Quaternary evolution of the Southern Apennines coastal plains: a review

NICOLETTA SANTANGELO, PAOLA ROMANO[†], ALESSANDRA ASCIONE
and ELDA RUSSO ERMOLLI

Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse–Università di Napoli Federico II, Italy;
nicsanta@unina.it, ascione@unina.it, ermolli@unina.it

[†]ad memoriam — *This paper is dedicated to the beloved memory of our friend and collegue Paola Romano who unfortunately left us too early*

Abstract: The Quaternary evolution of the main coastal basins located along the southwestern margin of the Southern Apennines has been reconstructed by integrating the huge amount of existing stratigraphical and geomorphological data. The information produced in the last twenty years has shed new light on the recent (late Middle Pleistocene to Present) history of the Campanian and Sele plains or basins. During the early Quaternary, the analysed coastal basins originated as half-grabens in response to opening processes active since the late Tortonian in the southern Tyrrhenian back-arc basin. In some of these basins (e.g. the Campanian Plain), volcanism has also played an important role. In the inner sectors of the coastal basins, the complex interplay between block faulting, sedimentary inputs and glacioeustatic fluctuations gave rise to relative sea-level change and related coastline migrations, leading to the formation of the present-day coastal plains. In the Sele Plain basin, the construction of the present-day landscape mainly resulted from the substantial ceasing of subsidence in the final part of the Middle Pleistocene. Conversely, a strong contribution to the recent evolution of the Campanian Plain has been provided by abundant volcaniclastic aggradation, able to hinder the effect of the vertical motions that occurred in the last 100 ka.

Keywords: Southern Italy, Campania Plain, Sele Plain, palaeogeography, Pleistocene–Holocene.

Introduction

Coastal plains are the result of the complex interaction between sedimentary inputs, tectonics and eustatism. In Italy, their evolution is also strictly controlled by the geological history of the Alpine–Apennine orogenic system. The coastal plains located along the Adriatic and Ionian seas (eastern flank of the Apennine orogenic system) originated during the end of the Miocene and the beginning of the Pliocene as foredeep basins (Ricci Lucchi 1986; Ciaranfi et al. 1992). During the Quaternary, they evolved under predominantly glacioeustatic and climatic control (Amorosi et al. 1999a,b; Kent et al. 2002; Amorosi et al. 2004). The coastal plains located along the western flank of the chain originated during the Pliocene and the Early Pleistocene (Antonioli et al. 1988; Brancaccio et al. 1991, 1995; Nisi et al. 2003). They represent the inland, sediment filled, portions of large grabens or half-grabens formed in response to back-arc extensional processes, which on a larger scale, led to the opening of the Tyrrhenian basin (Elter et al. 1975; Scandone 1979; Patacca et al. 1990). The sedimentary history of these coastal basins has been characterized by a general tendency to subside, which allowed deposition, during Quaternary times, of thousands of metre-thick sedimentary successions. Depending on the relative intensity of subsidence and sedimentation, as well as on glacioeustatic fluctuations, the coastal plains have repeatedly been invaded or abandoned by the sea. The Tiber and the Campanian plains have also been affected by severe volcanic activity (Ippolito et al. 1973; Locardi et al. 1976; Aprile & Ortolani 1978; Brancaccio et al. 1991, 1995; Milli 1997; Amorosi & Milli 2001; Acocella & Funiciello 2006) that further conditioned their evolution and sedimentary history.

The long-term evolution of the coastal basins located along the Campanian sector of the Southern Apennines, namely the Campanian and Sele plains, is the main focus of this paper. In particular, we provide an accurate revision and critical synthesis of all data published in the last twenty years. The last synthesis on this matter, in fact, goes back to the 1990s (Brancaccio et al. 1991); since then several studies based on various data sets (stratigraphical, structural, volcanological, geophysical) have been carried out. New insights mainly come from detailed stratigraphical data from two chronological intervals, the Middle Pleistocene and the Late Pleistocene–Holocene. In particular, two palaeo-environmental proxies have been analysed and re-interpreted: (1) the distribution of the main geomorphological features, such as marine and fluvial terraces, ancient emerged or submerged coastal morphologies etc.; (2) the distribution, nature and facies of the main marine and continental successions covering this time interval.

Age and facies of the marine sediments allowed the location of submerged and emerged areas to be defined, whereas palaeontological and palynological data were used to give

insights into the evolution of palaeo-environments and climate. Our synthesis allowed new palaeogeographical reconstructions for the Campanian and Sele coastal plains to be produced for the most significant time intervals between 1.8 Ma and 6 ka. In particular, the presented palaeogeographical schemes have been reconstructed on the basis of the spatial distribution of emerged/submerged areas and the main landscape and environmental features for six selected time spans, with a particular focus on tectonically and/or glacioeustatically controlled coastline migrations.

Geological and geomorphological setting

The Southern Apennine is a NE-oriented orogenic belt, which developed from Miocene to Quaternary times as a result of interaction between the Adriatic promontory of the African plate and the Sardinia–Corsica block of the European plate (e.g., Channel et al. 1979; Dewey et al. 1989; Mazzoli & Helman 1994; Cello & Mazzoli 1999; Turco et al. 2012 and references therein). Starting from the late Tortonian, thrust sheet emplacement in the Southern Apennines occurred parallel to the extension that led to the opening of the Tyrrhenian back-arc basin, and to the drowning of the innermost portions of the orogenic belt (e.g., Malinverno & Ryan 1986; Patacca et al. 1990; Sartori 1990, 2003 and references therein; Doglioni et al. 2004). Since Early Pleistocene times, active extension caused formation of large, thousands of metre-deep peri-Tyrrhenian basins (e.g., Sartori 1990; Savelli & Schreider 1991), namely — from the N to the S — the Garigliano Plain–Gaeta Gulf, the Campanian Plain, the Sele Plain–Salerno Gulf and the Policastro Gulf. Uplift of the horst blocks separating the basins, coeval to the basin subsidence, is indicated by flights of raised marine terraces (e.g., Caiazzo et al. 2006 and references therein; Fig. 1A).

Large amounts of surface, subsurface and offshore data indicate that the Southern Apennines peri-Tyrrhenian grabens share a common, large-scale structural setting. In fact, they consist in half-grabens bounded towards the NW by roughly NE–SW trending master fault systems. The latter control the asymmetrical — northward thickening — basin fills and lower the carbonate successions, cropping out in the adjacent horst blocks, down to 3000–4000 m depth (e.g., Bartole et al. 1984; Moussat et al. 1986; Mariani & Prato 1988; Argnani et al. 1989; Ascione et al. 1997; Bruno et al. 1998; Florio et al. 1999; Milia et al. 2003; Caiazzo et al. 2006; Milia & Torrente 1999; 2015 and references therein). The largest Southern Apennines peri-Tyrrhenian basin, namely the Campanian Plain, is further dissected by S and SW-dipping fault zones (e.g., Florio 1998; Bruno et al. 2000; Casciello et al. 2006; Milia & Torrente 2013, 2015), which define the boundaries of two distinct sub-basins: the Volturno Plain and the Gulf of Naples (Fig. 1A). In the northern half-grabens, volcanism locally occurred during the Early Pleistocene in the Campanian Plain and, starting from the Middle Pleistocene, intense volcanism affected the Garigliano Plain and various areas of the Campanian Plain

(e.g., Radicati di Brozolo et al. 1988; Brocchini et al. 2001; Rolandi et al. 2003).

The Campanian Plain is a 35 km-wide alluvial-coastal plain with a very flat topography and maximum elevation ranging between 35 and 50 m above sea level (a.s.l.). It is bounded by carbonate ridges and includes, in its central part, the volcanic districts of the Phlegrean Fields and Somma-Vesuvius, which separate the Volturno river plain to the North from the Sarno river plain to the South (Fig. 1A). The geological and geomorphological evolution of the Campanian Plain has been extensively studied by several authors (e.g., D'Erasmo 1931; Ippolito et al. 1973; Aprile & Ortolani 1978; Brancaccio et al. 1991, 1995; Brocchini et al. 2001; Aprile et al. 2004; Putignano et al. 2007). In particular, stratigraphical studies based on interpretation of shallow (≤100 m deep) boreholes have allowed reconstruction of the recent evolution of both the northern (Romano et al. 1994; Barra et al. 1996) and southern sectors (Bellucci 1994, 1998) of the plain.

Surface and subsurface information indicates that extensional tectonics and associated strike-slip motions have affected the Campanian Plain area since the beginning of the Early Pleistocene (Brancaccio et al. 1991; Cinque et al. 1993). Extensional processes caused the subsidence and consequent submersion of large portions of the Campanian Plain, as inferred from the recovery of Early Pleistocene marine sediments on top of Mesozoic or Miocene rocks in deep wells (e.g., Trecase, Castelvolturno, Villa Literno and Cancello wells; Fig. 1B; Ippolito et al. 1973; Bernasconi et al. 1981, Balducci et al. 1983; Brancaccio et al. 1991; Brocchini et al. 2001; ViDEPI 2009). From the Middle Pleistocene, strong subsidence led to the submersion of the entire plain (Brancaccio et al. 1991; Hippolyte et al. 1994) while during the Late Pleistocene, volcanism started intense activity in different source areas of the Campanian Plain. The onset of volcanic activity is recorded at Ischia (Gillot et al. 1982) and the Phlegrean Fields (Rosi & Sbrana 1987) in the first part of the Late Pleistocene, and at Somma-Vesuvius in the later part of the Late Pleistocene (Brocchini et al. 2001; Di Renzo et al. 2007).

The Sele Plain (Fig. 1A) rests on Quaternary sediments that accumulated within a coastal half-graben, which extends in the offshore with the deep Salerno Gulf. The Sele Plain–Salerno Gulf structure is described by Sacchi et al. (1994) for the offshore sector and by Cinque et al. (2009) for the faults running both near the coast and on land. The logs of Mina, Milena, Margherita Mare and Sele (Fig. 1B; Brancaccio et al. 1991; ViDEPI 2009) account for the deep stratigraphy of the basin infill, although the age of its lowest terms and, consequently, the beginning of the collapse are not well defined. However, most authors agree on the assumption that the present-day morphostructural setting is due to Quaternary extensional tectonics. On land, the first phases (1.5 Ma) of collapse generated a high-energy relief, the growth of which is testified by the deposition of epiclastic conglomerates, preserved in both the northeastern horst block (Picentini Mts.) and its piedmont (Capaldi et al. 1988; Cinque et al. 1988, 1991, 2009;
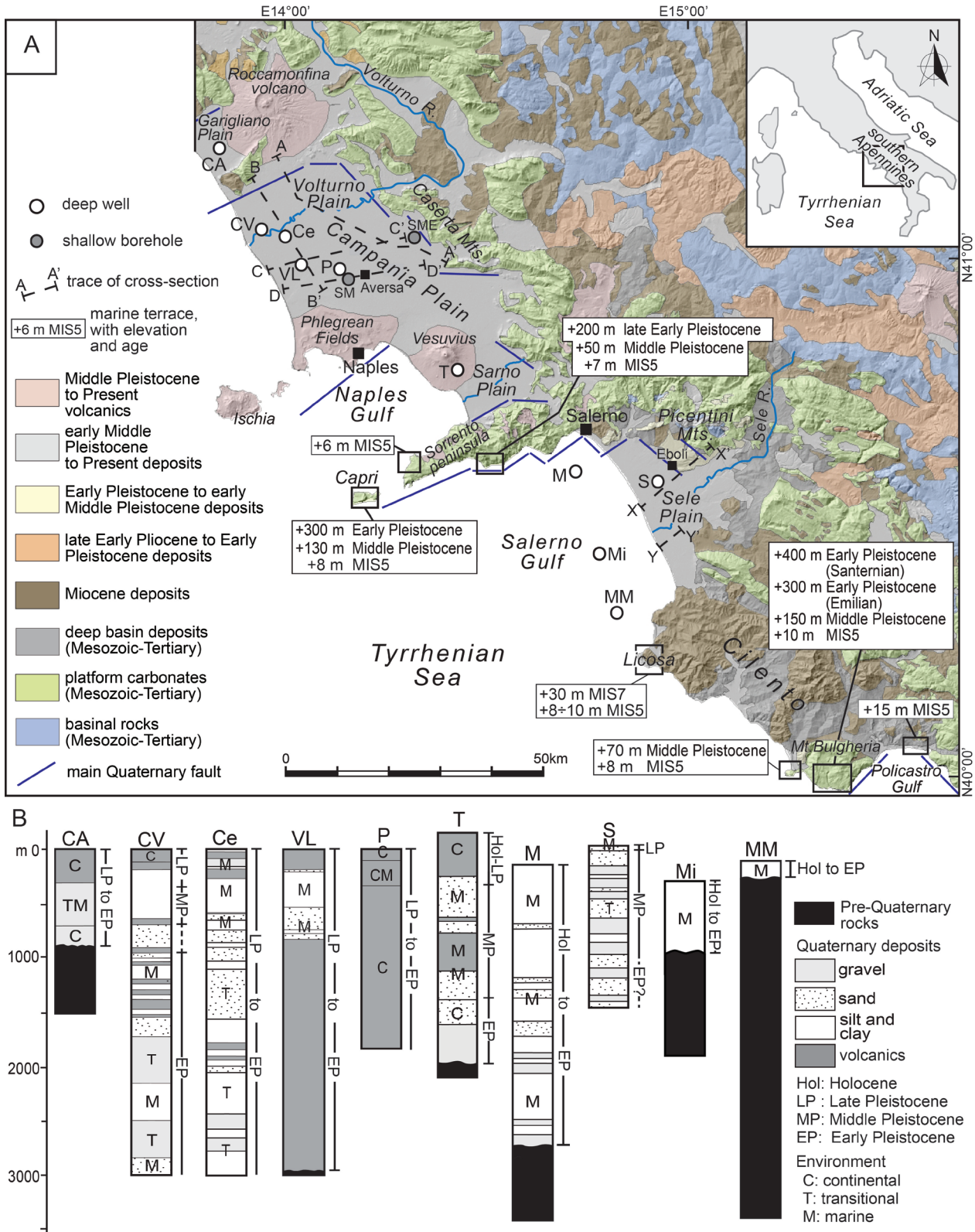
Fig. 1. **A** — Simplified geological map of the northern part of the Southern Apennines Tyrrhenian margin (modified after Ascione et al. 2013), showing the coastal half-grabens analysed in this study and the main Quaternary faults at their boundaries. Location, elevation and age of uplifted marine terraces that occur in the coastal horsts are also reported (data from various authors; see text). Location of deep well logs of frame (B) and of shallow boreholes SM (Fig. 4) and SME (Fig. 5). Traces of cross sections A–A' to D–D' of Fig. 4 and cross sections X–X' and Y–Y' of Fig. 2. **B** — Logs of the main deep wells drilled onshore and offshore in the Campanian and Sele coastal basins. CA: Cellole Aurunci; CV: Castelvolturno; Ce: Cancello; VL: Villa Literno; P: Parete; T: Trecase; M: Mina; Mi: Milena; MM: Margherita mare; S: Sele. Well logs are redrawn and modified after Ippolito et al. (1973), Brancaccio et al. (1991 and references therein), Brocchini et al. (2001) and ViDEPI (2009).

Brancaccio et al. 1987). The thick and widespread deposits forming the foothills of the Picentini massif are mostly composed of fanglomerates with clasts derived from erosion of the Mesozoic limestones and dolostones cropping out in that massif. This Early Pleistocene unit, named Eboli Conglomerates, is strongly deformed and deeply buried in the southwestern part of the plain (Fig. 2A; Cinque et al. 1991; Hippolyte et al. 1995; Hippolyte 2001; Cinque et al. 2009).

Evolution of the Southern Apennines coastal plains in the last 1.80 Ma

Overall surface and subsurface information on the Campanian and Sele coastal basins and on the horst blocks bounding them, allows the most significant stages of the geomorphological and stratigraphical evolution of such basins to be defined. A picture of the main evolutionary stages is provided
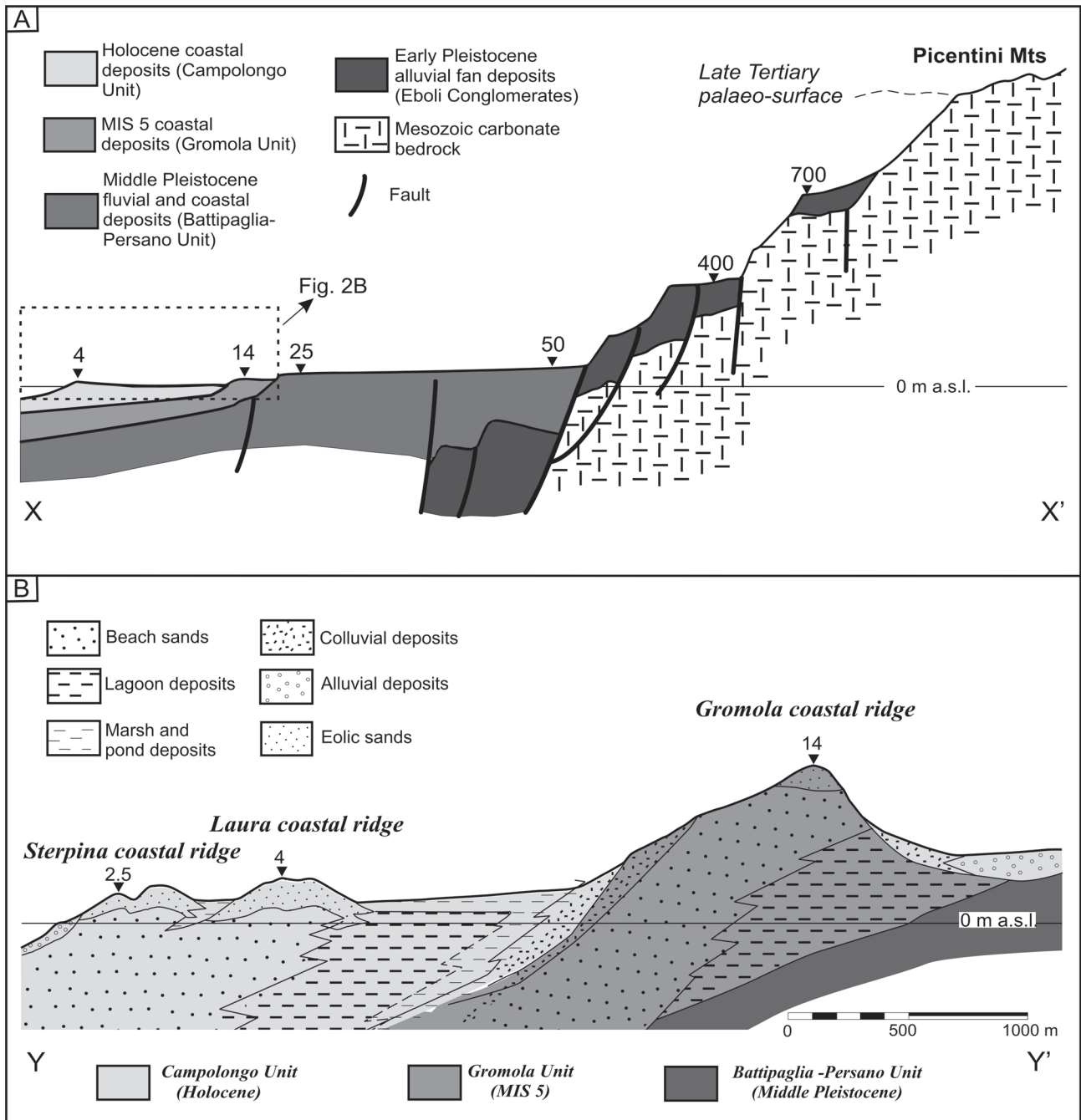

Fig. 2. A — Stratigraphic-structural scheme along the section X–X', showing the relationship among the main sedimentary units of the Sele Plain infilling. **B** — Geological cross-section Y–Y' in the western part of Sele river coastal plain, showing the stratigraphic relationship between the Gromola and Campolongo Units. For location of XX' and YY' see Fig.1. Modified after Cinque et al. (2009).

in the palaeogeographical schemes of Fig. 3, where past positions of the coastline are outlined.

The late Early Pleistocene (Calabrian stage, 1.80–0.78 Ma)

Most of the data covering this time interval are rather scattered and mainly come from the reinterpretation of deep well logs (Fig. 1B; Cellole Aurunci, Castelvolturno, Cancello, Villa Literno, Parete and Trecase in the Campanian Plain; Mina, Milena, Margherita Mare and Sele in the Sele Plain–Salerno Gulf. Ippolito et al. 1973; Brancaccio et al. 1991; Brocchini et al. 2001; ViDEPI 2009) drilled both onshore and offshore during the 70's. The hypothetical morphology of the Tyrrhenian coastline was already characterized by the presence of two gulfs (Fig. 3A), although they were probably less pronounced than at present. In the basins, in fact, the coastline was located westward with respect to its modern position and the promontories separating the basins were wider than at present.

These hypotheses are based on the presence, in the Sele Plain–Salerno Gulf half-graben, of marine sediments, not older than the Gelasian (2.58–1.8 Ma), between 2000 and 990 m depth in the Mina borehole (Cinque et al. 2009). Subsidence of the western portion of this basin was accompanied by deposition in its inner portion, namely at the toes of the Picentini Mts., of the thick epiclastic Eboli Conglomerates, dated from 1.5 to 0.9 Ma (Brancaccio et al. 1987, 1991; Cinque et al. 1988).

The presence of a gulf in the northern part of the Campanian Plain is testified by the marine and transitional (delta facies; ViDEPI 2009) deposits drilled in the Castelvolturno and Cellole wells (Figs. 1B and 3A). Marine silts and clays, not older than the Emilian substage (1.5–1.2 Ma), have been drilled down to 2400 m depth in the Castelvolturno well (Fig. 1B; Brancaccio et al. 1991). In the central part of this coastal basin, continental volcanic deposits (mainly lavas), encountered by the Parete borehole down to 1800 m depth and by the Villa Literno well down to about 2900 m (Fig. 1B), testify to the presence of an ancient volcanic centre, known in the literature as the Parete volcano (Fig. 3A). In the Parete well, the base of the volcanic deposits has a K/Ar age of 1.8 Ma (Di Girolamo et al. 1976).

In the southern part of the Campanian Plain, the thick continental conglomerate deposits found in the Trecase well above the basal dolostones and aged older than 1.24 Ma (Brocchini et al. 2001; Fig. 1B), suggests a strong erosional phase following the first uplift phases which affected the Sorrento ridge horst block during the Early Pleistocene (Caiazzo et al. 2006). According to these authors, the extensional faulting caused a strong vertical fragmentation, which led to the development, along NW–SE to N–S trending faults, of a horst-and-graben structure. Slope and alluvial sediments were then deposited along the main footslopes and in newly created structural basins (i.e. the Agerola basin). The absence of Early Pleistocene marine terraces all along the Sorrento Peninsula (Caiazzo et al. 2006) and the Licosa promontory, in northern Cilento

(Cinque et al. 1994; Iannace et al. 2001; Fig. 1A), suggests that during that time span these headlands were wider and had different shapes. However, the presence of Early Pleistocene marine terraces on Capri island (Fig. 1A; Barattolo et al. 1992) and the flight of Early Pleistocene (Santernian and Emilian substages, 1.8–1.2 Ma) marine terraces in the Mt. Bulgheria area (Fig. 1A; Ascione & Romano 1999), proves that the Tyrrhenian coastline had reached both the western part of the Sorrento–Capri ridge and the southern Cilento in the early part of the Early Pleistocene.

The early Middle Pleistocene (0.78–0.40 Ma)

Following a strong phase of block faulting at the beginning of the Middle Pleistocene, the coastal promontories reached a perimeter quite similar to their present state (Fig. 3B). Raised marine terraces, Middle Pleistocene in age, are noteworthy in the Sorrento Peninsula headland (Cinque & Romano 1990; Caiazzo et al. 2006) and in the southern part of the Cilento promontory (Ascione & Romano 1999).

The marine deposits, found in the Trecase borehole above the conglomerate layers (down to 1490 m depth) and dated 1.24–0.90 Ma through nannofossils (Brocchini et al. 2001), provide evidence for a strong subsidence phase at the beginning of this interval, which caused the flooding of the southern part of the Campanian Plain (Fig. 3B). In the northern part of the plain (Volturno Plain, Castelvolturno well; Brancaccio et al. 1991; Fig. 1A and B) marine sands and clays, drilled between 1000 and 150 m depth, indicate the persistence of a marine environment during the early Middle Pleistocene. Regional stratigraphical data indicate that subsidence also affected the perimeter zone of this basin, as testified by fluvial-lacustrine sequences recovered in the main feeding river valleys (Corniello & Russo 1990; Brancaccio et al. 1995).

In the Sele Plain, block faulting caused the uplift of the inner portion of the graben, as testified by the deformation and relative uplift of the Eboli Conglomerate Unit and the coeval subsidence of blocks to the W and SW of that area (Fig. 2A). At that stage, a pronounced gulf existed (Fig. 3B) in which the deposition of the marine/transitional Battipaglia–Persano Unit occurred (Amato et al. 1991; Cinque et al. 2009; Fig. 2A). These deposits are mainly made up of gravels and clays and reach a minimum thickness of 250 m. Although not directly dated, they can be ascribed to the Middle Pleistocene on the basis of their stratigraphical position. The Battipaglia–Persano Unit, in fact, covers the Eboli Conglomerate Unit (1.5–0.9 Ma) and underlies littoral deposits related to MIS 5.5 (Fig. 2A). The younger part of this succession was investigated in detail with numerous new drillings, palaeo-ecological analyses and correlation with many pre-existing shallow borehole logs (Cinque et al. 2009). It is composed of several coastal parasequences, recording various regressions and transgressions. Based on pollen data and relative chronology criteria, these relative sea-level fluctuations are tentatively framed between MIS 9 and 5.5 (Fig. 2A and B).
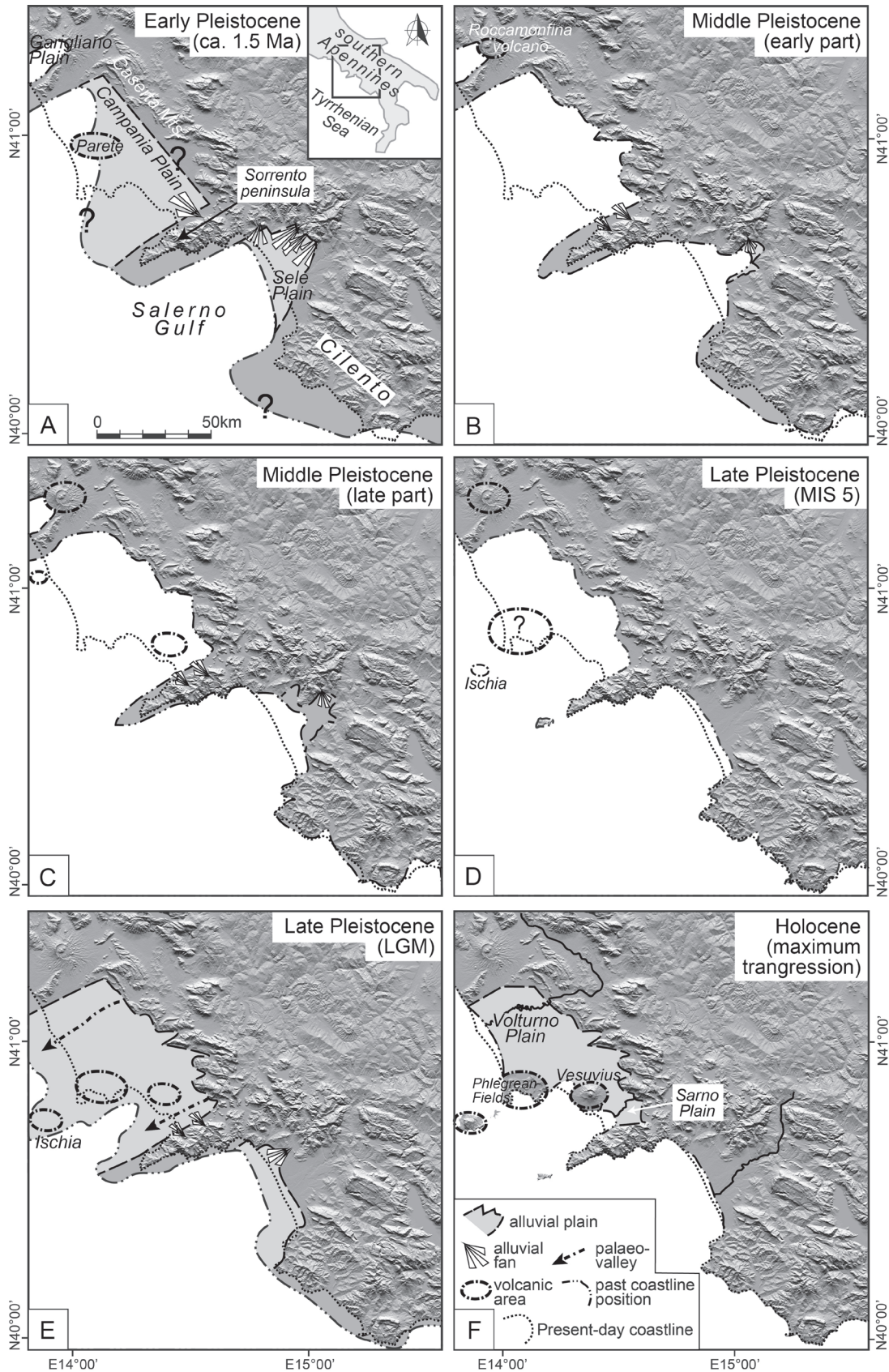
Fig. 3. Schematic palaeogeographic sketches showing the main evolutionary stages of the Campanian and Sele plains during the Quaternary. Position of palaeo-coastlines are based on spatial distribution of continental, marine and transitional deposits inferred from surface stratigraphy, geomorphology, subsurface data from deep wells, shallow boreholes and offshore data.

From the late Middle Pleistocene to the Last Interglacial (0.40–0.10 Ma)

Recent studies provide new data useful to reconstruct the palaeolandscape during this time interval, especially for the Campanian Plain (Fig. 3C and D).

Collection and re-interpretation of data coming from more than 500 shallow boreholes, 30 to 200 m-deep, drilled in the northern part of this coastal depression (Romano et al. 1994), have pointed out the presence of a widespread marine unit (Fig. 4, number 6) in the central and south-eastern sector of the plain (sections A–A', B–B' and C–C' in Fig. 4). Due to the fact
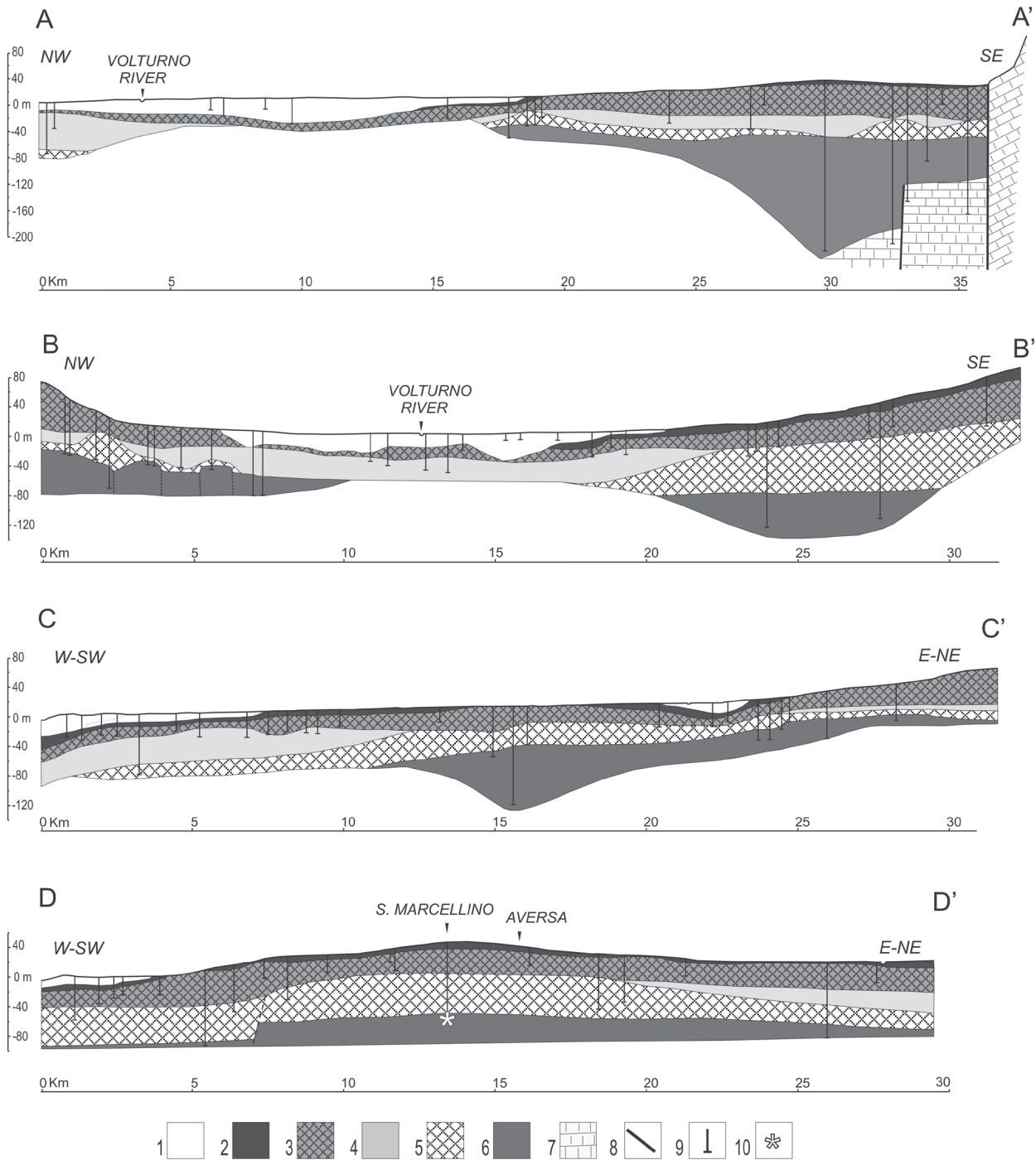

Fig. 4. Geological cross sections of the northern portion of the Campanian Plain. For location see Fig. 1. 1 — Holocene beach sands and lagoon clays; 2 — pyroclastic deposits, locally reworked (Late Pleistocene–Holocene); 3 — Campanian Ignimbrite Formation (CI, 39 ka); 4 — marine sands and lagoon clays (Late Pleistocene, MIS 3); 5 — pyroclastic and lava deposits (Late Pleistocene); 6 — marine sands (late Middle–Late Pleistocene); 7 — Meso–Cenozoic bedrock; 8 — faults; 9 — boreholes; 10 — dated fossiliferous layer (0.126±0.011 Ma). Modified after Romano et al. (1994).

that no borehole has reached the base of this unit, its minimum thickness is estimated to be ca. 50 metres. The lower portion of this unit has been ascribed to the latest Middle Pleistocene–Late Pleistocene based on the $^{230}Th/^{234}U$ age of *Cladocora coespitosa* fragments (0.126±0.011 Ma; Romano et al. 1994) sampled at its top (S. Marcellino borehole, section D–D' in Fig. 4). It is mainly made up of silts and sands with remnants of shells, but the log data do not allow a better definition of the sedimentary environment and, consequently, of the bathymetry. The reconstructed cross sections of Fig. 4 also show that, at the top of these marine sediments, a continental volcanic unit is present (number 5 in Fig. 4). This unit, which is mainly made up of pyroclastic sands and ashes and subordinately of tuffs and lavas, reaches a maximum thickness of about 40 metres in the surroundings of Aversa and San Marcellino (cross section D–D' in Fig. 4), where it also shows a dome-like shape. In this portion of the plain, it is covered by the Campanian Ignimbrite Formation (CI), the most ancient product of the Phlegrean Fields volcanic district, aged 39 ka (number 3 in Fig. 4; for its description see section 3.4). Moving towards both the NW and NE of the Aversa–S. Marcellino area, the two volcanic units are separated by marine sediments mainly made up of sands, silts and clays with fossil remains, which locally include peaty-clay layers of a probable transitional environment. This unit, the top of which is found at depths ranging from –30 to –10 m a.s.l., has tentatively been ascribed to MIS 3.3, on the basis of its stratigraphical position.

An 80-m deep core (SME core, Santangelo et al. 2010; Figs. 1A and 5), drilled near Caserta in the northeastern sector of the Campanian Plain, made it possible to better define the features of the marine and volcanic successions lying below the CI deposits. On the basis of macro- and micro-palaeontological data, palynological and tephrostratigraphical information and direct dating, the authors identified four stratigraphic units, defined their depositional environment and constrained their age (Fig. 5). The lower lagoon environment (Unit 1 in Fig. 5), with its top located at –40 m a.s.l., has been ascribed to MIS 7 thanks to the 142 ka $^{40}Ar/^{39}Ar$ age of a tephra layer sampled two metres above its top. These data indicate that at around 150 ka the coastline was close to the SME borehole site, placing it 28 km inland with respect to its present position (Fig. 3C).

A strong phase of volcaniclastic aggradation (Unit 2 in Fig. 5) occurred in the northern sector of the Campanian Plain from 142 ka to 130 ka, together with the sea level fall related to MIS 6, and produced a temporary emersion of that area. Subsequently, and probably as a consequence of tectonic subsidence, the coastline reached again the SME borehole area
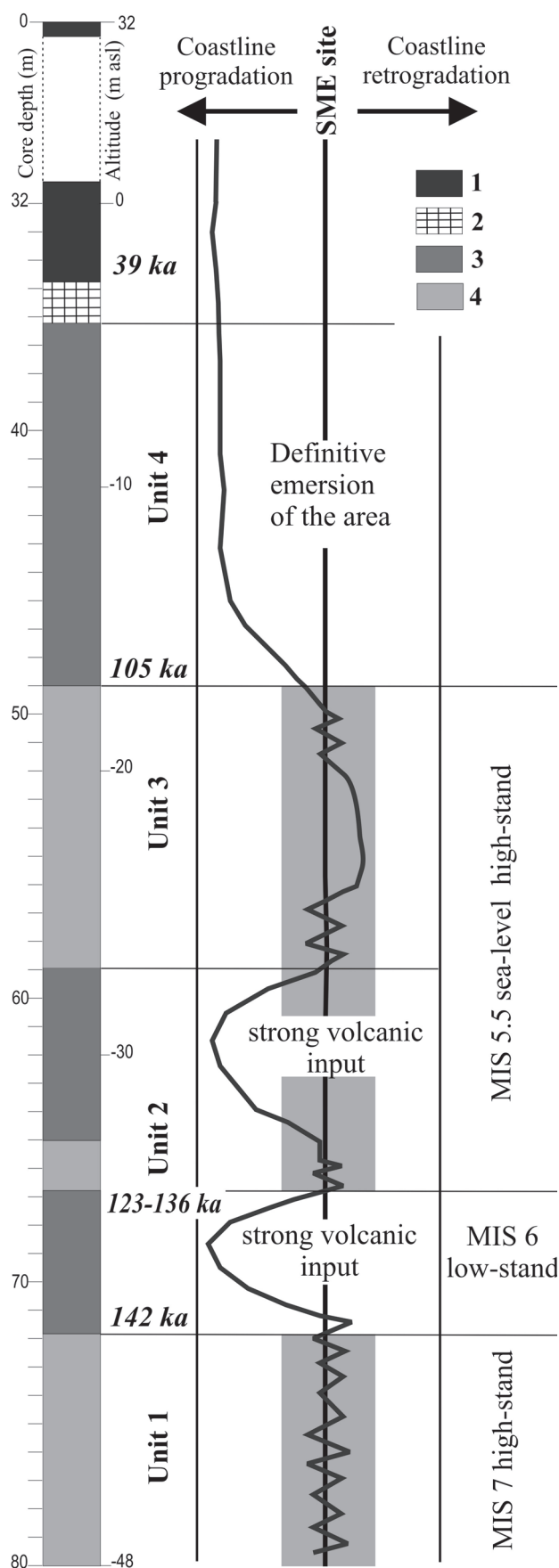

Fig. 5. Inferred coastline fluctuations along the SME record. The grey bars in the coastline progradation/retrogradation plot indicate the periods of sea level high stands. 1 — Campanian Ignimbrite Formation, 39 ka; 2 — palaeosoil; 3 — continental deposits, mainly volcanic in nature; 4 — lagoon and marine (emerged/submerged beach) deposits. Modified after Santangelo et al. (2010).

(see Section 3.3), allowing deposition of lagoon and infra-littoral sediments (Unit 3 in Fig. 5). This unit was constrained to MIS 5.5 thanks to tephrostratigraphic correlation with the X-5 tephra marker layer (Keller et al., 1978), aged 105 ka. This attribution is also supported by pollen analyses, which highlighted in these levels a warm and humid vegetation including *Zelkova*, a tree that disappeared from central Italy during the last glacial period (Follieri et al. 1986). Based on their stratigrahical position, Unit 3 deposits can be correlated to the marine sediments drilled at -80 m a.s.l. in the central part of the plain and dated to 126 ± 11 ka (San Marcellino borehole; Romano et al. 1994).

These new chronological and stratigraphical constraints show that during MIS 7 and MIS 5 the northern Campanian Plain was characterized by the presence of a pronounced gulf with lagoon systems located on its eastern flank (present day Caserta Mts area; Figs. 3C and 3D). This palaeolandscape was affected by two significant volcanic events at 140 and 130 ka that allowed either temporary (SME area) or definitive emersion (Aversa-San Marcellino area) of several sectors of the gulf. In particular, strong volcanic activity at the end of the Middle Pleistocene is testified by the eruptive event recorded by the tephra layer (Sep 8 in Santangelo et al. 2010) with an age, constrained between 156 and 128 ka, that slightly overlaps the age of the Taurano Ignimbrite (157.4 ±1 ka; De Vivo et al. 2001) cropping out on the eastern margin of the Campanian Plain.

Aprile et al. (2004) correlated to the Taurano Ignimbrite the pyroclastic deposits found in the subsurface of the southeastern part of Campanian Plain (present day Sarno Plain) on top of marine sediments. Such sediments (the top of which stands at -35 m a.s.l.; Aprile & Toccaceli 2002) have been related to MIS 7 by Cinque & Irollo (2004) and are very close to the inner boundary of the plain, thus indicating that also the southeastern sector of the Campanian Plain, as the northern one, was entirely submerged in the late part of the Middle Pleistocene. The thick succession of sands, drilled from 700 to 365 m depths in the Trecase borehole (Fig. 1B), should be ascribed to this same time interval (Brocchini et al. 2001). These sands, deposited in a marginal marine environment with a transition to a shore environment, rest on tephritic lavas aged 0.3 ±0.045 Ma, testifying to the presence of effusive centres in the south-central portion of the Campanian Plain between 0.4 and 0.3 Ma.

More recent beach and transitional deposits, occurring in the subsurface of the present-day Sarno Plain, have been correlated by Barra et al. (1991) to the Last Interglacial period. Such deposits (the top of which is found at −23 m a.s.l.), allow the Last Interglacial coastline position to be identified at about 13 kilometres inland with respect to the present-day shoreline (Barra et al. 1991; Cinque 1991).

In the Sele coastal half-graben, the beach and lagoon deposits of the Battipaglia-Persano Unit experienced some uplift (up to about 30 m) at the end of the Middle Pleistocene (Fig. 2A). Both stratigraphical and geomorphological evidence indicates that the western part of the plain was also affected by fault

activity, which resulted in both terracing of deposits of the Battipaglia-Persano Unit, and westward migration of the coastline. At 0.13 Ma (Fig. 3D) the coastline was located about 3.5 kilometres inland with respect to the present one, as testified by the sedimentary succession of the Gromola Unit (Fig. 2A and 2B; Russo et al. 1992; Cinque et al. 2009; Aucelli et al. 2012). This transgression first advanced with transitional (lagoon to palustrine) deposits and then with sandy beaches (Fig. 2B). The back-barrier domains were eventually filled up with marshy and fluvio-palustrine sediments when the sea-rise stopped and aeolian sands were finally accumulated on the coastal ridge. Some isoleucine datings and stratigraphical evidence suggest that the Gromola ridge incorporates two peaks of MIS 5 (5.3 and 5.1).

From the Last Interglacial to the Holocene p.p. (0.10–0.06 Ma)

Data collected in recent decades fundamentally confirm that, in terms of vertical motions, the behaviours of the Campanian and Sele plains during the last 100 ka were different (e.g., Brancaccio et al. 1991 and references therein). A slight uplift of the Sele Plain after the end of the Last Interglacial is inferred from the occurrence of MIS 5.5 back-barrier terraces at 11÷14 m a.s.l., and coeval shoreface and dune sediments up to 13 and 23 m a.s.l., respectively (Fig. 2B; Aucelli et al. 2012). Conversely, the Campanian Plain basin was still undergoing subsidence, the pattern of which is nowadays better defined. In the southeastern part of the Campanian Plain, such subsidence is inferred by the lowering, down to −23 m a.s.l., of the top of the Last Interglacial deposits (Barra et al. 1991; Cinque 1991). In the northern part of the Campanian Plain, the elevation difference between the 126 ka marine deposits drilled in the S. Marcellino area (Romano et al. 1994) and the basically coeval lagoon sediments of Unit 3 of the SME core (Santangelo et al. 2010; Fig. 5), which stand at −80 and −18 m a.s.l. respectively, suggests that different rates of subsidence have affected the eastern and central sectors of this part of the plain since the Last Interglacial. In the SME core, the abrupt transition between Unit 3 and Unit 4, marked by barren pyroclastic deposits (Fig. 5), suggests that a new important eruptive phase supplied the volcaniclastic material, which caused the final emersion of the SME area. The alternation of pyroclastic deposits and palaeo-soils suggests that several eruptions took place in that area from 105 ka to 39 ka, when the catastrophic eruption of the CI occurred.

The Last Glacial regression (60–15 ka) and the CI eruption represent the main events which have affected the palaeolandscape of the study area during the Late Pleistocene (Fig. 3E and F).

The extremely violent explosive CI eruption (Di Girolamo 1968; Di Girolamo et al. 1973, 1984; Barberi et al. 1978; Deino et al. 1994; De Vivo et al. 2001) covered the entire Campanian Plain with the emplacement of pyroclastic flow deposits tens of metres thick. This unit is clearly identified from the onshore stratigraphic record all over the plain (Romano et al. 1994; Aprile et al. 2004; Fig. 4) and in the

offshore area. In the eastern part of the northern Campanian Plain, the CI covers older volcanic deposits (e.g., SME core log; Fig. 5) while towards the coast it rests on marine sands and clays related to MIS 3 (Romano et al. 1994; Fig. 4).

Milia and Torrente (2003) interpreted a thick seismically chaotic unit recognized in the Bay of Naples as the CI. This unit, with a thickness up to 135 metres, is identified in the central part of the continental shelf and its top lies between 150 and 100 m below the sea level. Both at the base and the top, it is bounded by erosional surfaces characterized by incised valleys, indicating a subaerial environment for this eruption (Milia 1998, 2000).

These data indicate that most of the Campanian Plain was located above the sea level at the moment of the CI emplacement. This was possible thanks to the progressive sea level drop during the Last Glacial period (Fig. 3E). Data from several authors indicate that the sea level at 37 ka was about 80 metres lower than at present and reached a minimum of −120 m at about 20 ka (Bintanija et al. 2005; Siddall et al. 2005; Caputo 2007).

According to Romano et al. (1994) and Amorosi et al. (2012), deep valley incision down to 30 metres occurred immediately after the CI deposition in the northern part of the Campanian Plain. This down-cutting phase was likely enhanced by the huge thickness of unconsolidated pyroclastic material emplaced instantaneously in that area. The following, further sea-level fall occurred at the Last Glacial Maximum, and caused additional river downcutting. Comparable evidence is available from the subsurface of the southeastern part of the Campanian Plain, namely in the present-day Gulf of Naples onshore area. In the northern part of this area, valley fill deposits, consisting in alluvial sediments with peat layers, occur on top of the CI (Pescatore et al. 1984; Bellucci 1994, 1998) whereas in the southern part (present-day Sarno Plain), the top surface of the CI is dissected by a valley shaped morphology, the bottom of which stands at around 30 m below the sea level in the Pompeii area (Cinque & Irollo 2004).

Based on new data from recent offshore geological surveys (ISPRA 2015), it was possible to outline the coastline shape during the LGM (Fig. 3E). It was located tens of kilometres westward with respect to the present one, allowing the connection of Ischia and Capri islands to the continent.

Re-emergence of volcanic activity at the present-day Somma-Vesuvius volcano occurred only after the CI eruption (Brocchini et al. 2001; Di Renzo et al. 2007). Magma rose along and at the intersection of linear and curved tectonic and volcano-tectonic elements. It gave rise to a number of small lava and scoria edifices termed "lava ridges", identified on top of the CI by Di Vito et al. (1998). One of these tephritic centres lies above the CI deposits in the subsurface of the area around the Trecase well, as shown by the tephritic lava sequence encountered between 250 and 200 m depth in this well (Fig. 1B; Brocchini et al. 2001). In addition, the chemical composition of the 290–275 m-deep fallout level of the Trecase well is comparable to that of the deposits of the Codola

eruption that is aged 33 ka (Giaccio et al. 2008), and testifies to the onset of the Somma volcano activity.

The progressive growth of the Somma-Vesuvius and Phlegrean Fields volcanic edifices, during the Late Pleistocene-Holocene, caused the final separation of the Campanian Plain into two main zones: the Volturno Plain to the NW and the Sarno Plain to the SW (Fig. 3F). Combined geomorphological and stratigraphical evidence of latest Pleistocene (post-CI) or Holocene faulting at the boundaries of such plains (Cinque et al. 2000; Irollo et al. 2005), indicates that these areas were subject to subsidence until very recent times.

The latest Pleistocene–early Holocene (ca. 15–6 ka) sea level rise promoted the rapid flooding of the lower Volturno Plain, leading to a generalized widening of the shelf. Based on subsurface data, the lower transgressive portion of the latest Pleistocene–early Holocene succession, which reflects the sedimentary evolution of a back-stepping estuary system, is bounded on top by a wave ravinement surface overlain by transgressive barrier sands (Amorosi et al. 2012). Since ca. 6.5 ka, the turnaround from transgressive to 'regressive' (highstand) conditions marked the onset of the present Volturno river delta and the late Holocene progradation of 3–6 kilometres of the adjacent coastal plain (Barra et al. 1996; Amorosi et al. 2013). Deceleration of the post-glacial sea level rise is testified by middle–late Holocene prograding deposits of prodelta and delta front/strandplain facies, capped by modern alluvial, delta plain and coastal plain deposits (Amorosi et al. 2012; Sacchi et al. 2014).

In the Sarno Plain, at the Holocene transgressive maximum, the sea formed a beach ridge (Messigno, 5600 and 4500 yr B.P.) more than 2 kilometres inland from the present-day shore, whereas progradation of the plain, due to high volcanic supply during the following highstand, resulted in a new beach ridge formation (Bottaro-Pioppaino, 3600 yr B.P.), 0.5 kilometres seaward of the Messigno ridge (Barra et al. 1989; Cinque 1991).

The Sele Plain was not directly affected by the devastating CI eruption, with the exception of the Salerno–Fratte and Pontecagnano areas (Pappone et al. 2009). The landscape evolution was mainly dominated by fluvial dissection during the Last Glacial regression. During this period (probably in the late part of it), the deposition of alluvial sediments took place along the lower Tusciano River course. The load carried by the Sele River probably fed the deposition of less inclined valley floor beds, nowadays found under similar Holocene deposits (Budillon et al. 1994).

After the marine regression of MIS 4 and largely before the Holocene optimum, the southernmost part of the plain was affected by deposition of calcareous tufa (Amato et al. 2009; Cinque et al. 2009).

The deposition of the Campolongo Unit (Fig. 2B; Cinque et al. 2009) in the lower Sele Plain dates from the late part of the Post Glacial transgression and the following period of highstand. The early Holocene part of the Campolongo Unit shows a clear transgressive trend, while the late Holocene part has a progradational trend (Fig. 2B). This last transgression was pre-announced by lagoon deposits, basal part of which has

been ^{14}C dated to around 9000 yr B.P. The ingression peak recorded at around 5300 yr B.P. caused the formation of the innermost part of the composite Laura coastal ridge, up to 1.5 kilometres from the present-day coastline (Fig. 2B). The beach deposits, forming the most internal part of the composite Sterpina coastal ridge (generally located at some 250 metres from the modern shore), have ages ranging from the 6th century B.C. to about 2000 years ago (Cinque et al. 2009; Amato et al. 2013).

Conclusion

The present study, by means of an accurate revision and critical synthesis of all data published in the last twenty years, provides a comprehensive framework of the Quaternary geomorphological evolution of the main coastal plains of the Southern Apennines. It focuses, in particular, on tectonically and glacio-eustatically controlled coastline migrations.

During the Early Pleistocene, the studied plains were strongly subsiding and, up to the first part of the Middle Pleistocene, the coastline was located in the innermost part of the basins, at the foot of the main border carbonate massifs. Starting from the late part of the Middle Pleistocene, the tectonic behaviour of the Sele Plain changed to uplift. The shape of the present-day landscape mainly resulted from the substantial ceasing of subsidence in this period. Conversely, the Campanian Plain was affected by significant subsidence all through the Middle and Late Pleistocene and a strong contribution to its recent evolution has been provided by important volcaniclastic aggradation. The subsidence rates were not homogeneous all over the plain, and recent data suggest that, in the last 130 ka, periods of relative tectonic stability alternated with moments of increasing subsidence that occurred mainly after the main volcanic events. Huge explosive events occurred between 150 and 130 ka, strongly influencing the coastline position during MIS 7 and 5, and between 105 and 39 ka. An outstanding phase of volcaniclastic aggradation occurred at about 39 ka, when the tens of metres thick CI pyroclastic flow deposit was emplaced. In response to the dramatic CI eruption, the Campanian Plain was completely emerged and affected by fluvial downcutting, also induced by the sea level lowering of the Last Glacial regression. At this stage, the palaeolandscape was characterized by a coastline located at its most westerly position, never reached during the Pleistocene. During the Holocene, in concomitance with the peak of the post-glacial transgression, lagoon and swamp systems formed in both plains some kilometres inland from the present coastline.

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