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MARTA PAPPALARDO [1], ALESSANDRO CHELLI [2*], MONICA BINI [1],
HELMUT BRÜCKNER [3], CATERINA MORIGI [1] & LUCA RAGAINI [1]

ON THE ROLE OF SEDIMENT COMPACTION AND TECTONIC SUBSIDENCE IN RELATIVE SEA-LEVEL RECONSTRUCTIONS – A CASE STUDY FROM THE APUO-VERSILIAN COASTAL PLAIN (NW MEDITERRANEAN)

ABSTRACT: PAPPALARDO M., CHELLI A., BINI M., BRÜCKNER H., MORIGI C. & RAGAINI L., *On the role of sediment compaction and tectonic subsidence in relative sea-level reconstructions – a case study from the Apuo-Versilian coastal plain (NW Mediterranean).* (IT ISSN 0391-9838, 2021).

This paper investigates the impacts of sediment compaction and tectonic subsidence on Mediterranean relative sea-level (RSL) reconstructions, using as a case study a coastal plain in NW Italy (Apuo-Versilian Plain). We coupled sedimentological and detailed micro and macrofaunal analyses on a 9-m-thick sediment sequence in order to produce two relative sea-level index points and two limiting points. The chronology of these sea-level data was based on a set of new radiocarbon dates performed on organic layers found within the sedimentary sequence. The new dataset allowed for better quantify the role of compaction-driven subsidence in the Apuo-Versilian plain providing evidence that its influence may be more pervasive than is commonly appreciated in medium-sized coastal plains dominated by minerogenic sediments. We discuss that the misfit of the RSL data with existing GIA models in these environmental settings should be accounted for considering the possible role of sediment compaction, so that neglecting to correct for this effect in reconstructing past relative sea levels from the sedimentary record may be critical.

KEY WORDS: Relative sea-level change, Vertical land movements, GIA models validation, Minerogenic sediments, Holocene, NW Italy.

[1] *Department of Earth Sciences, University of Pisa, Italy.*
[2] *Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Italy.*
[3] *Institute of Geography, University of Cologne, Germany.*
* *Corresponding author: A. Chelli (alessandro.chelli@unipr.it)*

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RIASSUNTO: PAPPALARDO M., CHELLI A., BINI M., BRÜCKNER H., MORIGI C. & RAGAINI L., *Il ruolo della compattazione dei sedimenti e della subsidenza tettonica nelle ricostruzioni dei livelli relativi del mare – un caso di studio dalla pianura costiera Apuo-Versiliese (Mediterraneo Nordoccidentale).* (IT ISSN 0391-9838, 2021).

Questo lavoro si propone di analizzare l'impatto che la compattazione dei sedimenti e la subsidenza tettonica hanno sulla ricostruzione delle variazioni relative del livello del mare lungo le coste del Mediterraneo, attraverso il caso di studio della Pianura Apuo-Versiliese (Italia Nord-occidentale). L'analisi sedimentologica e micro-macro-faunistica di una sequenza sedimentaria di 9 m di spessore ha consentito di porre quattro specifici vincoli altimetrici ai paleo-livelli del mare in un intervallo cronologico ben definito attraverso la datazione ^{14}C di livelli organici presenti nella sequenza. I dati ottenuti consentono di stimare l'entità della subsidenza dovuta alla compattazione dei sedimenti nell'area di studio, dimostrando che il suo ruolo può essere più importante di quanto sinora comunemente creduto nelle pianure minori caratterizzate da sedimenti in prevalenza minerogenici. Si argomenta infine l'ipotesi che in questi contesti sedimentari le discrepanze tra le variazioni relative del livello del mare testimoniate dagli indicatori e quelle previste dai modelli possa dipendere in larga parte dal fatto che la compattazione dei sedimenti è spesso stata considerata trascurabile e quindi le quote dei paleo-livelli relativi del mare non sono state corrette per questo effetto.

TERMINI CHIAVE: Variazioni relative del livello del mare, Movimenti verticali del terreno, Validazione dei modelli glacio-idro isostatici, Sedimenti minerogenici, Olocene, Italia Nordoccidentale.

INTRODUCTION

Holocene Relative Sea Level (RSL) records are often compared with geophysical models of glacial isostatic adjustment (GIA) in order to unravel the signal of ongoing vertical land movement (VLM, Engelhart & *alii*, 2009). The effect of VLM should, therefore, be disentangled and reliably quantified before cross-checking relative sea-level index points (SLIs, i.e. a point constraining the past sea levels in time and space, Hijma & *alii*, 2015) with geophysical predictions of sea-level change. Negative VLMs, generally known as subsidence, may be triggered by different factors causing sudden or gradual sinking of the ground, such as vertical displacement of the bedrock due to tectonic movements, bedrock dissolution, natural or anthropogenic water/gas/oil removal or sediment compaction due to sediment loading (Carminati & *alii*, 2003; Cenni & *alii*, 2013; Zhu & *alii*, 2015). The role of sediment compaction in RSL reconstructions has been widely investigated (Törnqvist & *alii*, 2008; Horton and Shennan, 2009; Brain, 2016 among others). Procedures for correcting SLIs in order to emend them from the effect of sediment compaction have been developed (Törnqvist & *alii*, 2006) and applied usually to peat-rich sediments (Long & *alii*, 2006; Van Asselen, 2011; Horton & *alii*, 2013).

Less frequently compaction has been considered in RSL reconstructions employing minerogenic sediments from coastal plains (Marra & *alii*, 2013; Chelli & *alii*, 2017; Johnson & *alii*, 2018; Bungenstock and Weerts, 2012; Scheder & *alii*, 2018, 2019), notably in the Mediterranean. For this reason, there is a need to investigate if in minerogenic sedimentary sequences typical of medium-sized (ca. 500- 1000 km²), Mediterranean coastal plains, neglecting to correct index points elevation for the effect of sediment compaction may be irrelevant and confidently overcome e.g. assigning to index points elevation an error bar, or if, conversely, it may have influenced the calibration of the GIA models in the area, impacting on our understanding of the relationship between ice sheets melting and relative sea-level changes. In fact, in the early 2000s, a sediment core retrieved Apuo-Versilian plain (NW Italy, western Mediterranean) and known as ENEA borehole, (Antonioli & *alii*, 1999) was considered a benchmark for validating a GIA model (Lambeck & *alii*, 2004) that has been extensively employed as a reference for the Italian coast (Lambeck & *alii*, 2011). This model underestimates past sea-level elevation in a number of case-studies (e.g. Valenzano & *alii*, 2018; D'Orefice & *alii*, 2020; Vacchi & *alii*, 2020).

New data from Apuo-Versilian plain collected in the last decades (Bini & *alii*, 2006; 2009; 2012) and especially Chelli & *alii* (2017) addressed the importance of sediment compaction in Holocene RSL change reconstruction in this part of the NW Mediterranean.

In this work, two sediment cores were studied with a multiproxy approach in order to produce a new suite of sea-level data. The aims of this study are: i) improve the RSL record for the Apuo-Versilian Plain region; ii) quantify the role of compaction-driven subsidence in the newly produced RSL record; and finally iii) tackle the issue of discrepancy between GIA models available for this area.

We considered this case study suitable to address these subjects because: i) the sedimentary record investigated in this work was accumulated during the last 2 kyr, when predictions from the two models available for this area (K 33 and ICE-5G,) display a remarkable mismatch; ii) the ENEA borehole, that was used to validate one of the aforementioned models, was drilled in the same physiographic unit, although 50 km apart.

More generally, the purpose of this work is to highlight the role of sediment compaction in determining the entity of the relative sea-level change signal in similar geological contexts to the presented area.

STUDY AREA

The study area (fig. 1) is at the northernmost edge of the wide coastal plain known as Apuo-Versilian Plain (Bini & *alii*, 2012; Baroni & *alii*, 2015), stretching along the foothills of the Apuan Alps; the uppermost part of its sediment pile was built throughout the Holocene. The geological model for this area accounts for a long lasting aggradation due to an extensional tectonic regime, affecting both the continental shelf and the major fluvial system of the northernmost Apuo-Versilian Plain (the so-called Magra Plain), i.e., the Magra drainage basin (Molli, 2008; Bartolini, 2003). Vertical land movement in the Apuo-Versilian Plain is considered negligible during the Holocene (Lambeck & *alii*, 2004; 2011; Vacchi & *alii*, 2016). For the Magra Plain a tectonic subsidence rate of 0.5 mm/yr since the mid-Holocene was calculated by Chelli & *alii* (2017). The coastal plain has been extensively explored as a bio-sedimentary archive concerning the spatio-temporal evolution of the area (Delano Smith, 1986; Fazzini and Maffei, 2000; Bini & *alii*, 2006, 2013); especially the palaeogeographic scenario during the Roman period was reconstructed in detail (Bini & *alii*, 2012). Sedimentological evidence from drilled cores, complemented by microfaunal and geochemical analyses and chronologically constrained by radiocarbon age estimates, provides insight into the environmental evolution of the area since the Mid-Holocene (Bini & *alii*, 2009; 2012; Pappalardo & *alii*, 2015; Chelli & *alii*, 2017). The maximum Holocene flooding occurred in the area around 6.5 ka BP, when the sea was lapping onto the foothills of the Apuan Alps. Subsequently a spatially discontinuous coastal plain developed in connection with the major river and stream mouths. Particularly, in the northern edge of the area, the Magra River formed at its mouth a delta that incorporated beach barriers/spits, behind which small lagoons developed. These gradually evolved into swamps and finally into a floodplain that was recently drained through anthropogenic reclamation. The Magra delta-front area was sediment-depleted during the last 150 yr, following the exploitation of bedload materials for extensive quarrying that took place in the second half of the 20th century, thus experiencing a landward shift in the coastline of up to 800 m, being reshaped into an estuarine state (Bisson and Bini, 2011; Pratellesi & *alii*, 2018). The sediment sequence analysed in this research is located within the residual part of the delta, not far from the present-day position of the river mouth (fig. 1). Other sequences within the study area described in previously published papers (Bini & *alii*, 2012; Pappalardo & *alii*, 2015; Chelli & *alii*, 2017) were drilled in brackish wetlands and their sedimentary features are rather different from those described in this work.

METHODS

A sedimentary sequence of 9 m was studied based on two reference cores, LUNI_6 and LUNI_6A, one hundred metres apart (locations noted in fig. 1).

The coring site was located in an area where geomorphological evidence suggested that the Magra River delta was developed in the past. Although not as suitable as more protected sedimentary environments for sea-level recon-

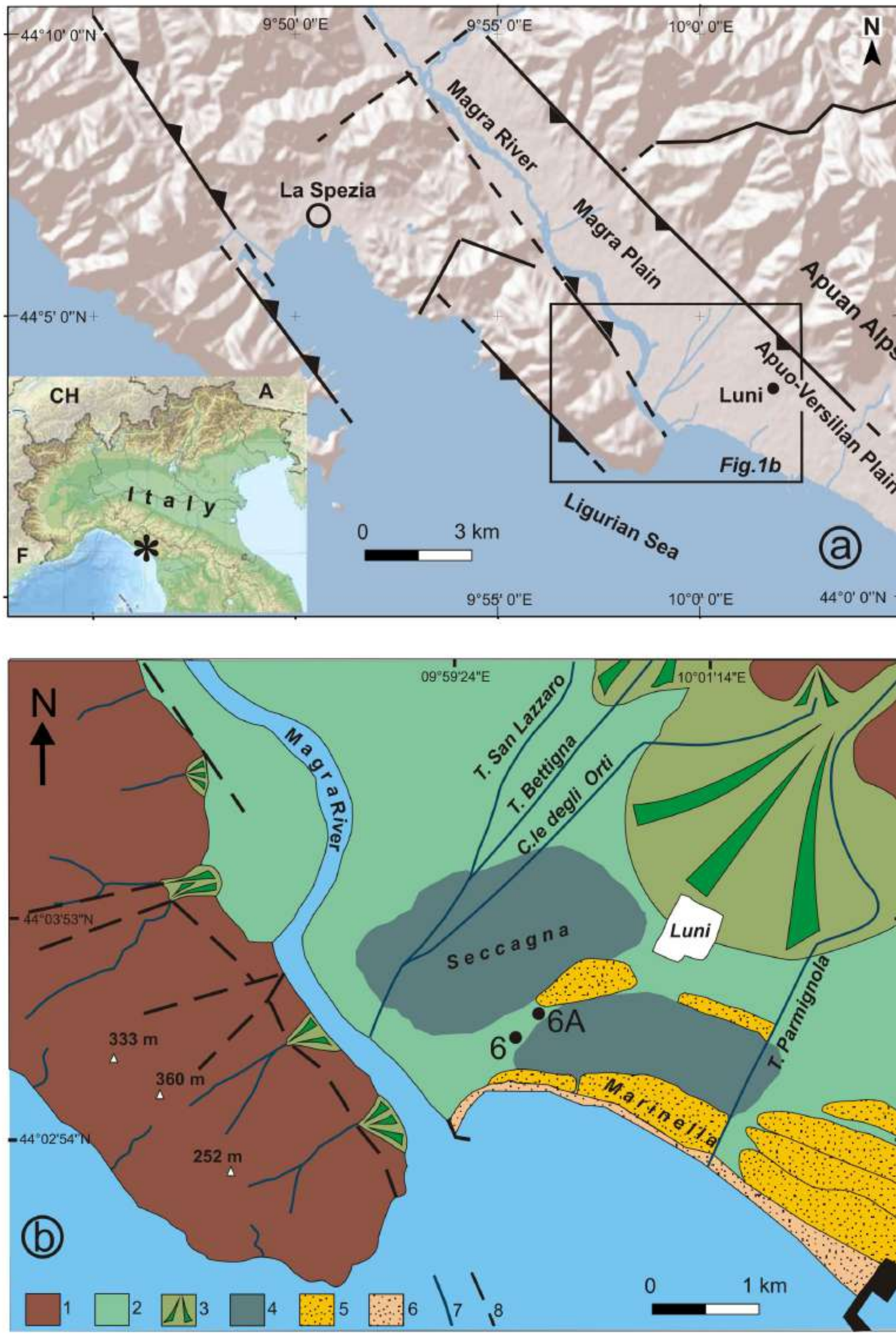

FIG. 1 - (a) Location map of the study area (base map from ESRI 816 ArcMap® database). The main faults are plotted (solid line = certain fault; dotted line = uncertain fault; filled triangles point out the downthrown side of fault). (b) Geomorphological sketch map of the lower Magra Valley. (1) bedrock, (2) alluvial plain, (3) alluvial fan, (4) wetland, (5) beach ridge, (6) present-day beach, (7) main stream and/or channel, (8) fault. The black filled circles indicate the locations of boreholes LUNI_6 and LUNI_6A (modified after Chelli & *alii*, 2017).

structions, this geomorphological setting was selected because similar to others previously investigated in the same area (Antonioli & *alii*, 1999; Aguzzi & *alii*, 2005).

These two cores were selected as very close to one another, and thus strictly representative of the same sedimentary environment. Moreover, they are representative of a short-term sedimentation phase. One of the variables responsible for the rate of sediment compaction is time since deposition, that may vary significantly during long-term sedimentation. A single rate could be applied here owing to the short time since deposition of this sequence. The sequence was investigated through standard sedimentological analyses complemented with reconstruction of micro and macrofaunal assemblages. Core LUNI_6 was drilled to a depth of 13 m b.s. (below surface), whereas LUN_6A was limited to a depth of 9 m b.s.

The cores were retrieved using a continuous augering system through a percussion drilling technique (Atlas Copco, Cobra model, equipped with Eijkelkamp augers; Brückner, 2019). A differential GPS 'Leica GS09' (maximum error in elevation of acquired points ± 3 cm) was used to measure the elevation of ground surface at drilling points that was referenced to the Italian Ordnance Datum. Depths of the dated samples were measured within each 1 m long core segment using a meter stick. For this reason, but also for the possible compaction effect that the drilling technique can induce in the sediment, the degree of confidence was limited to the first decimal figure, being depths expressed in meters. One sample of sediment was taken from each lithological unit. Sedimentary facies determination was based on assessment of sedimentological, physical (electrical conductivity EC, pH), geochemical and palaeontological features. The grain size and distribution of the samples were measured using a laser diffraction particle analyzer (model LS 13320) of Beckman Coulter. The measurement of the pH-value and electrical conductivity were made from the same sample using a digital equipment manufactured by Metrohm. Organic matter content was crudely determined through loss-on-ignition analysis, according to DIN ISO 19684-3. Major elements (K^+, Na^+, Mg^{2+}, Ca^{2+}, $Fe^{2+/3+}$) were measured in the bulk sediment using a Flame Atomic Absorption Spectrometer of the Series ICE 3000 from Thermo Scientific. For geochemical data interpretation, the methodology outlined by Ito (2002) and Uścinowicz & *alii* (2020) was followed; their relative proportions were tentatively used to infer marine versus terrestrial influence. Diagnostic features of each sedimentary facies are reported in table 1. The same samples were also washed over a 125 µm and 1 mm sieve and both fractions were qualitatively examined for macro- and microfossil content (foraminifera, ostracods and molluscs). Foraminifera were identified at genus or species level. For the taxonomy of foraminifera, we followed Morigi & *alii* (2005), Hayward & *alii* (2021) and the website WoMRS (https://www.marinespecies.org/). Ostracods, when present, were reported throughout the cores, but not identified. Scarce mollusc remains were identified throughout the cores. Moreover only few of them, namely from three different layers in core LUNI_6A (fig. 2), could be determined. Owing to this fact, molluscs cannot provide quantitative palaeoenvironmental data based on the abundance/dominance of species. However, some qualitative information was inferred based on their presence.

Chronological constraints were provided through four radiocarbon dates (table 2) performed at CIRCE Laboratory (https://innova.campania.it/). The ^{14}C ages, expressed with a double standard deviation, and calibration details are reported in table 2.

Calculation of RSL was performed based on the standardized methodology currently adopted by the sea-level community (Shennan & *alii*, 2015; Rovere & *alii*, 2016; Vacchi & *alii*, 2016), which transforms qualitative and quantitative field evidence on RSL elevation into a number expressing the displacement of palaeo-sea level relative to present-day local mean sea level. Sedimentological indicators of palaeo-sea level were converted into index points that provide elevation boundaries to relative sea level in a restricted area for a specific time frame. The depth of index points was corrected for tectonic subsidence (Garrett & *alii*, 2015) adopting the vertical land movement value of -0.5 mm/yr independently assessed for the area by Chelli & *alii* (2017) using basal peats from a core nearby the study area.

We further compared the index points with the predictions derived from two geophysical models taking into account the glacial isostatic adjustment (GIA) signal: the GIA model used for the coast of Italy by Lambeck & *alii* (2011), based on the global ice model K33, from which the curve extracted for the Versilia Plain was considered, and the GIA model ICE-5G (VM2; Peltier, 2004; Spada and Stocchi, 2007) run through the SELEN program for solving the sea-level equation (Spada & *alii*, 2012), from which an envelope for the Magra Plain was determined (Chelli & *alii*, 2017). Our data were additionally compared with the statistical RSL curve by Vacchi & *alii* (2021), obtained from selected index points that are unaffected by vertical land movements.

TABLE 1 - Sedimentary environments, with sedimentologic features, micro- and macrofauna and geochemical features (fig. S1) as revealed by the two analysed cores. In brackets: biota exclusive of those parts of the distributary channel sequence in which connection to open sea was reduced.

Sedimentary environment	*Sedimentological features*	*Foraminifera*	*Macrofauna*	*Geochemical fingerprint (fig. S1)*
Open bay	Silty fine sand with shoal ripples; colour from 2.5Y 3/1 to 4/1	*Ammonia beccarii*	Undeterminable gastropods and bivalve fragments	Low C_{org} (generally < 2%); high Ca^{2+} (140-190 mg/l)
Distributary channel (ordinary conditions)	Silty fine to medium sand with interdigitated layers of organic clay; colour from 2.5Y 3/1 to 5/1	Ubiquitous: *Ammonia batava*; scattered: *Ammonia veneta*, *Haynesina depressula*, *Elphidium decipiens*, *Ammonia neobeccarii*	*Valvata piscinalis*, *Ocinebrina aciculata*, *Bittium reticulatum*, *(Cerastoderma glaucum)*	High C_{org} (generally > 3.5% with peaks); medium Ca^{2+} (100 mg/l)
Distributary channel (clastic sediment influx)	Fine to medium sand with rounded pebbles; colour from 2.5Y 4/1 to 5/1	absent	absent	Low C_{org} (< 2.5%); medium to high K^+, Mg^{2+} and $Fe^{2+/3+}$; EC peaks at its lower boundary (> 1500 µS/cm)
Floodplain	Alternating fine and coarse-grained layers; colour 2.5Y 5/2 to 4/3	absent	absent	-

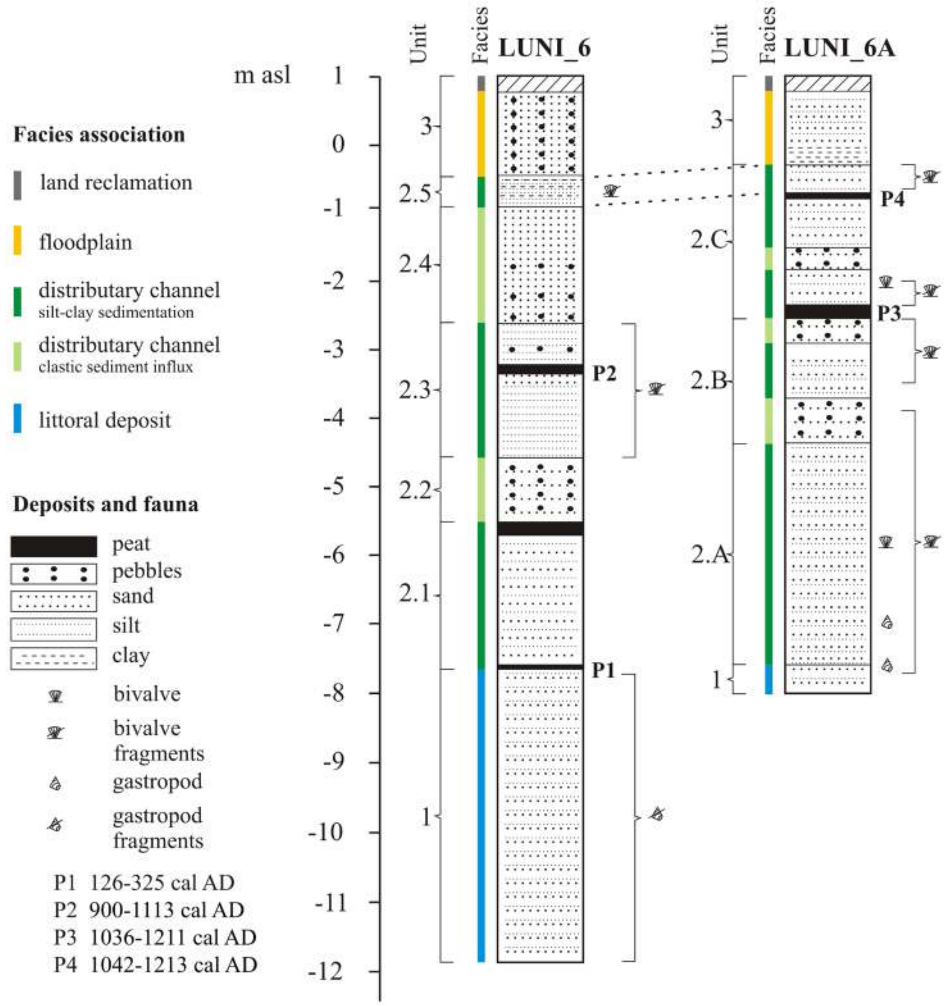

FIG. 2 - Synthetic profiles of cores LUNI_6 and LUNI_6A. Stratigraphic sequences with facies interpretation showing the succession of sedimentary environments, and with position of ^{14}C-dated organic layers.

TABLE 2 - Radiocarbon data sheet. AMS-^{14}C age estimates (2 sigma) from the samples retrieved from the analysed cores. Note that 2 sigma covers 95% of all possible cases. Calibration of conventional ages with Calib Rev8.2, IntCal20.14c (Reimer & *alii* 2020), http://calib.org/calib/calib.html. Lab code; numbers in brackets in the 7th column: relative area under probability distribution. DSH = INNOVA, Laboratorio CIRCE (Center for Isotopic Research on the Cultural and Environmental heritage; https://innova.campania.it/index.php/circe_services/); med. prob. = median probability; bsl = below present mean sea level.

Sample code	*Lab code*	*Depth (m bsl)*	*Conv. Age (a BP)*	*$\delta^{13}C$*	*Calibration with Calib8.2 (2 σ) Intcal20.14c (cal AD)*	*Calibrated age, 2σ (cal AD)*	*Material*
LUN 6A _165-174	DSH9302_PE	0.65-0.75 ± 0.10	910 ± 22	-31 (2)	1042-1087 (0.414) 1091-1107 (0.059) 1116-1213 (0.527) med. prob.: 1121	1042-1213	poorly decomposed plant remains
LUN 6A_340-353	DSH9303_PE	2.4-2.5 ± 0.10	918 ± 32	-39 (2)	1036-1180 (0.912) 1187-1211 (0.088) med. prob.: 1114	1036-1211	poorly decomposed plant remains
LUN 6_16H	DSH3613	3.2-3.4 ± 0.10	1035 ± 27	-18 ± 1‰	900-917 (0.029) 961-963 (0.001) 975-1040 (0.964) 1108-1113 (0.006) med. prob.: 1008	900-1113	decomposed organic matter
LUN 6_36H	DSH3612	7.6-7.7 ± 0.10	1829 ± 34	-34 ± 2‰	126-255 (0.845) 286-325 (0.155) med. prob.: 218	126 – 325	decomposed organic matter

RESULTS

Stratigraphy

Core LUNI_6

Unit 1, the basal part of core LUNI_6 from the depth of 11.9 m bsl up to 7.7 m bsl (fig. 2), represents a littoral environment (table 1). It is characterized by a fining upward sequence changing from silty medium sand over silty fine sand to clayey silt, with colour shifting between dark and very dark grey. The low value of organic C and high value of Ca^{2+} concentration account for a shallow marine environment, with influence due to freshwater from the near terrestrial environment, possibly a prograding delta front, as testified by high values of Fe_{tot} concentration and Fe_{tot}/Na^+ ratio (Supplementary table S1, fig. S1). Presence of shoal ripple features, like between the depths of 9.7-9.5 m bsl, are typical for shallow marine environments fed by littoral drift as well as by nearby sediment influx from continental waters from a river mouth. Very common, although undeterminable, are fragments of macrofaunas.

Unit 2, from 7.7 to 0.5 m bsl, represents the sedimentary stack formed during a phase of delta progradation, with alternating ordinary distributary channel deposits, layers of clastic sedimentation formed by river flood conditions and scattered centimetric organic layers (table 1). This unit is separated from the former by an organic layer, radiocarbon-dated between the first half of the 2nd and the first half of the 4th century AD (126-325 cal AD). This unit can be subdivided into five subunits, separated by unconformable lithological contacts:

2.1 7.7-5.5 m bsl, silty sand with organic matter between 5 and 8.5 %; EC values are moderately high (Supplementary fig. S1). The microfaunal analysis shows brackish species of the *Ammonia* genus from 7.6 m bsl. Globally these features are consistent with a distributary channel environment (table 1). This subunit ends with a 20 cm thick organic layer, testifying a phase of temporary deactivation of the channel.

2.2 5.5-4.6 m bsl, coarse to medium sand, with angular to subangular pebbles up to 2 cm. C_{org} is at minimum values. The contents of K^+, Na^{2+} and $Fe^{2+/3+}$ reach the highest values, indicating freshwater influence (Supplementary fig. S1). EC peaks at the lower boundary of this unit and then decreases gradually (Supplementary fig. S1), indicating coarser sediments fining upward and thus an energetic environment gradually shifting to calmer conditions. This subunit represents a flood phase.

2.3 4.6-2.6 m bsl, the lower part of this subunit replicates the distributary channel environment encountered below, with some fragments of undeterminable bivalves. Upwards, a centimetric organic layer, overlying a layer of medium sand, occurs at the depth of 3.3 m bsl. A radiocarbon date performed on it provided the age estimate of 900-1040 cal AD. Frequent undeterminable fragments of macrofauna and high Ca^{2+} concentrations both point to saltwater conditions within the channel (Supplementary fig. S1).

2.4 2.6-1 m bsl, is a fining upward sandy deposit with sub-rounded pebbles, with no fauna and no organic matter, typical of a flood energetic environment.

2.5 1-0.50 m bsl represents a distributary channel environment, where clay and organic matter accumulate, the latter reaching the peak value of 9%. Na^+ and Mg^{2+} are at minimum values, indicating a reduced marine influence (Supplementary fig. S1). Many shell fragments of *Cerastoderma glaucum* are included.

Unit 3, 0.50 m bsl to 1 m asl, is a sandy deposit with rounded pebbles, consistent with a stabilized floodplain environment (table 1) topped by a land reclamation layer.

Core LUNI_6A

Unit 1 of LUNI_6A (fig. 2), from 8 to 7.7 m bsl, represents a littoral environment (table 1). It is constituted by a dark grey silty coarse sand, fining upwards to silt deposit, with the occurrence of *Ammonia beccarii* (*A. papillosa* in Morigi & *alii*, 2005), typical of a shallow marine environment, characteristic of sandy substrate and strong hydrodynamic energy (Morigi & *alii* 2005), and undeterminable gastropods and bivalve fragments. The hydrodynamic regime is moderately energetic, as testified by the simultaneous presence of shell fragments and plant remains.

Unit 2, from 7.7 to 0.4 m bsl, is a thick delta sequence (table 1) separated from the former by a sharp boundary. It can be subdivided in three main subunits:

2.A 7.7- 4.5 m bsl, a silty fine-medium sand, dark grey in colour. Diffuse undeterminable shell fragments indicate an environment characterized by moderate energy. One individual of the gastropod *Valvata piscinalis*, retrieved between 7.56 to 7.65 m bsl, could be determined; this freshwater species may tolerate very low salinities and typically inhabits standing and slightly flowing waters (Grigorovich & *alii*, 2005). Foraminifera are represented merely by *Ammonia batava* that have been recorded from intertidal, as well as in open marine water; the simultaneous occurrence of these two biota points to the facies interpretation of a distributary channel. The sample located at ca. 6.90 m (6.87-6.93 m bsl) contained one echinoid spicule, two gastropod species and fragmented remains of venerids. *Ocinebrina aciculata* is a small carnivore protobranch inhabiting the intertidal area at the low water mark (Oehlmann & *alii*, 1996) but it can also be found in the sublittoral zone to a depth of 15 m (Franc, 1952). *Bittium reticulatum* is a micro-algal feeder usually living on a variety of substrates in the intertidal and sublittoral zone, but it shows remarkable adaptation within a large number of marine and estuarine habitats (Fernandez & *alii*, 1988). Most members of the venerid family live in shallow marine and occasionally estuarine habitats (Weber & Zuschin, 2013), but the lacking of a taxonomic identification at genus/species rank owing to the very poor state of shell preservation prevents to obtain more detailed ecological insights. The same sample contains also *Ammonia beccarii* and plant remains, suggesting that fragments of marine biota may have been living in a prtotected environment or transported into the channel by a storm event.

2.B 4.5 - 2.6 m bsl, within a main body of distributary channel sands with rare intertidal to subtidal inner-mid shelf depths (0-100 m) foraminifera (*Ammonia neobeccarii*, *Ammonia veneta*, *Protelphidium anglicum*, *Ammonia batava*, *Elphidium decipiens*, Morigi & *alii*, 2005; Hayward & *alii*, 2021), coarser sand layers are interbedded, void of foraminifera but containing plant remains. The latter were interpreted as derived from clastic sediment influxes, the major ones of which include rounded to flattened pebbles (table 1). Single valves of *Cerastoderma glaucum* were obtained from 2.26-2.30 m bsl. This bivalve is a shallow burrower in soft substrata ranging from muds to coarse sands (Beesley & *alii*, 1998) and usually regarded as a brackish species even if it may tolerate a wide range of salinity from 5 to at least 45 psu, the former value considered as a critical threshold for distribution of lagoonal taxa (Cognetti & Maltagliati, 2000). This subunit is sealed at its top by an organic layer (2.5-2.4 m bsl) radiocarbon dated to 1036-1211 cal AD (2σ).

2.C 2.6 - 0.4 m bsl, silty sands, with variable colour from very dark grey to grey, with bivalve fragments. A single sample at 1.5 m bsl contains one specimen of *Ammonia neobeccarii*, a species typical of a protected brackish environment; this sedimentary environment, similarly to the top part of unit 2 in core LUNI_6, is consistent with a distributary channel. A thin peat level at 0.6-0.7 m bsl yielded a radiocarbon age 1042-1213 cal AD (2σ).

Unit 3, from 0.4 m bsl to 0.7 m asl, represents a floodplain sequence (table 1), which starts with a clay layer and ends, between 0 and 0.7 m asl, with a coarser top part (sandy silt), testifying a likely transition from channel to levee facies, accompanying the migration of the watercourse within this portion of the alluvial plain. The core ends with a deposit (0.7-1 m asl) caused by land reclamation.

The stratigraphy of the sequence is typical of a delta environment; phases of calm stream activity are alternating with others of significant clastic sediment influxes driven by flood phases. Organic matter accumulations formed during temporary channel inactivation or channel avulsion are interbedded within the two cores. Periodic channel avulsion events are likely to justify the differences between the two cores in the stratigraphy of unit 2. A high magnitude flooding phase within the 11^{th} - 13^{th} centuries AD, accumulated 1.7 m of alluvium as revealed by LUNI_6A.

RSL calculations

Two relative sea-level index points (P1 and P3 in fig. 3) and two limiting points (P2 and P4 in fig. 3) were obtained from the dated organic matter layers (1-4 in fig. 2). According to the stratigraphic interpretations, all these organic layers represent a phase of low-energy within a distributary channel of a prograding delta. Their position in the stratigraphic sequence, though (fig. 2) suggests that they are differently related to sea level at the time of deposition.

P1 was formed at the transition between shallow marine and transitional environments, at the front of the prograding lower delta. The most reliable modern analogue available to infer channel depth is provided by the 1882 bathymetric map of the delta system in Pratellesi & *alii* (2018, fig. 3), at the end of the phase of delta progradation. The sea-bottom morphology outlined by this map suggests that the transition between the delta front and the foreshore is constrained within the -6 - -4 m a.s.l., which can be used to assess the indicative meaning for this index point (indicative range = 2 m, reference water level = -5 m, table 3). Considering the resolution of the map and possible vertical datum issues and the measurement errors, consequent paleo RSL uncertainty can be quantified in ± 1 m.

P2 and P3 are products of different phases of sedimentation inside a distributary channel. P2 is enclosed within a sandy unit (2.3, fig. 2), with undeterminable bivalve fragments and brackish foraminifera. Moreover, sample LUN 6-16H (table 2) has a relatively enriched ^{13}C value, suggesting it is associated with a higher marine influence than other dated samples, that have depleted ^{13}C values common to terrestrial C3 plants. Research on benthic faunal assemblage at the Magra River mouth (Morri & *alii*, 1990), account for water stratification affecting lowermost river channel, so that saltwater can be found at the channel bottom up to 4 km inside from the mouth. In this framework P2 was interpreted as deposited at the bottom of a distributary channel but cautiously considered a marine limiting point. Conversely P3 conformably overlays a sandy layer with sub-rounded pebbles, no fauna and no organic matter, typical of an energetic flood influx; on top of ordinary sedimentation within a distributary channel conditions are restored. Based on the morphology of the modern river mouth as accounted for in Pratellesi & *alii*, 2018 and Morri & *alii*, 1990, P3 is thus considered as deposited between -3 and 0 m a.s.l., the related index point indicative range was quantified in 3 m and the reference water level stated at -1.5 m, table 3). Considering all the different error sources, paleo RSL uncertainty can be quantified in ± 1.5 m.

P4 was formed within unit 2.C (fig. 2), representing a lower delta plain environment owing to the presence of *Ammonia neobeccarii*, a foraminifera species typical of subtidal to inner-mid shelf depths (0-100 m) (Hayward & *alii*, 2021). Being also very close to the final transition to the bottom of unit 3, testifying the final transition to a floodplain environment, P4 is considered a terrestrial limiting point.

Details about RSL calculation are reported in table 3 and in its extended version (Supplementary table S2).

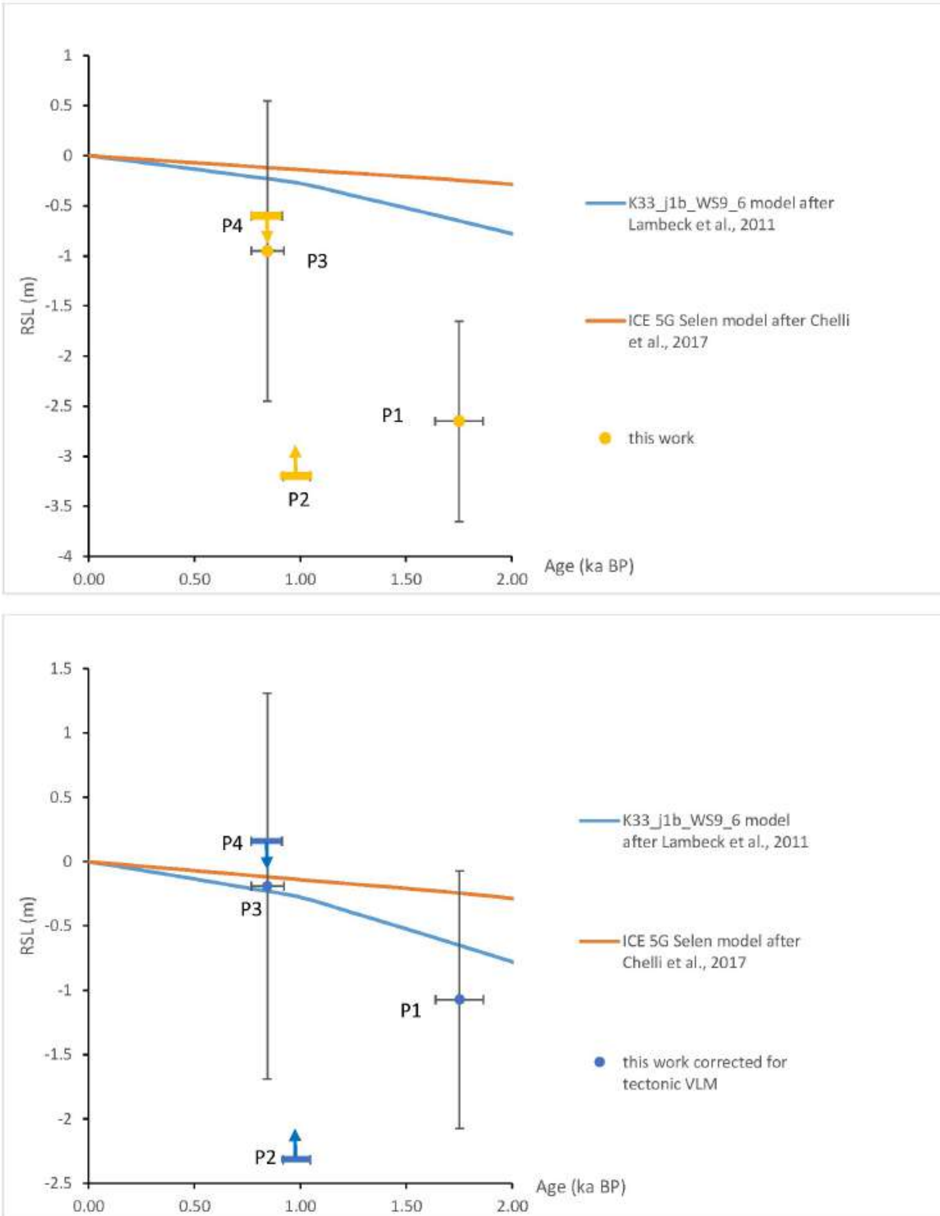

FIG. 3 - (a) Age-elevation plot of relative sea-level (RSL) data obtained from the RSL reconstruction performed in this work for cores LUNI_6 and 6A (see table S2), in comparison with two different glacial isostatic adjustment (GIA) geophysical models available for the study area, and with the empirical spatio-temporal hierarchical RSL model by Vacchi & *alii* (2021) for the Corsica sub-region. Dots represent index points and lines limiting points (pointing up arrow = marine limiting point, pointing down arrow = terrestrial limiting point). Horizontal uncertainties are due to 2 standard deviations of the ^{14}C age estimates; vertical uncertainties are due to the indicative range (see table S2); (b) Same as (a) with data corrected in elevation for the effect of tectonic vertical land movements

DISCUSSION

Role of sediment compaction in study area. The stratigraphy of the top 9 m of the examined sedimentary wedge accounts for a basal shallow marine highstand unit overlapped by a thick delta sequence affected, in the upper half, by coarse horizons due to repeated flood phases. This succession of sedimentary environments and its timing are consistent with the palaeogeographic scenario available for the study area (Bini & *alii*, 2012) and, more in general, for many coastal plains along the coast of Italy facing the Tyrrhenian Sea (Amato & *alii*, 2013; Bellotti & *alii*, 2018; Kaniewsky & *alii*, 2018). The progradation of these plains, in fact, started in the Mid-Holocene soon after the contribution of ice sheets meltout to sea-level rise became negligible. At the northernmost edge of the Apuo-Versilian Plain, the major river mouth of the area (Magra River) started forming a delta system and fed with its sediment discharge a fringe of coastal plain at the foothill of the Apuan Alps (fig. 1), containing brackish lagoons and bays enclosed by sand barriers (Bini & *alii*, 2012). The river delta front reached the position where the LUNI_6 and 6A cores drilling points are located, 3.5 km seaward from the foothills, at the beginning of Common Era (table 2), when modelled sea-level was 0.3-0.8 m below its present elevation (fig. 3).

Relative sea-level obtained for P1 and P3 index points (fig. 3; table 3), was compared to ICE-5G model predictions of glacial isostatic adjustment, which represents the worst-case misfit of our measured data relative to modelled sea-level. The position of P1 is 2.4 ± 1 m lower than the model. The other index point within the delta sequence,

TABLE 3 - RSL calculations based on the four sea-level index points considered (the correspondence between index point and sample code in table 2 is: P1 = LUN 6_36H; P2 = LUN 6_16H; P3 = LUN 6A_340-353; P4 = LUN 6A_165-174).

	Type of RSL Indicator	Calibrated age, 2σ (cal AD)	Upper limit of modern analogue (m asl)	Lower limit of modern analogue (m asl)	Indicator elevation (m asl)	Reference water level (m asl)	Indicative range (m)	Relative palaeo-sea level (m asl)	Relative palaeo-sea level uncertainty (± m)
P4	Poorly decomposed plant remains (lower delta plain)	1042-1213	?	0	-0.7	NA	NA	-0.75 (TLP)	NA
P3	Poorly decomposed plant remains (flood in distributary channel)	1036-1211	0	-3	-2.4	-1.5	3	-0.9	1.5
P2	Decomposed organic matter (flood in distributary channel)	900-1113	0	?	-3.3	NA	NA	-3.2 (MLP)	NA
P1	Decomposed organic matter (between littoral and distributary channel)	126-325	-4	-6	-7.6	-5	2	-2.6	1

(P3, fig. 3) shows a sea-level displacement of 0.9 ± 1.5 m relative to the same model. P4, that was considered a terrestrial limiting point, falls 0.5 m below modelled sea-level (fig. 3), which is inconsistent with its palaeoenvironmental interpretation. The gap between RSL evidence and GIA modelled sea-level change can be assumed as the effect of subsidence due to tectonic vertical land movement (VLM).

In a previous work Chelli & *alii* (2017) inferred for the area a tectonic subsidence of 0.5 mm/yr on average since the Middle Holocene. This value was obtained, thanks to the presence of a basal peat, calculating the amount of compaction experienced by the mostly minerogenic sediments of a silted up swamp (Seccagna, fig. 1) located not far from cores LUNI_6 and LUNI_6A drilling points. In this previous case-study a stratigraphic log from the swamp edge with a dated basal peat sample (Brain, 2015) was available, so that decompaction of sediments within the swamp could be performed. Moreover, decompaction was performed also applying a geotechnical model, obtaining results consistent with the basal peat approach. This estimate is consistent with the geological model accounted for this area, i.e. a subsiding graben bottom (Bernini, 1991), and can be extended to all the northernmost part of the Versilia coastal plain. Chelli & *alii* (2017) paper also states that VLM due to tectonics has varied over time and that for the period from 2500 BP to present the rate has been -0.9 mm/yr.

RSL elevation calculated in this work was thus corrected using this rate of tectonic land subsidence of 0.9 mm/yr (fig. 3b). After the correction the terrestrial limiting point (P4) rests above both GIA curves and the marine limiting point (P2) remains below, consistently with their palaeoenvironmental interpretation. P3 fits with both models, that in very recent times are almost overlapping. Conversely, P1 still remains below both model curves showing a misfit as high as 0.8 ± 1 m (ICE-5G) and 0.5 ± 1 m (K33). The residuals between RSL evidence and GIA modelled sea-level change increase going back in time and become significant at the beginning of the Common Era. This misfit is likely to be provided by a sediment compaction rate on average of 0.5 ± 0.1 mm/yr. Evidence suggests that compaction rate has not been steady during the last 2 ky. In fact P3 and P4, bracket a phase of fast sediment aggradation in LUNI_6A (1.7 m in a few decades), as they are chronologically constrained within a very short time lapse between the 11th and the beginning of the 13th century AD. According to their interpretation in terms of index/limiting points they both indicate the same RSL, underestimating ICE-5G model. After the correction their position is reconciled with their palaeoenvironmental interpretation and fits both modelled RSLs. This fact suggests that the amount of overburden accumulated during this phase of fast aggradation, likely fostered by the Medieval Climate anomaly (Bradley & *alii*, 2003), triggered the compaction of the underlying sediments.

In terrestrial sedimentary bodies, sediment compaction contributes to overall subsidence rates in very variable proportions. In some case-studies compaction was demonstrated to be the primary subsidence cause (Törnqvist & *alii*, 2008; Van Asselen, 2011), in others it is very small or even negligible (Brain & *alii*, 2015, 2017; Kemp & *alii*, 2015; Gerlach & *alii*, 2017). The rates of compaction in Holocene salt marsh sediments estimated from different locations around the world range mainly from 1 to 5 mm/yr (Horton and Shennan, 2009; Tanabe & *alii*, 2010; Marriner & *alii*, 2012; Brain & *alii*, 2017; Nooren & *alii*, 2020). This value is broadly in line with estimates of sediment compaction rate from our case study.

Implications for regional RSL change. Rates and relative importance of sediment compaction are controlled by a number of factors. Virtually only basal samples (i.e. those directly overlying the incompressible substrate) should be employed in relative sea-level reconstructions. Basal index points, though, are normally infrequent relative to intercalated ones so that the latter, if correctly handled, permit to greatly refine RSL reconstructions (Brain & *alii*, 2015). Post-depositional lowering of an intercalated layer depends mostly on sediment type (of the layer itself and of the whole sequence), thickness of the overburden and of underlying sediment (Engelhart and Horton, 2012; Horton & *alii*, 2013), depth of the incompressible bedrock relative to the intercalated layer (Marriner & *alii*, 2012), overall content in organic matter (Törnqvist & *alii*, 2008; Brain & *alii*, 2011; Van Asselen, 2011) and water saturation (Todesco & *alii*, 2014). Thin sedimentary sequences (e.g. 1 m for the last 2 kyrs, Gerlach & *alii*, 2017) are more likely to be unaffected by sediment compaction. Moreover, organic-rich sediments are generally considered more compressible than minerogenic ones (Brain & *alii*, 2015), because of their initial low density and great porosity. This general statement, though, has not a universal value. The role of minerogenic sediments in triggering vertical land movements in transitional sedimentary environments, in fact, has been recognized in several case studies (Brain & *alii*, 2011; Johnson & *alii*, 2018).

In recent databases compilations, where SLIs are inferred from previous publications, the necessity of correction for compaction is generally accounted for. In some cases, particularly when enough sedimentological information is available in original papers, index points are decompacted through an indirect geotechnical approach. For example, Khan & *alii* (2017) used a linear model, conditioned upon basal index points, relating the amount of compaction to overburden thickness whereas Engelhart & *alii* (2015) assessed compaction through an empirical-Bayesian spatiotemporal statistical model.

In Mediterranean case studies sediment compaction in SLIs assessment has been accounted for in some cases (Marra & *alii*, 2013; Chelli & *alii*, 2017; Bruno & *alii*, 2020), whereas in others it was considered negligible or impossible to disentangle from the tectonic component of vertical land movement (Lambeck & *alii*, 2004; Amato & *alii*, 2013; Ferranti & *alii*, 2011; Salomon & *alii*, 2020).

To calibrate their K33 GIA model Lambeck & *alii* (2004) used index points retrieved from the so called "ENEA borehole" drilled south of Massaciuccoli Lake, at the southernmost edge of the Apuo-Versilian plain (Antonioli & *alii*, 1999; Nisi & *alii*, 2003; Carboni & *alii*, 2010). These data are uncorrected for sediment compaction. Actually in the ENEA borehole a 10 m thick sequence of peaty-clay layers alternating with silty and sandy ones, accounts for sedimentation of the last 7 ka; in the core analysed in this work the same thickness of sediments represents the last 2 ka. It is thus reasonable to hypothesize that in the ENEA core sediment compaction effects, at least for the Late Holocene, are negligible or can be compensated through the vertical error bar associated to the point (Vacchi & *alii*, 2016). In order to employ these points for model calibration, though, VLMs driven by tectonic subsidence should be accounted for.

In building the K33 model Lambeck & *alii* (2011), instead, adopted the rheological parameters from Lambeck & *alii* (2004) and, highlighting the optimal fit between RSL and model prediction, state that the Versilia Plain is tectonically stable; this conclusion is consequently drawn through a circular reasoning. As shown in fig. 4, the most recent SLI available from the ENEA borehole (2.2 ka BP old) fits with the model. A 2.8 ka BP old point, instead, underestimates K33 model of ca. 0.9 m. There is no independent evidence that the elevation of these index points should not be affected by some type of VLM (either tectonic subsidence or sediment compaction, or both).

These results are coherent with recent sea level data collected in different portions of the Italian coasts. In fact, a suite of mid to early Holocene sea-level index points found above the K33 predictions were produced in some Italian areas not affected by positive crustal movements such as the Mar Piccolo in Taranto (Ionian Sea, Valenzano & *alii*, 2018), the Burano coastal plain (NE Tyrrhenian Sea, D'Orefice & *alii*, 2020) and in the Bonifacio strait (NW Tyrrhenian Sea, Vacchi & *alii*, 2020). This last dataset fed the empirical spatio-temporal hierarchical RSL model by Vacchi & *alii* (2021) for the Corsica sub-region which was compared to our index points and with the two previously discussed models (fig. 4), supporting the relevance of compaction effects both in the SLIPs produced in this paper and those available from the ENEA borehole.

ICE-5G model (fig. 4), instead, which was created independently from field evidence, overestimates RSL compared to the ENEA borehole SLIs up to over 1.5 m. This offset is to be explained as the effect of VLMs.

We hypothesize, based on our experience in the study area and on the case-study presented in this paper, that the K33 model (Lambeck & *alii*, 2011) may have been biased because it was validated against the ENEA borehole RSL dataset, that was not corrected for sediment compaction and/or tectonic subsidence. Being based mostly on SLIs from intercalated samples (Edwards, 2006) it underestimates not only the elevation of sedimentological indicators, provided they are corrected for the effect of VLMs, but also the ICE-5G model predictions. Far from being resolving, our hypothesis might stimulate further research in order to eventually reconcile the views of scholars that have been proposing two different types of GIA models for the Mediterranean area.

CONCLUSIONS

Through the study of a 9-m-thick sediment sequence of a coastal plain, totally accumulated during the Common Era, and its interpretation in terms of palaeoenvironmental evolution, four sea level index points (SLIs) were retrieved. The residuals between relative sea level (RSL) evidence and GIA modelled sea-level change for the area suggest that there is a misfit between the two that can be explained by the effect of vertical land movements (VLMs), due to both tectonic subsidence and sediment compaction. Based on available rates of tectonic subsidence from previous studies, RSL was corrected for them and the residuals relative to two GIA models available for the area (ICE-5G, Chelli & *alii*, 2017 and K33, Lambeck & *alii*, 2011) were attributed to the effect of sediment compaction, which was quantified as being in the order of magnitude of 0.5 ± 0.1 mm/yr.

We argue that the effect of sediment compaction may be relevant not only in organic-rich sedimentary stacks, but also in those, typical of medium-sized coastal plains (ca. 500-1000 km^2), where minerogenic sediments prevail. The

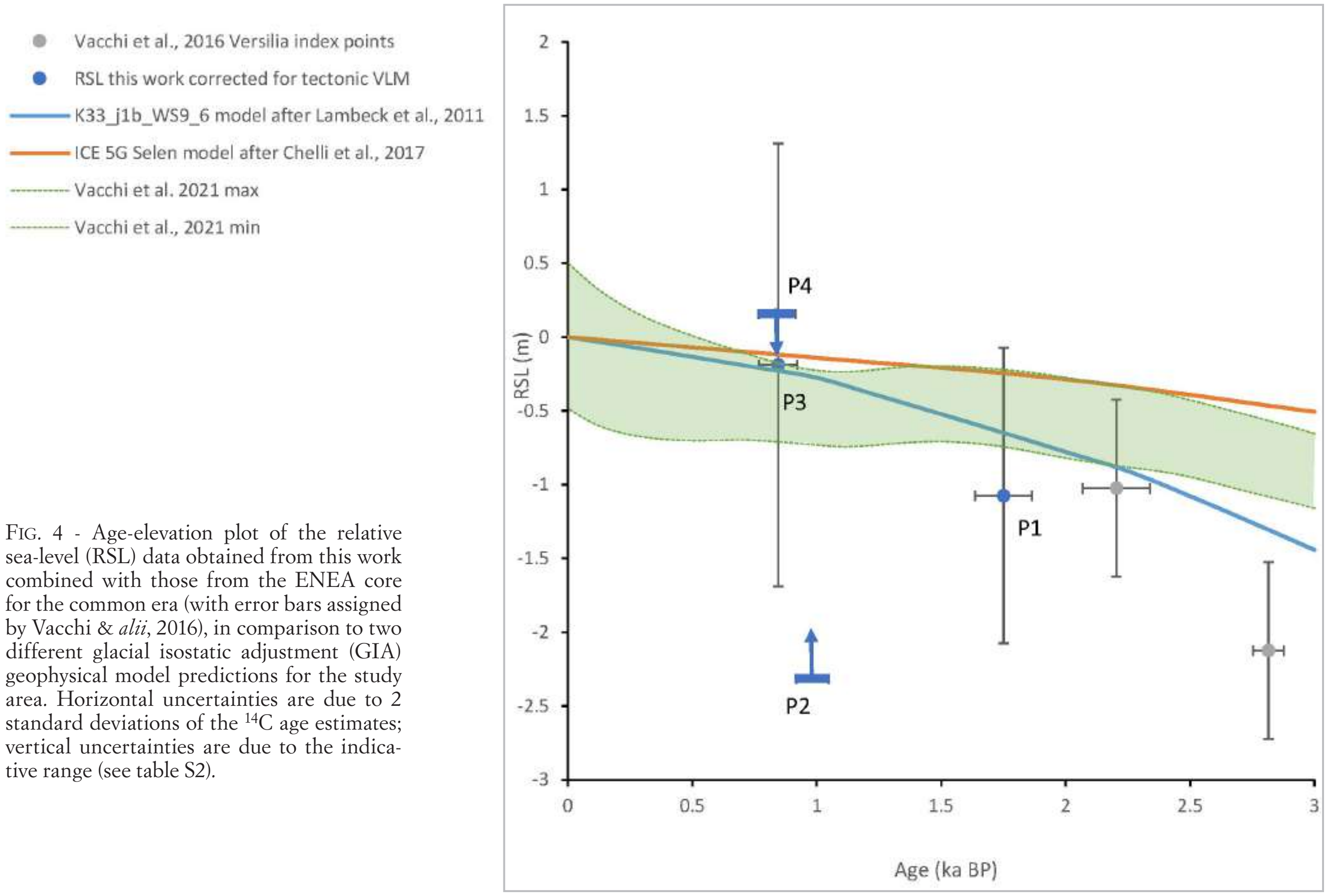

FIG. 4 - Age-elevation plot of the relative sea-level (RSL) data obtained from this work combined with those from the ENEA core for the common era (with error bars assigned by Vacchi & *alii*, 2016), in comparison to two different glacial isostatic adjustment (GIA) geophysical model predictions for the study area. Horizontal uncertainties are due to 2 standard deviations of the ^{14}C age estimates; vertical uncertainties are due to the indicative range (see table S2).

effect of compaction and/or tectonic subsidence may have been underestimated in past relative sea-level reconstructions in the study area, which in turn may have affected the calibration of the K33 GIA model. Our work emphasizes that caution must be used when comparing RSL data from intercalated samples with GIA models, especially when the latter indicate a RSL higher than the evidence from field data.

SUPPLEMENTARY MATERIAL

Supplementary materials associated with this article can be found in the online version, at http://gfdq.glaciologia.it/044_2_04_2021/

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