The role of the geological model in the analysis of land subsidence: a key lecture from the Volturno River alluvial plain (southern Italy)

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Short Note

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ABSTRACT

The present study focused on the relationships between subsidence and geological and geotechnical features of the Volturno River alluvial and coastal plain (northern Campania, Italy). Subsidence rates were determined through InSAR data analysis. A lithostratigraphic reconstruction was provided for the Holocene succession that overlay a continuous, thick, volcaniclastic unit (Campania Grey Tuff) deposited 39 ka B.P. The digital surface model carried out for this unit showed a palaeovalley morphology, allowing the reconstruction of the palaeodrainage network and a better modeling of the stratigraphic architecture of the post-CGT deposits. The subsidence map was overlain spatially with geological data. In the whole plain, the major ground deformations affect the sedimentary piles filling the palaeovalley engraved in the volcanic compaction-free basement. Inside the general subsidence trend, differential compaction was detected within these deposits corresponding to the occurrence of clay and peat of different thicknesses, suggesting that the subsidence rates are due in part to the primary consolidation and in large part to the secondary consolidation.

KEY-WORDS: Volturno River alluvial-coastal plain, subsidence, lithostratigraphic reconstruction, Holocene, Campania Grey Tuff.

INTRODUCTION

All over the word in the last decades, the river deltas and the relative alluvial plains are sinking, due to two main causes, often working together: i) sea level rise related to the climate change; ii) subsidence, both natural and anthropogenic. The latter phenomenon has many effects both on human life and environment, like the aquifer salinization, inundation of lowlands, coastal erosion and amplified vulnerability to flooding and storm surges. The drivers of the subsidence are many, like the extraction of fluid, tectonics or isostatic adjustment and the chemical-physical changes of the deposits (Herrera-García et al., 2021). While much research in the coastal and delta areas has focused on the anthropogenic drivers of the phenomenon, few investigate the composition of the subsoil, consisting mainly of compressible deposits like sand, clay and peat, that in these environment are usually organic-rich and compact under their own weight (Long et al., 2006; Massey et al., 2006; Meckel et al., 2006, 2007; Shi et al., 2007; Tornqvist et al., 2008; van Asselen, 2011).

The majority of the studies on compaction rates focuses on the first meters of the subsoil, while only in a few analyses it is possible to find data about the whole Holocene sequence (Meckel et al., 2006; Tornqvist et al., 2008; Teatini et al., 2011; Higgins, 2016).

The present study aims to provide a contribution to the understanding of the phenomenon through an insightful lithostratigraphic characterization, assessing the role of the sediments in ground deformation trends recorded for almost two decades (1992-2010) in the alluvial coastal plain of the Volturno River (VR).

The plain is located along the eastern coast of the Tyrrhenian Sea, in the north of Campania region (southern Italy; Fig. 1); it is a small part of the wide tectonic graben of the Campanian Plain, formed during the Quaternary and characterized, since the Late Pleistocene, by an intense volcanic activity that provided the massive deposition of pyroclastic products which contributed to the filling of the graben, together with fluvial and transitional-marine deposits (Santangelo et al., 2017). One of the last explosive eruption of the Campi Flegrei volcanic district, in particular, emplaced the Campania Grey Tuff deposits (CGT; ~39 Ky; De Vivo et al., 2001; Rolandi et al., 2020; Ruberti et al., 2020) that covered the whole plain with a thick, laterally continuous, volcaniclastic unit. These deposits constitute the incompressible substrate of the following Holocene sediments (Putignano et al., 2007; Ruberti et al., 2022).

The CGT upper surface was eroded by the rivers flowing on the plain during the Last Glacial Maximum sea level drop. During the Pleistocene-Early Holocene (ca. 15 ka-6 ka) the post-glacial rising of sea level caused a broadening of the inner shelf with a rapid flooding of the lower part of the VR plain; since 6.5 ka, a coastal progradation phase, established at the termination of the transgressive phase, allowed the formation of the present-day delta system (Ruberti et al., 2018; Budillon et al., 2020).

The recent evolution of the plain has been mostly influenced by anthropic impacts, which began with the Bourbon reclamation of the delta and coastal plain and the canalization of the Clanio River in the present Regi Lagni (Fig.1, Fig. 2a). The transformation of the territory has led to a strong urbanization and to the development of agriculture and animal farming (Vigliotti & Ruberti, 2017); the impact on the river courses leads to a negative sedimentary balance and to an increase in the erosion rates, that coupled with the subsidence phenomenon and the sea level rise, represents a serious hazard, expecially in the coastal zone, as it can lead to an increased vulnerability to flooding and the disappearance of coastal ecosystems (Donadio et al., 2018; Busico et al., 2021).

MATERIALS AND METHODS

More than 1500 shallow borehole stratigraphies (mostly up to 20-30 m in depth) located along the lower VR plain were the base for the Quaternary stratigraphic reconstruction. Since in the present study CGT is considered the non-deformable substrate of the following Holocene sedimentation, these two units were first identified. Among the Holocene sediments, a further classification was made based on the lithology in order to identify the spatial distribution of those deposits that have a direct influence on vertical displacements due to their geotechnical characteristics (i.e. primary and secondary compression).

The geo-database was managed into a GIS environment to develop: i) a surface model of the upper CGT surface; ii) a 3D lithological model of the plain. GIS tools (Surfer®; Global Mapper®) were used to analyze the morphological features of the CGT surface.

The evaluation of the subsidence rates was based on a temporal analysis and mapping of Persistent Scatterers data, obtained from interferometric processing of radar satellites ERS-1/2 and RADARSAT of the study area (Matano et al., 2018). The data obtained were compared with the sedimentary architecture reconstructed for the whole VR lower alluvial plain to figure out significant relationships between subsidence patterns and stratigraphic settings.

RESULTS AND DISCUSSIONS

The analysis of the lithostratigraphies allowed the reconstruction of the upper surface of the CGT. This is characterized by a slight depression along the course of the VR and along the eastern part of the Regi Lagni channel, reaching a depth of 40 m bsl, in the northernmost part of the current course of the VR. The analysis of the digital surface model of CGT highlights a wide valley characterized by an intricate morphology, likely associated with the presence of a complex river network (Fig. 2). The latter, highlights

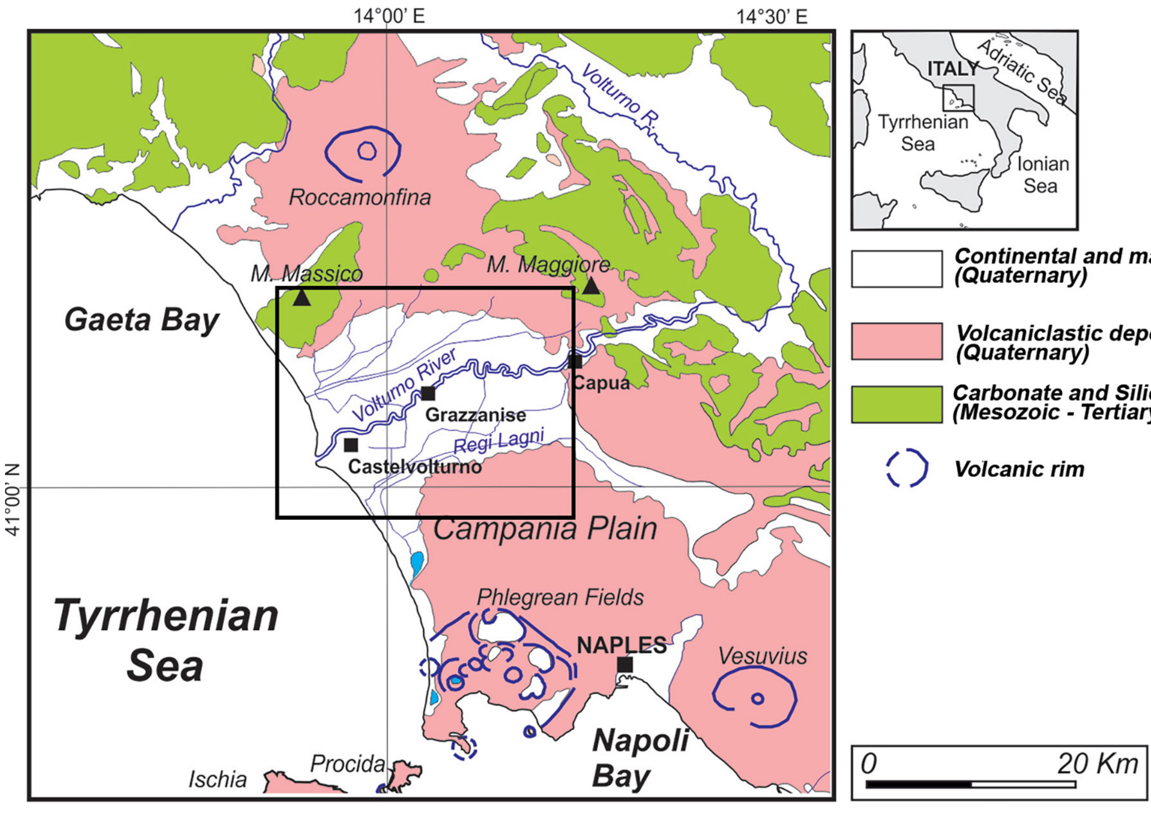

Fig. 1 - Simplified geological map of the northern Campania coastal setting. The black box refers to the study area.

two main downcuttings presumably relative to the modern VR course and the former Clanio River, currently Regi Lagni (Fig. 2a). The position of these courses is very similar to the recent one, especially in the highest part of the plain (Fig. 2b).

The trace of the river courses reconstructed on the basis of the digital surface model of the CGT was superimposed on the map of the stratigraphic boreholes to evaluate any sedimentological evidence of the presence of river activity. We recognized the presence, in the first metres above the CGT, of lithofacies usually considered fluvial-channel deposits (Amorosi, 2006) characterized by pyroclastic gravel-to-poorly sorted sands often reworking tuff pebbles from the substrate Fining upward trends are locally deducible from the descriptions of the borehole lithostratigraphies. Upward and laterally these deposits alternate with grey silt, silty sand and clay in which plant remains are common. Brownish peaty clay and silty clay bearing calcite nodules can be recognized more commonly in the stratigraphically higher levels, although they are not always described in the available lithostratigraphies. It is not possible to identify pedogenic features, but it can be assumed that these latter deposits represent palaeosols and the lithology complex associated with can be referred to an alluvial plain facies association. All the above sedimentary assemblage constitutes aquifers in the plain (Corniello & Ducci, 2014).

These facies pass, towards the current deltaic and coastal plain, to lithofacies rich in clay and silty clay, that are intercalated with peaty organic rich soil, dark grey to black in color; freshwater gastropods are common as well as vegetation remains. These deposits usually represent swamp sequences developed in a coastal plain and occur in a back-stepping stacking toward the inner plain.

Towards the coastal sector and upwards, these lithofacies pass to fine-grained deposits with brackish fossil debris and wood fragments, indicating a thorough lagoonal facies, in which the interaction with the open sea is highlighted by the presence of marine mollusc shells.

The present beach-dune system is characterized by more than 20 m thick yellow, well sorted, fossiliferous sand, documenting the persistence, in this position, of a transgressive-barrier.

The formation of the coastal plain is linked to the maximum ingression (6,5–4,5 ka BP) and late stage progradation (<4,5 ka BP), together with the shifting of the depositional systems towards the sea. This in turn brought about the formation of the modern alluvial plain of the VR, the coastal lagoon and beach barrier system by the rapid filling of the accommodation space above the former incised valley. South of the mouth of the Volturno delta, a lagoon-swamp system was found, thought to have been supplied by the ancient river Clanio, whose outlet is recognizable in the medium-fine sand intercalations in the lagoonal deposits in the subsoil south of the Regi Lagni canal.

Amorosi et al. (2012) and Sacchi et al. (2014) recognized the approximate location of the line of maximum ingression, sketching the shape of the palaeogulf outlined around 6.5-4.5 ka BP, and indicated in the Figure 2a with the yellow dotted line.

The lithological analysis (Fig. 3) led to the recognition, close to the present coastline (section DD'), of thick fine-grained deposits, mostly silty and clay with frequent peaty intercalation; thick sand units occur along the strandplain of the present VR delta. Landwards (section CC') silt and clay prevail with peaty layers resting above the CGT surface. On the whole, the thickness of the sediments resting above the tuff surface decreases inland.

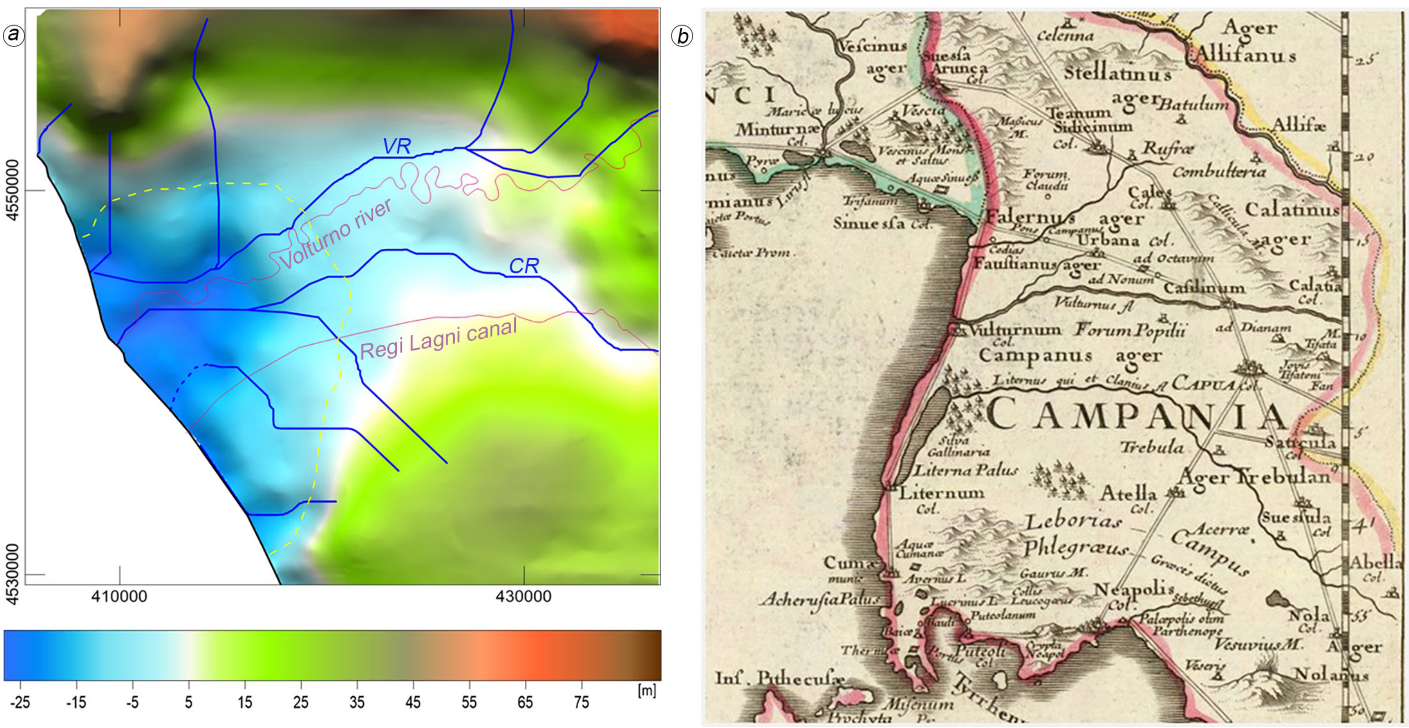

Fig. 2 - a) Digital Surface Model of the upper surface of the CGT. The palaeodrainage network, referred to the maximum sea level drop, is reconstructed on the basis of the palaeomorphology by using Surfer®; Global Mapper®. VR and CR correspond to the inferred palaeo-Volturno and Clanio Rivers respectively. The current VR and Regi Lagni (formerly Clanio River) courses are reported. The dotted yellow line is the inferred coastline at the maximum sea level transgression. See text for further explanation. b) Map by Guillaume de Lisle (1711) - "Regionum Italiae mediarum tabula geographica" - showing the position of the CR before the reclamation interventions. The position of natural courses actually reflects the reconstructed network.

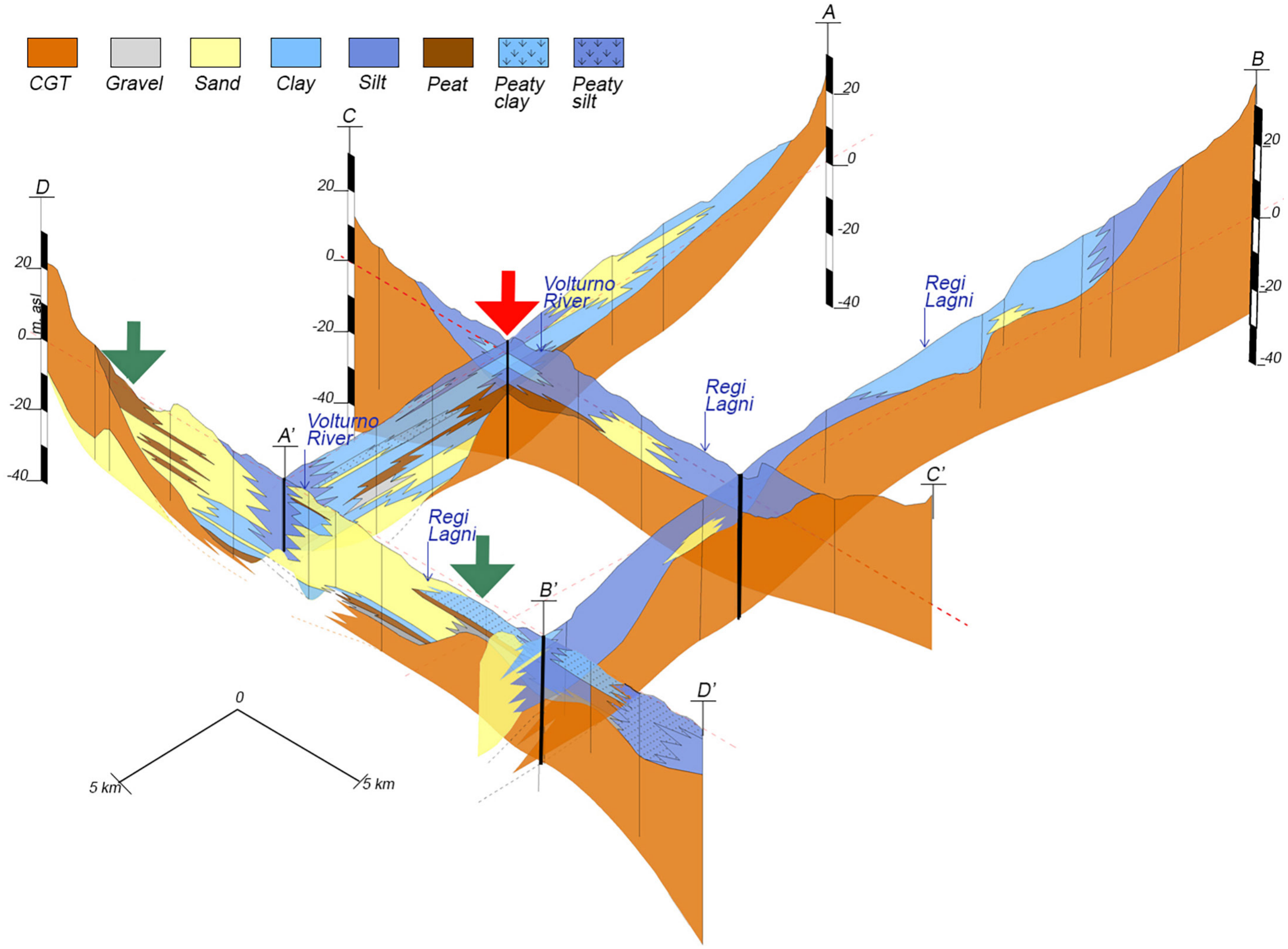

Fig. 3 - Three-dimensional lithostratigraphic restoration of the VR plain showing the along-dip and lateral variability of the recognized lithologies. Red and green arrows indicate the position of the subsidence negative peaks displayed in Figure 4. The track of the sections is reported in Figure 4.

Taking into account the subsidence rates assessed by interferometric data and considering as stable the area with subsidence rates between -1 and +1 mm/yr, a clear correspondence between the major vertical displacements and the area corresponding to the palaeovalley in the tuff is evident (Fig. 4). Mosty of the VR plain is subject to subsidence rates in the order of at least -15 mm/yr, with significant peak of -21 mm/yr, close to Grazzanise (Fig. 1; Fig. 4). In the coastal area the subsidence is moderate (-5 to -15 mm/yr), while elsewhere the subsidence rates fluctuate between -10 to -3 mm/yr.

Overlapping the cumulative subsidence profiles associated with two of the most significant geological cross sections (DD'and AA' in Fig. 4) it is possible to highlight the relationship between the lithological composition of the substrate and the variations of the displacement rates. In the section DD', two peaks are outlined, characterized by average -8 mm/yr vertical displacement. They correspond to peaty layers occurring through the entire stratigraphic sequence. A major displacement (-18 mm/yr) occurs where the post-CGT succession thins, characterized by peat and alternations of silt and clay (cf. section AA'), although the thickness of the peaty soils, like silt and clay, increases landwards.

The examples shown are representative of what has been observed over the whole area considered in the present study. It was also noticed that the variability in the subsidence rates has a close relationship with the presence of considerable thicknesses of compressible layers but not with the extent of the thickness of the whole Holocene sequence (cf. Buffardi et al., 2021), the greatest displacements occurring in sectors with a lower thickness of post-CGT sediments.

It is noteworthy to mention that these type of soils experience different deformations due to two processes: a) primary consolidation process, that derives from change of effective stresses; b) secondary consolidation (or creep) process, that is the continuous soil deformations under constant effective stress.

Lastly, another very important aspect that can be pointed out is the age of the sediments in relation to the subsidence rates. The clayey-peat deposits that characterize the basal intervals of the coastal zone have ages between 10ka and 12ka cal B.P., while those identified in the innermost sections, and stratigraphically higher, have an age of about 6ka cal B.P. (Amorosi et al., 2012).

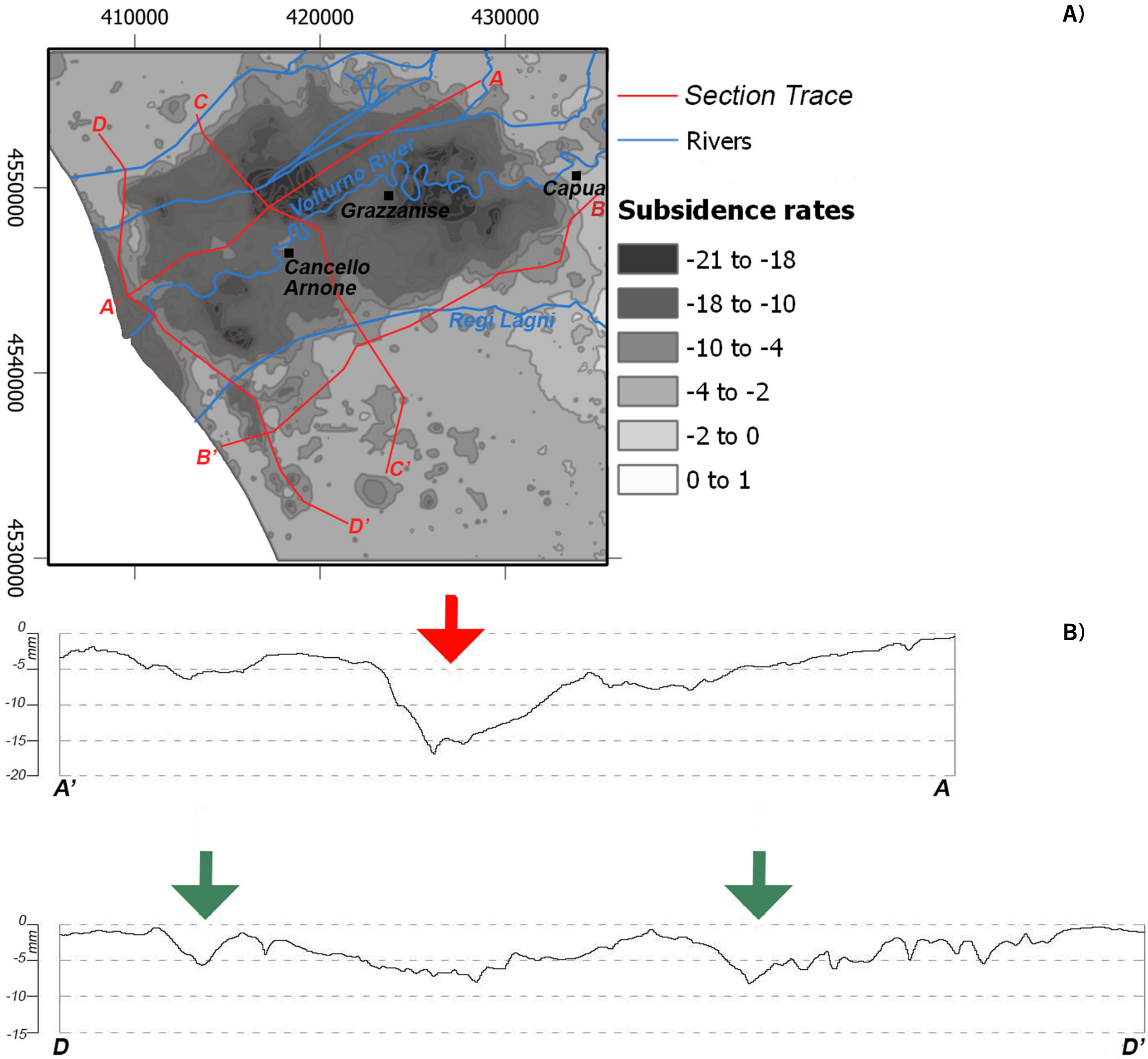

Fig. 4 - A) Cumulative vertical ground displacement estimated during 1992-2010 (based on Matano et al., 2018). B) Subsidence profiles of the sections AA' and DD' are shown as representative of the general trend across the plain. Red and green arrows indicate negative peaks, discussed in the text and displayed on the 3-D lithostratigraphic reconstruction in Figure 3.

SUMMARY AND CONCLUSIONS

The spatial analysis between subsidence and geological and geotechnical features of the VR alluvial and coastal plain highlighted the relationship between major ground deformation and the filling of the incised paleaovalley, corresponding to the Holocene alluvial/transitional deposits that overlies the compaction-free Pleistocene basement characterized by a continuous, thick, volcaniclastic unit (CGT).

Inside this general trend, differential compaction was detected proceeding from the coastal zone towards the interior; the highest land displacement values are recorded in correspondence with high thicknesses of compressible materials, but not necessarily corresponding to highest thicknesses of the whole Holocene deposits. This can be explained as deposits like clay, silt and peat can be classified as fine-grained soils with weak mechanical properties by a geotechnical point of view; moreover, the peaty and organic materials are characterized by high values of the coefficient of secondary compression. The compaction also seems to depend on stratigraphic position (i.e., age and depth) rather than thickness since the consolidation is time-dependent. This suggests that the viscous component of these materials plays an important role in their behavior: the geologically younger soils are still subjected to secondary compaction while the older ones have already undergone much consolidation also because of the lithostatic load. The inclusion of a significant amount of peat and organic matter clearly reflects high values for the coefficient of secondary compression, as documented in several floodplains and deltaic coastal plains around the world. With this respect, a detailed reconstruction of the Holocene sedimentary succession appears to be of paramount relevance to characterize the geomechanical behaviour of each horizon and assess the evolution of the subsidence trend in these complex environmental settings.

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