, which helped us improving our work.

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Ms. received: May 7, 2019
Final text received: November 3, 2019