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GEOGRAPHIC VARIABILITY OF THE MILLENNIAL SEA-LEVEL CHANGES ALONG THE COASTS OF ITALY

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ABSTRACT: The large abundance of geological and archeological evidences of past sea-level stands have made the Italian coasts a major focus for the Mediterranean Sea-level science since the beginning of 20th century. We have populated an open-access database including the postglacial relative sea-level (RSL) data available for the coasts of Italy. The creation of this database, produced following the most recent protocols of sea-level research, also allowed to evaluate the drivers that majorly controlled the variability of the Holocene (last 12 ka BP) sea-level histories along the Italian peninsula. Major subsidence trends (driven by tectonics and sediment compaction) characterize the coastal plains of the north-eastern Adriatic and northern Tuscany. Major uplift trends (often co-seismic) were found in NE Sicily and in the southernmost tip of Calabria. The most complex RSL evolution was observed in the Phlegrean fields volcanic district where, in the same area, we observed the juxtaposition of the highest relict of a mid-Holocene shoreline (more than 34 m above the present sea-level) and evidence of Roman buildings more than 8 m below present sea level.
The comparison of the Italian sea-level with the geophysical models routinely used for the prediction of the RSL position through time yielded contrasting results. In particular, our analysis showed that caution should be used in paleogeographic reconstruction for periods older than 8.0 ka BP and only based on geophysical predictions. In fact, none of the models is able to reconcile the proxy-based RSL evolution in the Early Holocene period. This proposed database is an open repository and future production of new RSL data can be easily stored following the same scheme presented in this work.

Keywords: Relative sea-level, Italian Coast; Holocene, Mediterranean Sea.

1. INTRODUCTION

Located in the middle of the Mediterranean basin, the Italian peninsula and the two major Italian islands (Sardinia and Sicily) constitute articulation points between the northern and the southern sides of the Mediterranean Sea. This geographical setting has resulted in an impressive array of coastal landforms (Soldati & Marchetti, 2017), shaped by both climatic and tectonic processes. Italian coasts have also preserved a wide range of geomorphological and sedimentological proxies of Late Quaternary sea-level fluctuations which have been widely investigated since the late 19th century. In fact, geological sections rich in marine fauna were described along the Italian coasts by Doderlein in 1872, by Gignoux in 1910 and by Issel in 1914 who introduced the Accademia dei Lincei to the term “Tyrrhenian stage” to indicate the period corresponding to the last Interglacial (MIS 5e ~125 ka BP, Cita et al., 2006; Rovere et al., 2016) and characterized by warmer climate and higher sea-level.

At a shorter time scale (last few millennia), sea-level reconstructions carried out along the Italian coasts have often coupled the geosciences with archaeology (i.e. Antonioli et al., 2007; Anzidei et al., 2013; Mattei et al 2020a; Caporizzo et al., 2021; Aucelli et al., 2021). These investigations mainly resulted from the presence of submerged or semi-submerged coastal archaeological structures, which has attracted the attention of generations of sea-level scientists. For instance, pioneer geologists, such as Lyell, recognized the importance of the pillars of the Ancient Roman market of Pozzuoli (Naples) in linking sea-level change and Earth deformation with volcanic activity more than 120 years ago. In more recent times and since the seminal work of Schmiedt (1972), the Italian coasts have been a major scientific hub for investigations based on the use of archaeological evidence of maritime structures, such as ancient harbours or fish tanks, as proxies to measure the sea-level evolution, notably since the Roman times (Caputo & Pieri, 1976; Leoni & Dai Pra, 1997; Lambeck et al., 2004b; Aucelli et al., 2021). Those geoarchaeological data, coupled with more traditional sea-level investigations based on the analysis of cores taken from coastal plains and/or on the analysis of fossil remains of littoral bioconstructions or beachrocks, show that the Italian sea-level record is the richest in the Mediterranean basin, notably for the postglacial period (e.g., last 21 ka BP; Vacchi et al., 2016).

In recent decades, several compilations of Holocene (last ~12.0 ka BP) sea-level data have been produced for Italy (Lambeck et al., 2004a; Lambeck et al., 2011; Antonioli et al., 2009; Vacchi et al., 2016; Mattei et al., 2022). These data have been significantly enriched in the last 5 years thanks to a significant number of cores performed in marginal marine areas (e.g., Valenzano, 2018; Valenzano et al., 2018; Mastronuzzi et al., 2018; D'Orefice et al., 2020) as well as by the mapping and sampling of submerged beachrocks and maritime structures (e.g., Vacchi et al., 2020b; Aucelli et al., 2021; Scardino et al., 2022). These data can be used to produce new suites of sea-level data, improving the spatial and temporal resolutions of the Italian sea-level record.

In this paper, we have compiled, critically analysed and updated a database of the Holocene RSL data available for the Italian coast (Fig. 1) following the international protocol developed in the recent INQUA project HOLSEA (Khan et al., 2019). We populated the database with sea-level data from cores taken from transitional and marine deposits, as well as with sea-level data from beachrocks, fossil remains of intertidal bioconstructions and archaeological indicators. The database includes 570 sea level points that have been populated into a dedicated webGIS where the whole dataset is available in an open-source repository (https://dist.altervista.org/seaproxy/). We compared the reconstructed sea-level records with a number of geophysical glacio- and hydro-isostatic (GIA) models, which are routinely used for the Mediterranean area, in order to assess the predictive performance of the sea-level evolution during the Holocene period.

2. METHODS

2.1. Classification of the sea-level data

Based on the latest protocols for sea-level research (Hijma et al., 2015; Khan et al., 2019) we have reinterpreted previous coastal studies producing the following types of sea-level data:

1) *sea-level index points* (SLIPs) which constrain the past relative sea-level in space and time. To produce a SLIP the following information must be available: (1) the location of the indicator; (2) the age of the indicator; and (3) the elevation of the indicator, corrected for the indicative meaning; (i.e. a known relationship between the indicator and a contemporary tidal level, the Mean Sea Level (MSL) in our database, Shennan et al., 2015). The indicative meaning is composed of the Indicative Range (IR), i.e., the elevation range over which the marker forms and the Reference Water Level (RWL), the mid-point of the above- mentioned range (Shennan et al., 2015). The frame to assess the indicative meaning for the Mediterranean sea-level data was developed by Vacchi et al., (2016) and, since then, has been widely applied in Mediterranean sea-level studies (e.g. Brisset et al., 2018; Karkani et al., 2017; Rached et al., 2022). For each dated sample, SLIPn were produced according to the following equation (Shennan & Horton, 2002):

$$SLIP_n = An - RWL_n$$

where An is the proxy altitude and RWLn is the reference water level of the proxy n.

Most of the SLIPs were already included in the recent databases produced for the western and central Mediterranean area (e.g., Vacchi et al., 2016; 2018, Mattei et al., 2022). They are derived from cores in coastal and alluvial plains, coastal marshes and lagoons. (e.g., Primavera et al., 2011; Fontana et al., 2017, Melis et al., 2017). The indicative meaning of these samples is generally based on biostratigraphy and, in particular, on the macro- and micro-faunal assemblages (i.e., malacofauna, foraminifera and ostracod assemblages, e.g., Rossi et al., 2011; Marriner et al., 2014; Giaime et al., 2017). The detailed description of the indicative meaning associated with the different depositional facies is provided in Vacchi et al. (2016).

Other SLIPs included in the database are beachrocks, fixed biological (mainly vermetids and *Lithophyllum byssoides* rims) and archaeological SLIPs. The latter sea-level data were widely used in the Mediterranean area (e.g., Lambeck et al., 2011; Morhange & Marriner, 2015) but caution should be used in the definition of the related indicative meaning (Vacchi et al., 2016; Benjamin et al., 2017). We only transformed into SLIPs those structures which are related to the former mean sea level (e.g., fish tanks and harbour structures) or when found covered by fossil biological encrustations which clearly define the relationship with the former tidal frame (Vacchi et al., 2020a).

2) *sea-level terrestrial and marine limiting points* (TLP and MLP, respectively) which constrain the past relative sea level above or below a given altitude. All the samples that did not show a clear and robustly established relationship with the former MSL were converted into limiting points (Mattei et al., 2022). However, these data are extremely important in constraining the RSL position below (TLP) or above (MLP) a reconstructed elevation (Mann et al., 2019).

For the Italian coasts, TLP are typically samples deposited in freshwater swamps, backshore deposits, fluvial environments and upper beach deposits. MLP are generally represented from samples deposited in the infralittoral zone, from fossil corals or other infralittoral bioconstructions found in living position or from interlaced roots and rhizomes of the marine seagrass *Posidonia oceanica*. Furthermore, we considered terrestrial limiting points those archaeological indicators that were theoretically above the MSL at the time of their functioning period, such as tombs and burials, floors of maritime villas, coastal quarries (Mattei et al., 2022).

The ages of the geological samples were estimated using radiocarbon (^{14}C) dating of organic material from salt and freshwater marshes as well as marine and lagoonal shells. All radiocarbon ages included in the present database were re-calibrated to provide dates in sidereal years with a 2s range using CALIB 8.2 (Stuiver & Reimer, 1993). We used a laboratory multiplier of 1 with 95% confidence limits and employed the IntCal20 (Reimer et al., 2020) and Marine20 (Heaton et al., 2020) datasets for terrestrial samples and marine samples, respectively. In calibrating the samples of organic sediment, we assumed that the original depositional environ-

Fig. 1 - Spatial distribution of the RSL markers collected in the SEAPROXY geodatabase. Sector 1 is the Liguria-Tuscany sector, sector 2 is the north-central Tyrrhenian Sea, sector 3 is Sardinia Island, sector 4 is Sicily Island and southern Calabria, sector 5 is mid to southern Adriatic Sea and the Gulf of Taranto, sector 6 is the northern Adriatic Sea.

ment was a transitional zone in the back-coastal area, influenced by fluvial processes as well as marine inputs. Therefore, for sediment dates where the percentage of marine carbon was available (e.g., Melis et al., 2017, 2018) a mixed IntCal13/Marine13 calibration method was applied (Di Rita et al., 2011). For archaeological samples, the age was provided by archaeological structures and/or by ceramics found in sedimentary layers (Aucelli et al., 2018, 2019; Mattei et al., 2018; Vacchi et al., 2020a).

2.2. Geophysical predictions of relative sea level

We compared the newly assembled suite of SLIPs and limiting points with two different geophysical Glacio-hydro isostatic adjustment (GIA) models that predict the RSL evolution in this portion of the Mediterranean Sea. Proxy-based sea-level data are fundamental to both constrain these models and to test the accuracy of their predictions. We compared all the data clusters included in the database with two Mediterranean predictions available in the literature. We adopted the recent RSL prediction based on the ICE-6G chronology developed by Prof. W.R Peltier and collaborators at the University of Toronto (Peltier et al., 2015), and the mantle rheological profile VM5a available in Vacchi et al., (2018). The second RSL prediction we adopted is developed by Prof. K. Lambeck and collaborators at the Australian National University (ANU, Lambeck et al., 2011) using the K33_j1b_WS9_6 geophysical model (hereafter ANU -K33).

2.3. WebGIS application

The web-application SEAPROXY (http://dist.altervista.org/seaproxy) was developed for both data management and visualization. For this purpose, two applications have been designed. The first application is dedicated to database management and is based on the open-source language PHP, supported by MySQL (Fig. 2a).

The second application for displaying spatial data is based on the open-source LeaLeft library, allowing the creation of functional and robust interactive maps based on JSON (JavaScript Object Notation) archives via JavaScript (Fig. 2b). This choice was driven by the fact that Leaflet is the leading open-source JavaScript library applied to the creation of mobile-friendly interactive maps and JSON (JavaScript Object Notation) is a database in text format used in the exchange of data between client/server applications, ideal for exchanging data between different applications.

The database implemented in this research is based on MySQL, an open-source RDBMS ("Relational Database Management System"), representing a reliable solution for web applications managing a large amount of data, in relation to each other.

This vertical web application has been developed with a twofold purpose: favouring the remote interaction of a multidisciplinary research group and providing a free access resource to the scientific community involved in sea-level studies.

SEAPROXY was designed to collect Italian sea-level data and it is consequently structured into four main sections:

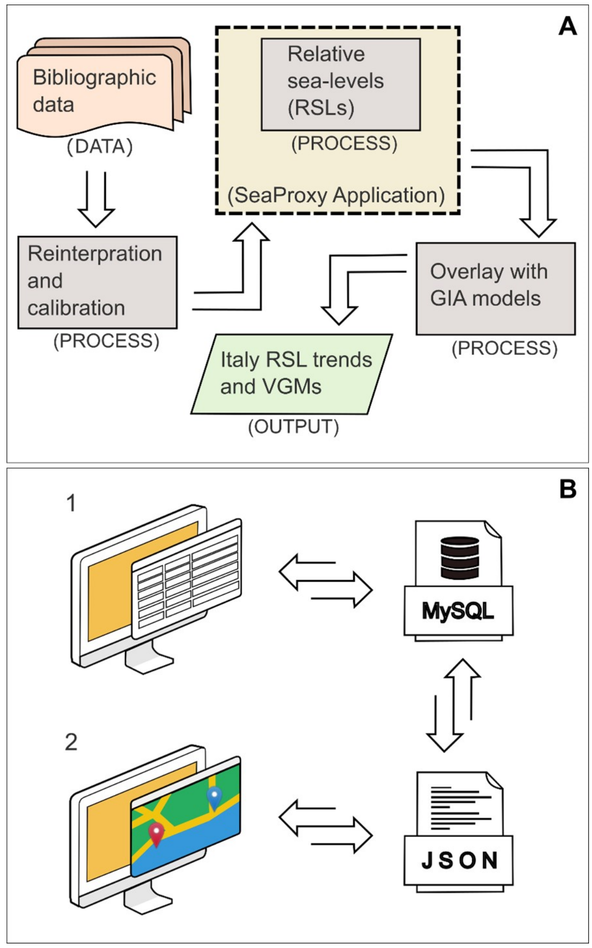

Fig. 2 - Workflows of a) data elaboration and interpretation and b) WebGIS application.

A. ID and bibliographic source
B. Geographic position
C. Dating information defining the horizontal position of RSL and uncertainty
D. Measurement methods including sampling technique, stratigraphic information, GPS configurations, tidal range, elevation, and related Indicative meaning information, RSLs deduced with related uncertainty.

3. RESULTS

The final database includes 391 SLIPs and 179 limiting points. The temporal range covers the last ~14 ka BP with a general increase in the number of datapoints through time. SLIPs number increase significantly in the last 8000 years representing the ~78% of the entire database (Fig. 3c). SLIPs number is particularly abundant (73) between 2.0 and 1.0 ka BP, when we found the maximal number of the archaeological proxies (Fig. 3c). The entire database is freely available at the following address: https://dist.altervista.org/seaproxy/

In Fig. 3a and 3b, we plotted the entire SLIPs record vs the whole suite of ICE-6G and ANU-K33 geophysical predictions for the Italian regions included in the database. The maximal difference between data and models is visible in the Early Holocene (12 -8 ka BP) period where ICE-6G seem to overestimate the RSL position while a general underestimation by ANU-K33 is shown by the data.

In order to analyse more in -depth, the general trends of the sea-level evolution along the Italian coast we have grouped the data in 6 macro-regions according to geographical proximity. This allowed us to have a broader picture of the sea-level evolution in the different sectors of the Italian coasts. However, we note that this is an open-access database that can be exploited for more detailed analysis of the RSL changes at a more local scale.

In sector 1 (Fig. 4a) we included the data collected from the seaboard of the northwestern Tyrrhenian and Ligurian seas (from Liguria to the border between Tuscany and Latium, see Fig. 1). Here, the RSL record is composed of 48 SLIPs, 7 MLPs and 10 TLPs. The oldest SLIP indicates that RSL rose by 45.1 ± 1.1m in the last ~12.6 ka. Younger data indicate major rising rates until ~7.1 ka followed by a significant stabilization of the RSL in the mid to Late Holocene. In this period, the maximal RSL variation was within 5 m even if we observe a scatter in the data which was likely related to subsidence processes driven by both compaction and tectonics (see section 4).

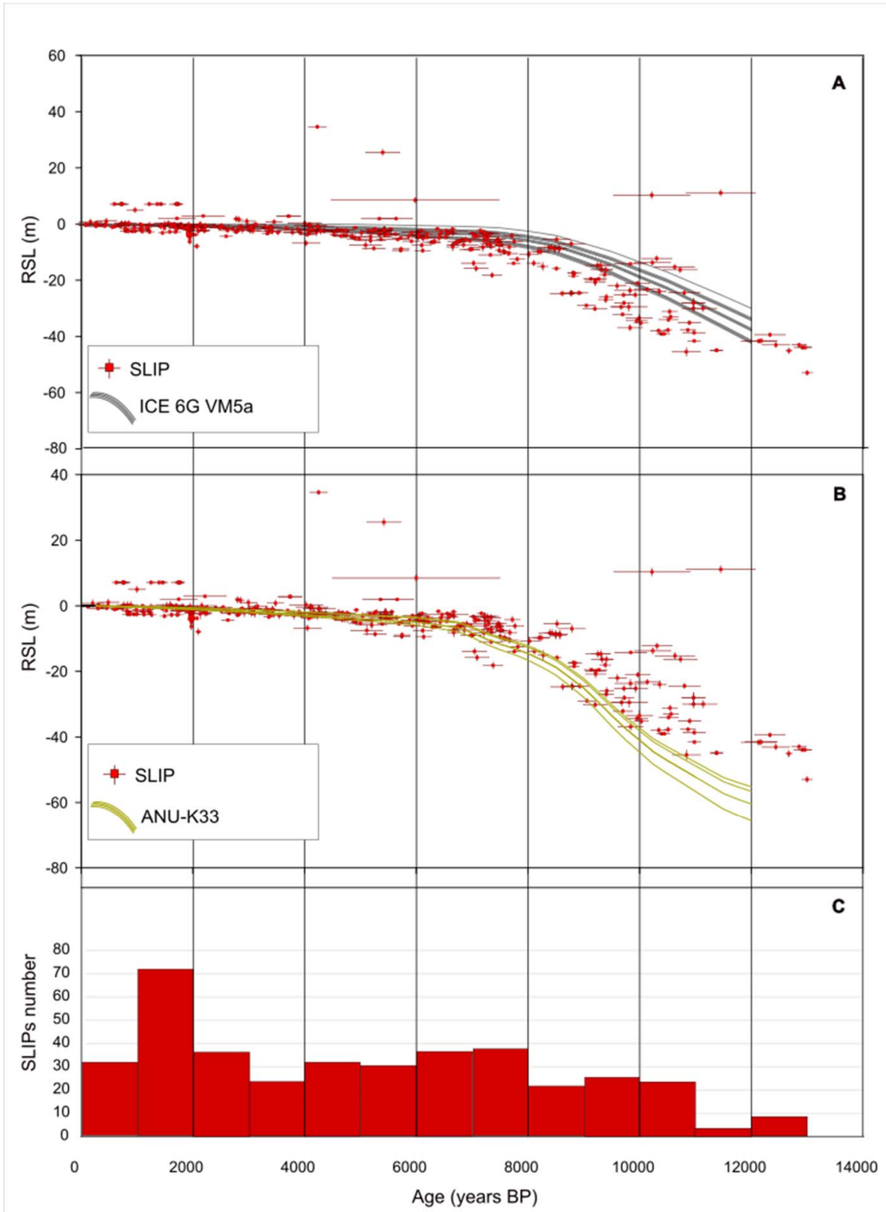

Fig. 3 - a) Total plot of the validated SLIPs compared to the suite of ICE-6G GIA predictions available for the Italian coast; b) Total plot of the validated SLIPs compared to suite of ANU-K33 GIA predictions available for the Italian coast; c) Stacked histogram of the validated SLIPs produced along the Italian coasts.

Sea-level data are also abundant along the mid to southern Tyrrhenian coast of Italy (e.g., from Latium to Campania, sector 2 Fig. 1 and 4b). Here, the RSL record is composed of 122 SLIPs, 21 MLPs, and 52 TLPs. The oldest SLIP indicates that RSL was at -43.9 ± 0.7 m at ~12.9 ka. Younger data show significant variability which is mainly driven by the data from the volcanic district of Naples where data are affected by major ground movements. However, the general trend in this area indicates a stabilization of the RSL at ~7.2 ka BP when a cluster of SLIPs indicates RSL was between 3 and 5 m. Data between 7.0 and 2.0 ka generally show good agreement among SLIPs and limiting points. Conversely, we observe a large scatter in the dataset for the last 2.0 ka when the RSL record is mostly composed of samples collected in the volcanic district of Naples.

In sector 3 (Fig. 1) we included data collected along the coasts of Sardinia (Fig. 4c). Here, the RSL record is composed of 40 SLIPs, 22 MLPs and 10 TLPs. The oldest SLIP indicates that RSL rose by 45.5 ± 1.5 m in the last ~10.8 ka BP. Early to mid-Holocene data show variability, probably related to compaction processes affecting the data collected in the Cagliari coastal plain (see section 4). The scatter in the data is

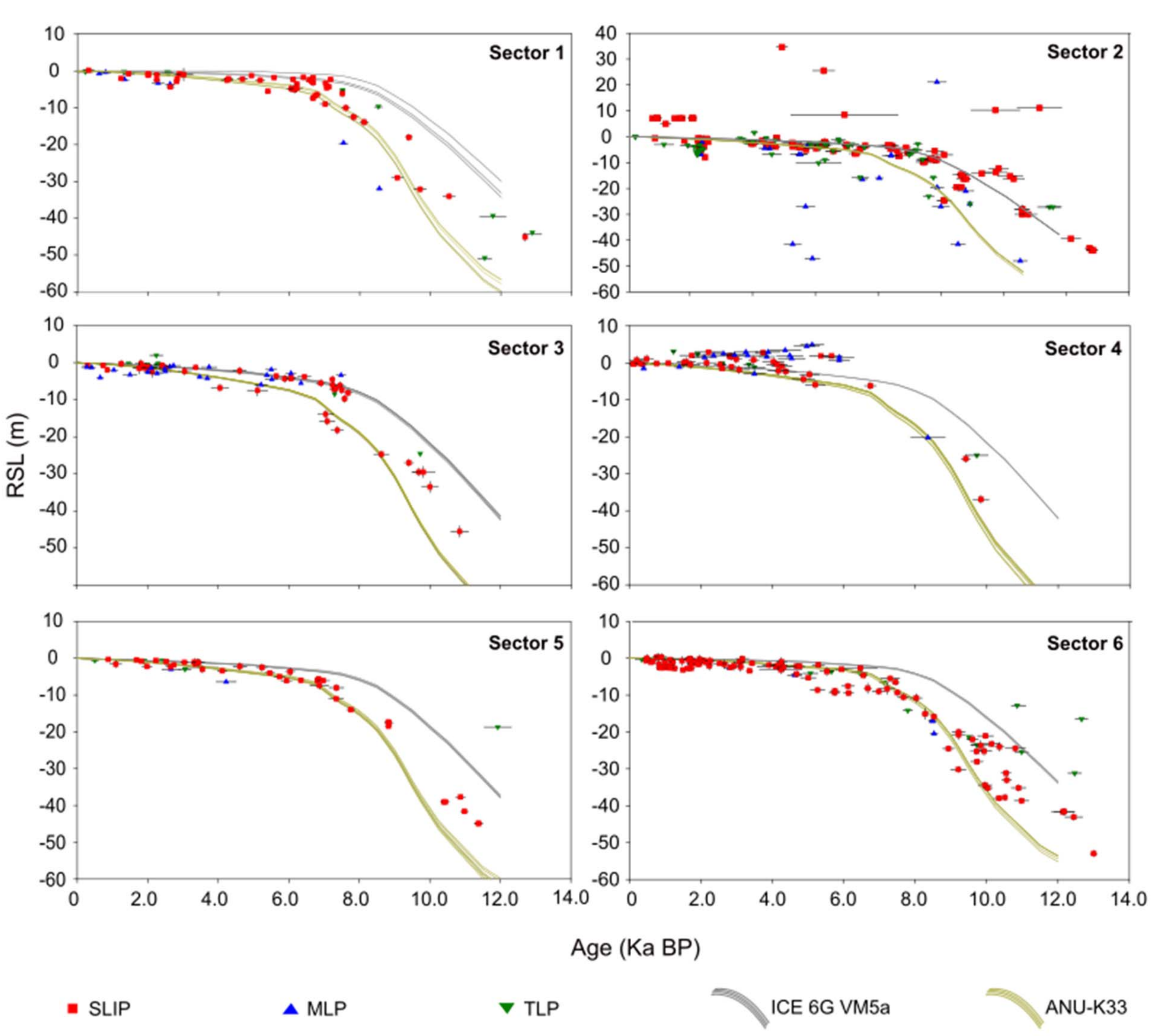

Fig. 4 - RSL evolution in the 6 sectors of the Italian coastline. SLIPs (red) are plotted as change in sea level relative to present against calibrated age. Limiting points are plotted as terrestrial (green) or marine (blue) horizontal lines. Vertical and horizontal errors for each RSL datapoint based on 2s elevation and age uncertainties. The RSL records compared to the suite of GIA predictions available for each coastal sector (see Fig. 1): grey line is the ICE-6G (VM5a) model and dark yellow line is ANU-K33 model.

reduced in the last 4.0 ka. Since that period, the total RSL variation has not exceeded 2 m.

In Sicily and southern Calabria (sector 4, Fig. 1), the RSL record is composed of 33 SLIPs, 7 MLPs and 7 TLPs (Fig. 4). Here, the oldest SLIP indicates RSL was at -36.9 ± 1.1 m at ~9.8 ka BP. Data were mainly collected in the easternmost and westernmost portions of the Island. We then observe an Early Holocene rising trend bringing the RSL at -6.2 ± 1.0 m at ~6.7 ka BP. A cluster of younger SLIPs indicates that the RSL variation in the last 4.0 ka was likely within 2.5 m. However, data from the area of Capo Milazzo (NE Sicily) show a significant departure from this pattern indicating that tectonic uplift brought the RSL above the present datum since 4.5 ka BP.

In sector 5 (Fig. 1) we included data collected along the mid-southern Adriatic (from mid-Abruzzo to southern Apulia) and in the Gulf of Taranto. The data suite comprises 39 SLIPs, 2 MLPs and 7 TLPs (Fig. 4). The oldest SLIP indicates that RSL was at -44.9 ± 1.1 m at ~9.8 ka BP. Younger clusters of SLIPs indicate RSL ~ -17.5 m at ~8.8 ka BP and at ~-6.0 m at ~6.9 ka BP. Mid to Late Holocene SLIPs show scatter likely related to differential compaction-driven subsidence. In the last ~3.5 ka BP, data seem to indicate that the maximum RSL variation has not exceeded 2 m.

In sector 6, we grouped the data collected in the northern portion of the Adriatic Sea (Fig. 1). Here the record is composed of 102 SLIPs, 6 MLPs and 13 TLPs (Fig. 4). The entire record is affected by a significant scatter related to the subsidence trends that are locally controlled by sediment compaction and/or tectonics. The oldest SLIP places the RSL at -53 m ± 0.9 m at ~13 ka BP. Early Holocene data are very scattered showing up to 15 m of elevational differences between coeval SLIPs between ~11 and ~9 ka BP. The scatter in the data is present, in minor terms, also in the mid to Late Holocene. In this time span, the virtually less compacted SLIPs indicate RSL was at -5.5 ± 0.7 m at ~7.3 ka BP and at -1.8 ± 0.7 m at ~5.3 ka BP. In the last 2.0 ka, the total RSL variation was within 1 m.

4. DRIVERS OF RSL EVOLUTION ALONG THE ITALIAN COASTS

The database presented in this work updates previous compilations (e.g., Lambeck et al., 2004a, b; 2011; Vacchi et al., 2016) by expanding the sea-level record along the Italian coast using a standardized protocol to produce sea-level data (e.g., Khan et al., 2019). The whole database, available in a GIS-based open-source repository, fits the most recent standard of sea-level studies (e.g., Khan et al., 2019) representing a solid base for multiple analyses relating to the coastal landscape evolution of the Italian coast during the Late Quaternary. However, our compilation lacks long and robust sea-level records in some Italian coastal regions such as the western Ligurian Sea, the central portion of the Adriatic, much of the Calabria coast as well as the southern coast of Sicily. Future investigations should prioritize data acquisition in these areas, notably for the production of SLIPs.

The global picture of the sea-level evolution (Fig. 3a,b) shows that, at the Italian scale, the maximum Holocene RSL variation did not exceed 50 m. Data further indicate that a general slowdown of the sea-level rising rates is observed after 7 ka BP, consistent with the end of the major ice-sheets melting in the northern hemisphere (Peltier, 2004; Lambeck et al., 2014; Vacchi et al., 2021). Since that period, we observe variability in the sea-level history which is mainly driven by the diverse vertical motions affecting the different portions of the Italian coast.

The quantification of these vertical motions was often assessed by comparing the local sea-level evolution with modelled GIA predictions (e.g., Lambeck et al., 2011; Anzidei et al., 2014). However, issues in the ability to correctly predict the GIA signal in the Mediterranean were raised in recent years thanks to an increase in available sea-level records for the basin (Melis et al., 2018; Vacchi et al., 2018; 2020b). A detailed analysis of residuals between data and models (see Mattei et al., 2022) is beyond the scope of this paper. However, the results of the present compilation indicate that none of the presently available GIA models is able to predict the Italian sea-level evolutions for the whole Holocene period. This is particularly evident in the Early Holocene period (12-8 ka BP) when, in all the Italian macro-regions, we observe a significant underestimation of the sea-level position by the ANU-K33 model. By contrast, ICE-6G overpredicts the sea-level during the same time span. This might depend on the ice-sheet models (shapes and sizes) as well as on the solid Earth parameters and stratification (Vacchi et al, 2020b). For this reason, the use of geophysical models for paleogeographic reconstructions between the Last Glacial Maximum and the end of the Early Holocene (e.g., ~21 to ~8 ka BP) can be significantly biased by the low predictive performance of these models.

In the Mid-to Late Holocene period (8 to 0 ka BP), many macro-regions still show a scatter in the data which is mainly related to differential subsidence rates driven by sediment compaction and local tectonics. In the Ligurian and northern Tyrrhenian Sea (sector 1), the quality of the dataset was much improved thanks to the significant amount of new data deriving from cores taken between Pisa and Livorno (Kaniewsky et al., 2018) and at the border between Tuscany and Latium (D'Orefice et al., 2020). This new dataset indicates RSL was significantly higher than the one derived from the Versilia, Arno and Magra coastal plains which are affected by subsidence related to sediment compaction and/or tectonics (e.g., Chelli et al., 2017). In this region ICE-6G is able to intercept the highest SLIPs (virtually uncompressed) while ANU-K33 is significantly below, notably between 8 and 3 ka BP. A similar pattern is observed in Sardinia (sector 3) where the mid- to Late Holocene record was significantly improved in recent years (Melis

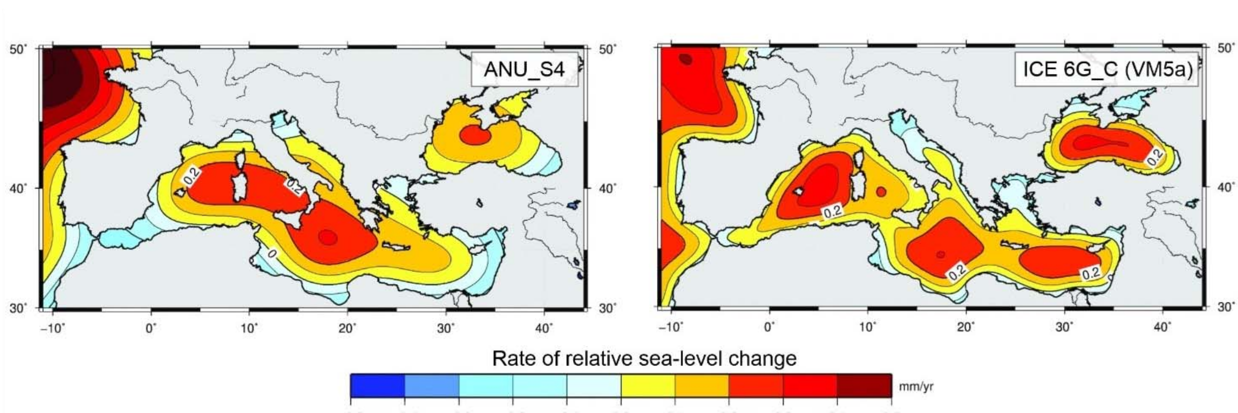

Fig. 5 - Maximal and minimal GIA contribution of RSL change expected in the next 2000 yr across the Mediterranean Sea according to the two models ANU S4 and ICE-6G C (VM5a). Modified from Spada and Melini (2022).

et al., 2017; 2018; Pascucci et al., 2018; Vacchi et al., 2020b). The updated sea-level record show very good agreement with the ICE-6G in the last 7.5 ka while ANU-K33 shows an underestimation of the sea-level position during the same period.

The complex tectonic setting affecting portions of the mid to southern Tyrrhenian Sea (region 2) and Sicily (region 5) means that it is challenging to analyse the predictive performance of the different models. Region 2 shows the maximum scatter in the dataset (Fig. 4). This is related to the volcano-tectonic influence that widely affected the RSL evolution near the volcanic districts of the Phlegrean fields and Vesuvius (see Mattei et al., 2022).

In this area, the multiple bradyseismic crises (rapid land movements of volcano-tectonic origin due to the evolution of the magmatic body and its hydrothermal system, Di Vito et al., 1999; Aucelli et al., 2017) occurring during the Holocene strongly interfered with the relative sea-level variation and related coastal changes, even if not always associated with main eruptions (Morhange et al., 2006; Isaia et al., 2019). In particular, the most-significant sea-level evolution can be associated with the third eruptive epoch of the Phlegrean fields, during which a major uplift (5.5-3.5 ka BP, Di Vito et al., 1999) resulted in a relative sea-level fall of more than 34 m (e.g., Starza terrace) which represents the most uplifted shoreline of the entire Mediterranean basin.

In the surrounding tectonically stable areas of sector 2 (e.g., Tiber and Sele coastal plains), the Early to Mid-Holocene are in very good agreement with ICE-6G while in the Late Holocene, data show too much scatter to accurately evaluate the predictive performance of the models. In sector 4, data from southern Calabria and from the NE sector of Sicily show a significant departure from the rest of the dataset due to the higher seismicity of the area (e.g., Antonioli et al., 2006a; Scicchitano et al., 2011; Spampinato et al., 2012; Anzidei et al., 2013). In these coastal sectors, the Holocene uplift trend (often characterized by co-seismic displacements, e.g. Scicchitano et al. 2011) played a major role in controlling the present elevation of the sea-level data which are presently placed several meters above those from the westernmost part of Sicily which is considered tectonically stable (Antonioli et al., 2006b).

In Sardinia (sector 3), there was a significant increase, in the last 5 years, of sea-level data derived from lagoonal cores and submerged beachrocks (e.g., Melis et al., 2017; 2018; Pascucci et al., 2018; Vacchi et al., 2020b). The island is tectonically very stable representing a key site to tune the GIA models along the Mediterranean basin (Vacchi et al., 2018). In the Mediterranean, the predicted GIA-driven land-level changes are controlled by the interplay between ice and water loading (Lambeck & Purcell, 2005; Stocchi & Spada, 2009). The latter resulted in widespread subsidence that reach the maximum in much of the basin (Lambeck & Purcell, 2005; Stocchi & Spada, 2009; Roy & Peltier, 2018) and that is also compensated by uplift along the continental margins (Stocchi et al., 2018). The Sardinia record constitutes a crucial benchmark to better evaluate hydro-isostatic subsidence in the Mediterranean basin because the island lies in the centre of the western Mediterranean basin, where all GIA models predict a maximum hydro-isostatic contribution (see Spada & Melini, 2022, Fig. 5). In the Early Holocene, both ICE-6G and ANU-K33 cannot reconcile the RSL evolution as already noticed in the other regions of the Italian coast. On the contrary, we observe a very good fit between ICE-6G and the mid to Late-Holocene RSL evolution in Sardinia. By contrast, the ANU-K33 prediction remains significantly below the large majority of SLIPs in this region further confirming an overestimation of the hydro-isostatic signal in this part of the Mediterranean basin.

The mid to Late Holocene RSL dataset for the coast of the southern Adriatic Sea and the Gulf of Taranto (sector 5) has been significantly expanded in the last 5 years (e.g., Valenzano, 2018; Valenzano et al., 2018; Mastronuzzi et al., 2018). In particular, the new data from the Gulf of Taranto (e.g., Valenzano, 2018, Valenzano et al., 2018) further confirm the poor prediction performance of both GIA models in the Early Holocene while there is a progressive reconciliation in the Mid- to Late-Holocene period with ICE-6G showing a better fit with the higher SLIPs (e.g., less compaction).

The northern Adriatic (region 6) has the richest sea -level dataset of the whole Italian coast. This is mainly composed of data derived from cores performed in the large coastal lagoons outcropping in the area (e.g., Amorosi et al., 2005; McClennen & Housley, 2006; Fontana et al. 2017) as well as along the wide continental platform (e.g., Correggiari et al., 2001; Ronchi et al., 2018a,b). The whole dataset shows a large scatter throughout the Holocene. The present position of the sea-level data in this portion of Italy is chiefly controlled by differential subsidence trends which are driven by both sediment compaction and/or tectonics. The latter plays a very important role along the north-eastern border of the Po plain which is the foreland basin of two fold-and-thrust belts: the north-northeastern vergent northern Apennines and the southern vergent southern Alps (Carminati et al., 2003). This geologic framework implies an increasing long-term component of subsidence between the Po Plain, the Venice lagoon and the Friuli coastal plain which is almost entirely controlled by the retreat and flexure of the Adriatic plate subducting underneath the Apennines (Cuffaro et al., 2009). Due to the major subsidence rates of this area, it is, at present, challenging to evaluate the predictive performance of the GIA models in the northern Adriatic.

5. CONCLUSIONS

We have assembled a comprehensive database of Holocene sea-level data (e.g., index points, marine and terrestrial limiting points) which are now available in an open-source repository in a GIS environment. All the sea-level data included in the repository were produced following the international protocols for sea-level studies. Furthermore, radiocarbon dates were re-calibrated according to the latest calibration curve.

The present overview of the Italian sea-level evolution indicates that the entire RSL in the last ~13 ka BP was within 50 m. We observe a rapid rise in the RSL between 13.0 to 7.0 ka followed by a sudden RSL stabilization in the last 7 millennia driven by the end of the major deglaciation period of the northern hemisphere ice-sheets. Since that period, land-level changes controlled by GIA, tectonics and sediment compaction have become the main drivers of the RSL change evolution along the Italian coast. In particular, we observed major subsidence trends (driven by tectonics and sediment compaction) in the coastal plains of the north-eastern Adriatic and in northern Tuscany. Major uplift trends (often co-seismic) were found in NE Sicily and in the southernmost tip of Calabria. A peculiar case constitutes the Phlegrean fields volcanic district where, in the same area, we observed the juxtaposition of the highest relict of a Holocene shoreline (more than 34 m above the present sea-level) and evidence of Roman buildings more than 8 m below present sea level. This area represents one of the most active volcanic districts of the entire Mediterranean where the short- lived alternation of subsidence and uplift has induced abrupt coastal landscape transformations in the last millennia.

The comparison of the assembled dataset with the GIA models routinely used for the prediction of the RSL position through time yielded contrasting results. In particular, none of the models is able to reconcile the RSL evolution in the Early Holocene period. For this reason, any paleogeographic reconstruction for periods older than 8.0 ka BP and only based on geophysical predictions should be used with caution.

The GIS database is a free tool available for future users for more specific assessments at smaller scales. Furthermore, it is an open repository and future production of new RSL data can be easily stored following the same scheme presented in this work.

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