

## Research Article

# Paleo-sea-level indicators in the Southern Tyrrhenian Sea: Insights into relative sea-level changes from the Last Glacial Maximum to the early Holocene

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## ABSTRACT

A relative sea-level (RSL) curve represents changes in sea level, typically at the scale of a sedimentary basin. It accounts for both global eustatic sea-level changes and local or regional factors, including tectonic vertical movements (subsidence or uplift), Glacial Isostatic Adjustment (GIA), ocean circulation, and climate. For the Central Mediterranean, several RSL curves have been proposed by integrating eustatic sea-level changes with GIA models; some of them also include corrections for local vertical movements since the Last Glacial Maximum (LGM). However, these curves rely on a limited number of geological and chronological markers distributed over timescales ranging from several hundred to several thousand years, which constrain their accuracy and resolution. This study identifies sea-level markers on high-resolution multichannel seismic profiles acquired in the Sant'Eufemia Gulf (SEG; southeastern Tyrrhenian Sea) and serves as a benchmark for sea-level changes. Integrating seismic data with calibrated radiocarbon dating of gravity cores reveals that these sea-level markers formed during the LGM and during subsequent sea-level rise. Paleo sea-level markers integrated with benthic foraminiferal assemblages and granulometric trends from core samples spanning 14.5 ka to the Holocene allow construction of a qualitative RSL curve for the southeastern Tyrrhenian region from the LGM to the Holocene using a multi-proxy approach. This is because the investigated area has experienced minimal long-term net vertical land movements, which simplifies the analysis of the impacts of RSL change on nearshore evolution. The RSL curve exhibits a non-linear pattern characterised by seven distinct step-like segments, each representing rapid sea-level rise events punctuated by intervals of stillstands or slight sea-level falls. This pattern indicates episodic accelerations and pauses in sea-level rise, reflecting complex interactions of glacial meltwater input and GIA. Subsequently, the RSL curve was compared with a suite of synthetic RSL curves generated by various GIA models covering the period from the LGM to the Holocene. Among these models, the ANU14-HV, ANU04-MED, and ANU14-LV demonstrate the closest match to our data. Our findings shed new light on RSL change for the Central Mediterranean from the LGM to the Holocene, improving predictive modelling capabilities and elucidating broader implications of climate change. Finally, the characteristics of the seismic data, combined with the rigorous and detailed workflow well described in this work, ensure reproducibility for future research focused on RSL change, including regions with tectono-sedimentary dynamics different from those of our study area.

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## 1. Introduction

An RSL curve refers to the variation in sea level at a specific area over time. RSL changes are influenced by global eustatic sea-level change (such as variations in ocean volume due to the growth and melting of continental ice sheets, thermal expansion of water, and changes in terrestrial water storage) and local factors, such as land motion (tectonic subsidence or uplift), Glacial Isostatic Adjustment (GIA), ocean circulation, and climate. They are constructed by analysing past sea-level indicators, such as geomorphological features, sedimentological and stratigraphic records, fossil assemblages, and archaeological evidence.

While global sea-level change provides a broad indicator of climate change, local and regional processes can amplify, dampen, or even reverse these trends in specific areas. Examples illustrate how Late Quaternary RSL variations critically altered sediment supply, bottom currents, and sediment gravity flows in regions like the SEG (South-eastern Tyrrhenian Sea; Cosentino et al., 2017; Martorelli et al., 2023), western New Guinea (e.g., García et al., 2020), and the Alboran Sea (Ercilla et al., 2021). RSL variations can make one process dominant (e.g., sediment gravity flows during sea-level lowstands; Catuneanu et al., 2009) or weaken another (e.g., weakening of contourite-related bottom currents during warm climatic phases in the Mediterranean; Miramontes et al., 2019; Martorelli et al., 2021). Thus, understanding regional sea-level variations is essential for assessing how RSL changes drive sedimentary processes that shape the stratigraphic architecture of sedimentary units on the continental shelf and slope (e.g., Matenco and Haq, 2020) and coastal morphology. Conversely, stratigraphic architecture and nearshore features, such as infralittoral prograding wedges, near-shore bars, paleo-water-depth markers (erosional and depositional), and paleoenvironmental indicators, offer key evidence for reconstructing detailed past regional and local RSL histories. Regions with lower long-term net uplift rates yield the most reliable signals of regional or global sea-level change, as they minimise undetected tectonic effects and GIA uncertainties (Lambeck et al., 2014).

Several studies have developed global sea-level curves (e.g., Gowan et al., 2021; Lambeck et al., 2014; Peltier, 2004) and regionally specific RSL reconstructions across various time scales. Examples include: a) Western Mediterranean (Lambeck et al., 2004a, 2004b; Lambeck et al., 2011; Vacchi et al., 2018), b) Atlantic and Pacific coasts of North America (Latham et al., 2021; Shugar et al., 2014; Medri et al., 2025), c) West coast of South Korea (Song et al., 2018), d) Western New Guinea (Gold et al., 2017), and e) Southern African coast (Carr et al., 2015; Cooper et al., 2018). For the central Mediterranean, RSL curves account for global sea-level variations by incorporating GIA predictions derived from ice-sheet and Earth rheology models (Cathles, 1975; Mitrovica and Milne, 2002; Mitrovica and Wahr, 2011; Nakada and Lambeck, 1987; Peltier, 2004; Peltier and Andrews, 1976). These were refined over ~ 20,000 years (Lambeck et al., 2011) and ~ 11,000 years (Lambeck et al., 2004a, 2004b) by integrating eustatic/isostatic GIA contributions (Cathles, 1975; Mitrovica and Milne, 2002; Mitrovica and Wahr, 2011; Nakada and Lambeck, 1987; Peltier and Andrews, 1976) with tectonic constraints. The latter include a) elevation of Marine Isotope Stage (MIS) 5.5 shoreline markers (e.g., Antonioli et al., 2018; Cardello et al., 2025), b) transgressive sand bodies marking past marine transgressions (e.g., Díaz and Maldonado, 1990; Bassetti et al., 2008; Ridente, 2018), and c) speleothems with marine overgrowths recording flooding events (e.g., Stocchi et al., 2017). Additionally, archaeological markers, such as Roman piscinae altitudes, constrain vertical tectonic movements (e.g., Lambeck et al., 2004a, 2004b; Aucelli et al., 2020). Although Lambeck et al. (2011) proposed RSL curves for 30 sites along the Italian coast from the LGM to present, these curves rely on limited geological and chronological markers and lack independent validation beyond their age constraints.

This research identifies paleo-sea-level indicators spanning thousands of years, from the LGM to the early Holocene in the SEG, the offshore extension of the Strait of Catanzaro, chosen for its minimal

long-term net vertical movements (see Section 2 for details). We applied a multi-proxy approach, integrating high-resolution multichannel seismic profiles (converted from time to depth) with sedimentological and benthic foraminiferal micropaleontology and calibrated radio-carbon ages to constrain seismic units.

Newly integrated data, combined with previously published datasets, enable reconstruction of a qualitative RSL curve for the SEG spanning from the LGM to the Holocene. Chronological control is limited to two key stratigraphic horizons, constrained by calibrated AMS  $^{14}\text{C}$  ages and a gravity core age model. Despite these limitations, this integrated framework yields a more robust and reliable reconstruction of past sea-level changes than single-proxy approaches. Additionally, we applied the ANU14-HV solution (Lambeck et al., 2014) to produce RSL contour maps for the central Mediterranean at 11, 15, and 20 ka, the temporal range of the available data.

Accurate reconstructions of past RSL variations are crucial for constraining tectonic and paleoenvironmental evolution in the Central Mediterranean, refining predictive modelling, and illuminating broader climate-driven processes.

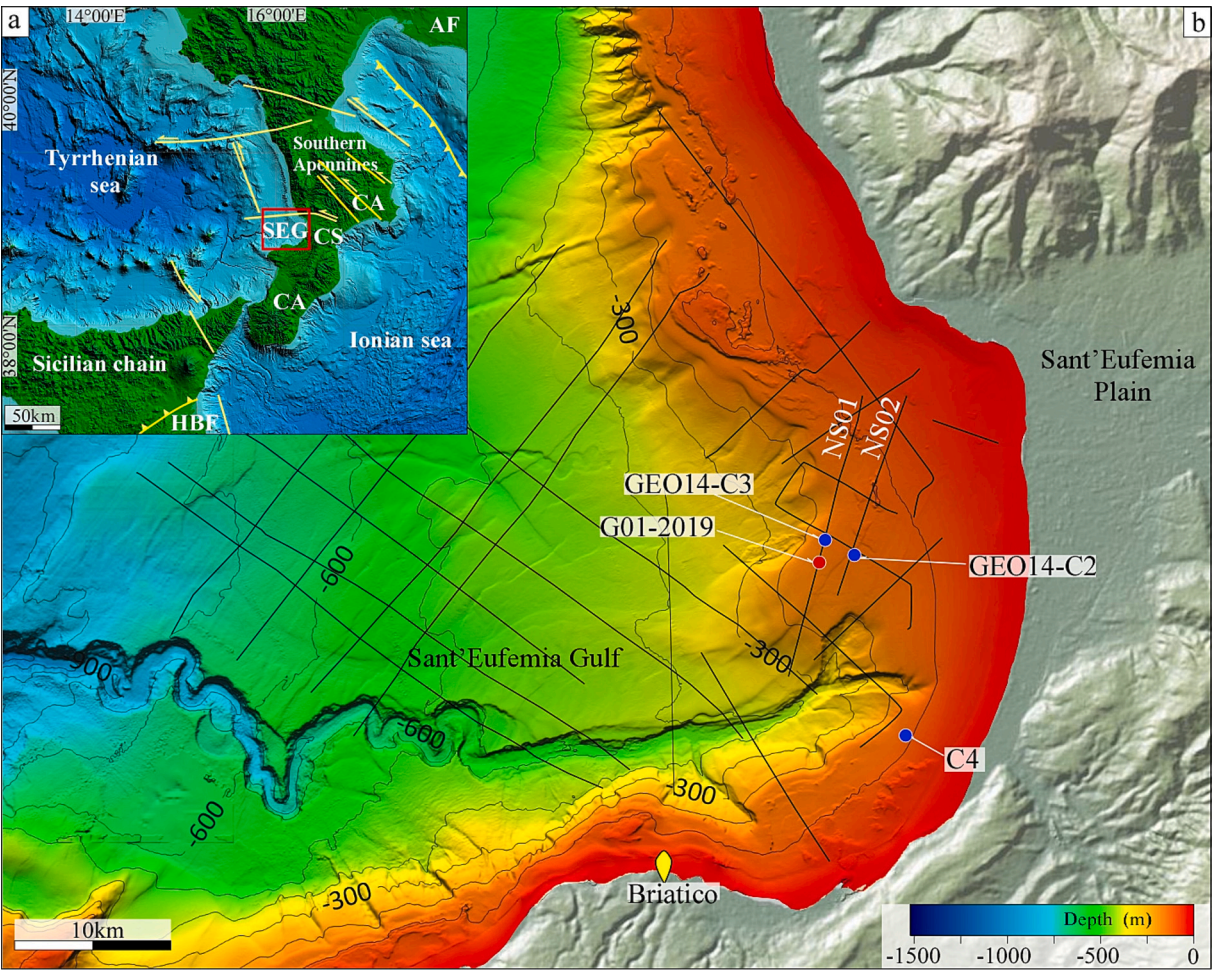
## 2. Geological background

The SEG is located in the Tyrrhenian offshore of the central Calabrian Arc, a segment of the Apennine-Maghrebien fold and thrust belt (Figure 1a). The evolution of the Calabrian Arc is linked to the south-eastward migration of the Apennine belt and its diachronous collision with the Apulian and Hyblean foreland to the north and south, respectively (Mattei et al., 2007). NW-SE to WNW-ESE-trending regional strike-slip fault systems developed obliquely and perpendicularly to the orogenic belt (Corradino et al., 2020; Corradino et al., 2021; Corradino et al., 2023; De Ritis et al., 2019; Cultrera et al., 2017; Ferranti et al., 2014; Pirrotta et al., 2021; Tansi et al., 2007; J. P. Van Dijk et al., 2000). These strike-slip fault zones fragmented the Calabrian Arc into two elongated blocks that moved independently southeastward with distinct displacements and rotations. (Van Dijk, 1992; Knott and Turco, 1991; Van Dijk and Okkes, 1991; Van Dijk and Scheepers, 1995).

Most of the northern and southern segments of the Calabrian Arc have experienced a maximum uplift rate of ~1 mm/y over the past 700,000 years reflected by elevated flights of Pleistocene coastal terraces (Bianca et al., 2011; Cucci and Tertuliani, 2006, 2010; Ferranti et al., 2009; Molin et al., 2002; Tortorici et al., 2003; Westaway, 1993), Holocene terraces and beach deposits (i.e. Antonioli et al., 2006; Ferranti et al., 2010 and references therein) and by the low-stand infralittoral prograding wedges in the offshore domain (Chiocci and Orlando, 1996; Pepe et al., 2014). On the contrary, the preservation of Lower Pleistocene shallow-marine deposits at about 40 m above present sea level (bpl, Longhitano et al., 2014) in the Catanzaro Strait (central sector of the Calabrian Arc) indicates a lower long-term net uplift rate for this area, on the order of only 0.05 mm/year.

The Catanzaro Strait, a WNW-ESE-oriented marine tidal seaway formed during the Early Pleistocene across the Calabrian Arc (Longhitano et al., 2014), is situated onshore near the SEG (Figure 1b). Its sedimentary infill rests unconformably atop Messinian evaporites, conglomerates, and older metamorphic basement units sourced from the Sila and Serre Massifs (Cavazza and DeCelles, 1998; Chiarella et al., 2012; Krijgsman et al., 1999). According to Longhitano et al. (2014), the sedimentary fill of the Catanzaro Strait is mainly composed of three depositional sequences (DS1, DS2, and DS3), each further subdivided into characteristic system tracts and delimited at their bases and tops by regional unconformities. The lowermost sequence, DS1, comprises a transgressive systems tract (TST1) and a highstand systems tract (HST1), consisting primarily of Lower to Upper Pliocene offshore siltstone, sandstone, and marl. Overlying DS1, the second sequence (DS2), dating to the Early Pleistocene (Calabrian), is divided into two systems tracts: TST2, characterised by cross-stratified mixed sandstone, and HST2, composed mainly of mixed siltstone and claystone. A complex of





**Fig. 1.** (a) Schematic tectonic map of the Tyrrhenian–Ionian system highlighting the main tectonic structures of the Calabrian Arc. Yellow lines with triangles indicate the thrust front of the Apennine–Sicilian chain, whereas yellow lines with double arrows denote strike-slip faults. The red rectangle outlines the study area. AF = Apulian foreland; CA = Calabrian Arc; CS = Catanzaro Strait; HBF = Hyblean foreland; SEG = Sant’Eufemia Gulf (modified from Van Dijk et al., 2000; Tansi et al., 2007; Ferranti et al., 2014; Cultrera et al., 2017; De Ritis et al., 2019; Pirrotta et al., 2021; Corradino et al., 2020, Corradino et al., 2021, Corradino et al., 2023). (b) Seismic survey grid (black lines) showing the location of profiles NS01 and NS02 discussed in this study, and the G01-2019 sediment core (red dot). Blue dots indicate cores GEO14-C3 and GEO14-C2 (Loreto et al., 2023) and core C4 (Cosentino et al., 2017). Curved grey lines represent bathymetric contours at 100 m intervals.

continental and shallow-marine conglomerates, dating to the Middle to Upper Pleistocene, forms the Lowstand Systems Tract of the uppermost depositional sequence (DS3).

In the SEG, Loreto et al. (2023) analysed two submarine cores, GEO14-C2 and GEO14-C3, collected from the outer shelf near core G01-2019, which was examined in this study (Figure 1b). Their work established a stratigraphic record extending back to the erosion surface formed during the LGM, dated to approximately 20.337 ka, with the uppermost sand layer dated to 10.75 ka (Table 1).

### 3. Data and methods

This study integrates gravity-sediment core data with multichannel, high-resolution seismic reflection data to identify paleo-sea-level indicators in the SEG (Figure 1b). The data are part of a dataset collected in 2019 for the project “Earthquake Potential of Active Faults Using Offshore Geological and Morphological Indicators” (Pepe et al., 2020).

**Table 1**

Radiocarbon ( $^{14}\text{C}$ ) ages of samples used for chronological constraints in this study. The table reports both newly obtained AMS  $^{14}\text{C}$  dates and radiocarbon data from the literature (Loreto et al., 2023). Radiocarbon ages were converted to calendar ages using Calib 8.2 (Stuiver and Reimer, 1993) with the marine20.14c calibration dataset (Heaton et al., 2020).

| Core     | Depth (cm) | ID        | $\delta^{13}\text{C}$ (‰) | $^{14}\text{C}$ age (BP) | 1 $\sigma$ range (cal BP) | 2 $\sigma$ range (cal BP) | Median probability (years) | Material                                    | Facies     | $^{14}\text{C}$ data source |
|----------|------------|-----------|---------------------------|--------------------------|---------------------------|---------------------------|----------------------------|---------------------------------------------|------------|-----------------------------|
| G01-2019 | 81–82      | LTL19522A | 9 $\pm$ 0,4               | 11,363 $\pm$ 80          | 12,614 – 12,793           | 12,502 – 12,901           | 12,708                     | Mollusca ( <i>Turritella</i> sp.)           | Sandy silt | This study                  |
| GEO14-C3 | 68–69      | S1        | ND                        | 9,910 $\pm$ 60           | 10,595 – 10,868           | 10,523 – 11,039           | 10,751                     | Mollusca ( <i>Saccella commutata</i> )      | Silty sand | Loreto et al. (2023)        |
| GEO14-C3 | 206–208    | S3        | ND                        | 1,7590 $\pm$ 100         | 20,181 – 20,491           | 20,009 – 20,661           | 20,337                     | Benthic forams ( <i>Elphidium crispum</i> ) | Silty sand | Loreto et al. (2023)        |

### 3.1. Core sample analysis

This study uses the sediment core G01-2019, collected in the SEG using a 100 mm-diameter gravity corer (see Figure 1b for the core location). The sediment core is 110 cm long and was retrieved at 38°50'43" N, 16°07'31" E, from a water depth of ~146 m bpsl.

The sediment core was visually examined at a centimetre scale using a 10x lens, complemented by microscopic observations of selected samples. Additionally, the grain size of selected stratigraphic intervals was analysed by laser diffractometry. Sedimentological analysis identified major lithologic intervals, sedimentary textures and structures, fossil content, and volcanoclastic layers. Subsamples 1 to 2 cm thick were collected for grain size and paleontological analyses. The sandy fraction was isolated from the bulk sediment by wet-sieving through a 63- $\mu$ m mesh. The coarser fraction was subjected to dry sieving, while the fine-grained portion was analysed using a laser particle sizer (Quixel/Sympatec). Textural analysis provided statistical parameters, including mean size, standard deviation, skewness, and kurtosis. These parameters were plotted on a logarithmic scale to facilitate facies interpretation.

The analysis of foraminiferal assemblages was conducted on 36 samples collected at 3 cm intervals. Samples were dried at approximately 60°C for 24 hours and then washed through a 63  $\mu$ m sieve. The wash residues were subsequently dry-sieved to isolate size fractions larger than 106  $\mu$ m for benthic foraminifera. In each sample, the selected size fractions were examined to collect, where possible, a minimum of 250 specimens of both benthic and planktonic foraminifera.

The taxonomic approach mainly follows the frameworks of Sgarrella and Moncharmont Zei (1993) and Milker and Schmiedl (2012) for benthic foraminifera. Based on benthic foraminiferal assemblages, a zonation of core G01-2019 was established using constrained cluster analysis with the Cavalli-Sforza method applied to orthonormal log-ratio (ORL) coordinates (Di Donato and Martín-Fernández, 2025).

Accelerator Mass Spectrometry (AMS)  $^{14}$ C radiocarbon dating was performed on approximately 0.25 g of mixed planktonic foraminifera specimens (Siani et al., 2000). The radiocarbon age of  $11.363 \pm 0.080$  ka BP was calibrated using CALIB 8.2 (Stuiver and Reimer, 1993), with the Marine20 Radiocarbon Age Calibration Curve (Heaton et al., 2020). Calibrated ages are reported in years before present in Table 1.

### 3.2. Seismic data acquisition, processing, interpretation, and depth conversion

Multichannel seismic reflection data were acquired using a high-resolution, 48-channel seismic reflection system equipped with slant streamers, with group spacing ranging from 1 to 2 meters. The system recorded signals generated by a multi-tip (400) Geo-Source Sparker array using negative-discharge technology (see Figure 1b for the seismic grid location). The shooting interval was 2.0 s, with a 1.5 s record length and a 0.1 ms sampling interval. A differential GPS positioning system was used to perform all necessary computations and determine the real-time positions of both sources and receivers. Sparker inline profiles were mainly oriented from NW–SE to N–S, while crossline seismic profiles were acquired along the NE–SW direction (see Figure 1b for seismic grid location).

The data processing involves the following steps: geometry assignment through binning of 2D CDP profiles, DC removal, signature deconvolution, F-K filtering, trace stacking, static corrections, velocity analysis, multiple attenuation, post-stack Kirchhoff time migration, receiver deghosting, time-variant bandpass filtering, and removal of automatic gain control to restore True Amplitude. Signal penetration exceeds 500 ms two-way time (t.w.t.), and vertical resolution reached up to 0.25 m near the seafloor. This paper presents a subset of this data set consisting of two NE-oriented seismic lines along the SEG, namely NS01 and NS02 (Figure 1b).

Seismostratigraphic and sequence-stratigraphic analyses were carried out to reconstruct the depositional architecture of the sedimentary

units. Potential sources of uncertainty in seismic interpretation were systematically assessed, with particular attention to lateral discontinuities and interfering reflections. Reflector correlation was performed based on seismic facies analysis, integrating the attributes of key reflectors and their stratigraphic relationships with overlying units (Fig. 5 for examples). Correlations were subsequently cross-validated against adjacent seismic profiles, and the full seismic dataset from the study area was utilised to enhance reflector continuity and reduce interpretative bias.

Following acoustic facies mapping, sediment thickness was estimated by converting two-way travel time to depth using interval velocities of 1,500 m/s for the water column and 1,700 m/s for post-LGM deposits. The latter value was derived as the average interval velocity using the Dix equation, based on stacking velocity variations between seismic reflectors within common midpoint gathers.

### 3.3. Glacial isostatic adjustment

Sea-level change in response to ice sheet melting exhibits significant spatial variability, resulting from the crust and ocean's responses to mass exchange between ice sheets and the oceans. When an ice sheet partially melts, the underlying crust rises as ice is removed, while ocean basins subside due to increased meltwater. The Earth's gravitational field is also perturbed by mass redistribution, resulting in a change in the shape of the geoid. The movement of Earth's crust and changes in sea level are determined by two main factors: near-field effects, which are influenced by Earth's rheology and ice thickness near ice margins, and far-field effects, which depend on large-scale Earth's rheology and changes in total ice volume at greater distances from the ice margins. This dynamic response of the Earth-ocean system to glacial cycles is known as Glacial Isostatic Adjustment (GIA, Cathles, 1975; Mitrovica and Milne, 2002; Mitrovica and Wahr, 2011; Nakada and Lambeck, 1987; Peltier, 2001; Peltier and Andrews, 1976). To assess GIA, researchers have reconstructed the history of ice sheets using geological and geophysical data to constrain paleo-sea level (Gowan et al., 2021; Lambeck et al., 2014, 2017; Peltier et al., 2015; Stokes, 2018).

#### 3.3.1. Sea-level Equation

The open-source Fortran code "SealEveL EquationN solver" (SELEN4; Spada and Melini, 2019) was used to numerically solve the gravitationally and topographically self-consistent Sea-level Equation (SLE) at high spatial and spectral resolutions, enabling the evaluation of a synthetic RSL curve for the study area. The SLE is the non-linear integral equation that quantitatively describes the physical interactions among the cryosphere, oceans, and solid Earth in response to the spatio-temporal evolution of ice and meltwater loads. The numerical solution accounts for horizontal shoreline migration and rotational feedback, as outlined in the revised theory presented by Mitrovica et al. (2005) and Mitrovica and Wahr (2011). All adopted models assume a spherically symmetric Earth structure with incompressible viscoelastic Maxwell rheology. The discretisation of the SLE is carried out on a global geodesic grid with a spatial resolution of approximately 40 km. It includes harmonic terms up to  $L_{\max} = 512$ , corresponding to a minimum wavelength of approximately 80 km on the Earth's surface. The present-day global topography is based on the bedrock version of the ETOPO1 global topographic model (Amante and Eakins, 2009). It is integrated with the Bedmap2 relief by Fretwell et al. (2013) for regions south of 60°S latitude. The numerical solution was achieved through five external iterations that progressively refine the paleo-topography and five internal iterations that solve the SLE for a specific estimate of time-dependent topography.

To explore the range of model uncertainties in the reconstructed RSL curves, we have incorporated a suite of GIA models into SELEN4. These models, developed by various research teams over time, are based on diverse constraints and assumptions regarding the spatio-temporal evolution of ice sheets and the Earth's radial rheological profile, as



well as on different numerical approaches. We considered several iterations of the ICE-X class of models by the Peltier research group, namely ICE-3G (VM1) (Tushingham and Peltier, 1991), ICE-5G (VM2a) (Peltier, 2004), ICE-6G (VM5a) (Argus et al., 2014), and ICE-7G (VM7) (Roy and Peltier, 2015, 2017); the "low-viscosity" and "high-viscosity" global GIA solutions (named ANU14-LV and ANU14-HV, respectively) by Lambeck et al. (2014); the nominal Mediterranean GIA model (named ANU04-MED) by Lambeck and Purcell (2005); and the PaleoMIST model by Gowan et al. (2021). It is important to note that the respective authors developed these models independently, based on distinct global RSL datasets. Synthetic RSL curves according to those GIA models have been obtained by integrating the corresponding input parameters (spatio-temporal evolution of ice loads and Earth's rheological profile) into the SELEN4 code.

## 4. Results

The integration of sediment core data with time-to-depth-converted high-resolution multichannel seismic reflection profiles allowed the identification of paleo-sea-level indicators spanning from the LGM to the Holocene. Chronological constraints derived from AMS  $^{14}\text{C}$  dating were used to calibrate the seismic stratigraphic framework and refine the interpretation of key stratigraphic horizons. The seismic dataset reveals diagnostic markers of paleo-water depth, including erosional surfaces, a nearshore bar, and infralittoral prograding wedges, which collectively constrain the reconstruction of the RSL curve across the investigated time interval.

### 4.1. Sedimentological and paleontological analysis of the core G01-2019

Core G01-2019 is subdivided into five units (A–E, from top to bottom; see Figure 2) based on sedimentological characteristics, grain-size distribution, and microfossil assemblages. Age attribution for each unit is derived from the age-depth model presented in Section 4.2.

- Unit A (25–0 cm / ~4.2 ka BP – recent) is composed of mud-supported lithofacies characterised by grey to olive grey homogeneous, bioturbated clayey silt, poorly sorted. A thin volcanoclastic layer, enriched in very fine sand composed of sanidine, pyroxene, and rare leucite, occurs 7 cm below the top, likely representing a tephra layer.
- Unit B (40–25 cm / ~5.5 – 4.2 ka BP) consists of grey, clayey, sandy silt, moderately bioturbated (grade 2/3D, Droser and Bottjer, 1991), containing rare, very thin interbedded bioclastic lenses and sparse *Posidonia* remains.
- Unit C (55–40 cm / ~7.3 – 5.5 ka BP) is characterised by grey and very poorly sorted clayey silt, with fine sand containing interbedded lenses rich in fragments of Molluscs and lithoclasts. A thin lens rich in volcanoclastics (small light pumices and glass shards) is present at 46 cm, most likely representing a tephra layer. At the top of the unit, bioturbation increases (grade 3/4D, Droser and Bottjer, 1991) and there is an enrichment in bioclasts, including fragments of well-preserved molluscs (*Nucula* sp., *Cardium* sp.).
- Unit D (85–55 cm / ~12.8 – 7.8 ka BP) consists of grey clayey silt with fine to very fine sand, normally graded, very poorly sorted, bioturbated (grade 2 to 3/4D, Droser and Bottjer, 1991).
- Unit E (110–85 cm / ~14.5 ka – 12.8 ka BP) is characterised by grey, silty, coarse-grained sand rich in bioclasts and lithoclasts, with a significant gravelly component. Constituents, including the bioclasts, are sometimes rounded, reddened, and abraded, and are mainly represented by Mollusc fragments, corals, and foraminifers. The lower portion is further distinguished by positive skewness values, reflecting a significant fine fraction.

Overall, the core displays a clear fining-upward trend, with mean grain size decreasing from ~3  $\phi$  in the lower interval to ~7  $\phi$  in the

upper part (Figure 4). Positive skewness characterises the lower portion of Unit E. In contrast, the overlying units (D to A) show predominantly negative to near-zero skewness values.

Paleontological analysis indicates the presence of abundant and well-preserved benthic foraminiferal assemblages throughout the samples. Unit E is characterised by relatively high abundances of shallow-water and epiphytic taxa (e.g., *Asterigerinata*, *Elphidium*, *Lobatula*, *Neconorbina*, *Rosalina*; Sgarrella and Moncharmont Zei, 1993). In Unit D, a decline in these taxa is accompanied by an increase in *Cassidulina carinata*, *Bulimina aculeata*, *Bolivina spathulata* (Figure 2), and *Uvigerina peregrina* (see Supplementary Figure S1). Peak abundances of *B. spathulata* mark Unit C. In contrast, in Units B and A, this species decreases, coinciding with higher proportions of *Amphicoryna scalaris*, *Sphaeroidina bulloides*, *Uvigerina mediterranea*, and arenaceous taxa (see Supplementary Figure S1).

### 4.2. Age-depth model derived from the G01-2019 core

The age-depth model for core G01-2019 (Figure 3) was constructed through linear interpolation between five chronostratigraphic tie points defined by planktonic foraminiferal and coccolithophore eco-biostratigraphic events (Table 2), integrated with one calibrated radiocarbon age (Core G01-2019 in Table 1). The chronostratigraphic robustness of the selected calcareous plankton bioevents in the western-central Mediterranean is well constrained, owing to their regionally consistent age calibrations and relatively low chronological uncertainties (Di Stefano et al., 2015; Lirer et al., 2013; Sprovieri et al., 2003). The basal section of the core captures the onset of the Bølling–Allerød interstadial. In contrast, the uppermost portion of the sedimentary succession, corresponding to the late Holocene, is likely truncated as a consequence of sediment disturbance and/or loss during coring operations.

The age-depth model was used to constrain the chronology of the five sedimentary units identified in core G01-2019. Sedimentation rates, ranging between 4.9 and 12.9 cm kyr<sup>-1</sup>, were calculated from the depth-age relationship derived by linear interpolation between chronostratigraphic tie points. These rates were subsequently applied to convert unit thicknesses into corresponding temporal intervals, thereby enabling the estimation of ages for the unit boundaries. The resulting chronological framework is presented in Section 4.1.

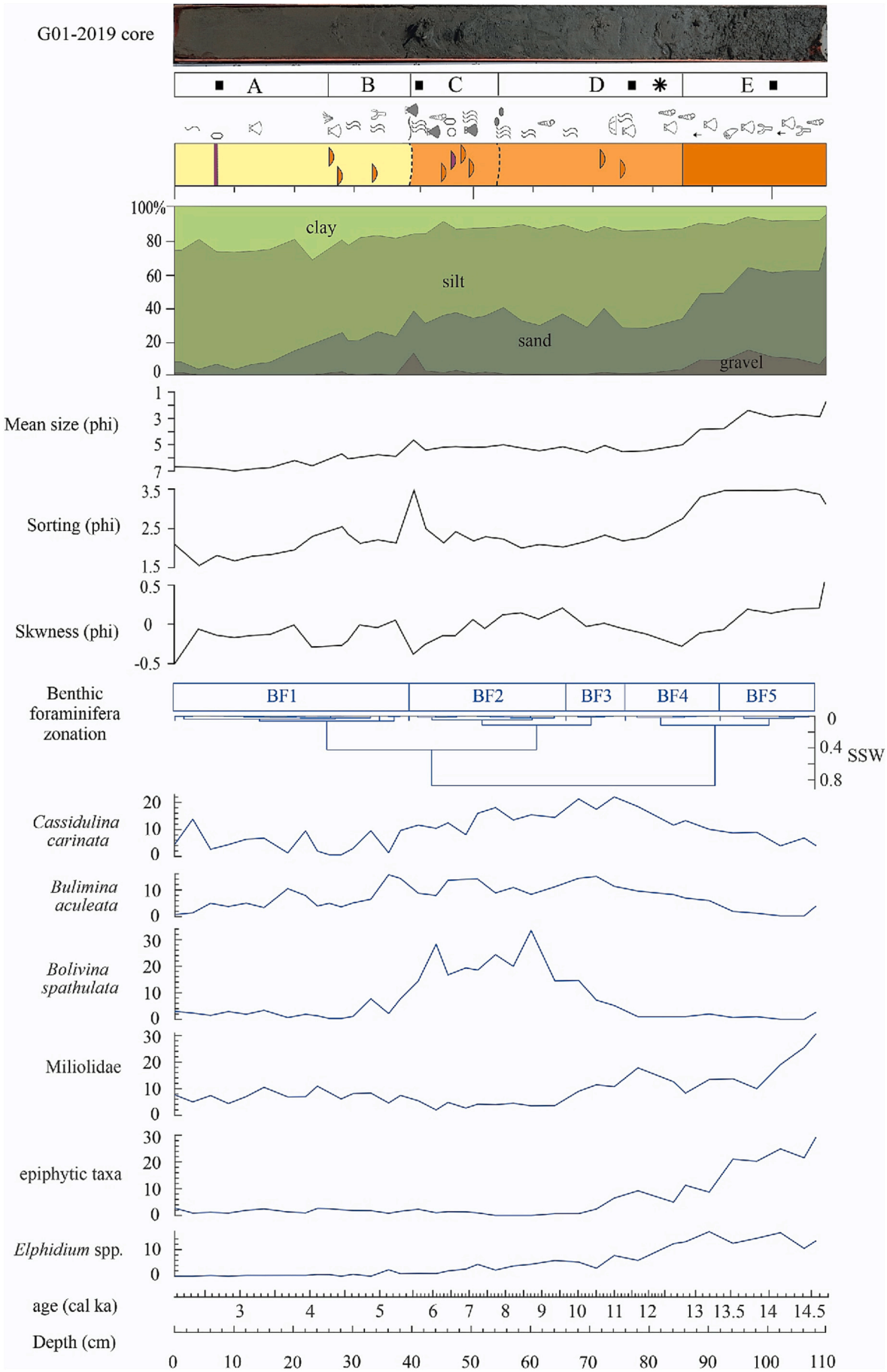
### 4.3. Seismo-stratigraphic analysis, interpretation, and calibration

Eight seismic units were identified in the high-resolution seismic profile NS02 (Figure 4) based on seismic attributes, including amplitude, lateral continuity, and frequency, as well as reflection terminations such as onlap, downlap, and truncation. Unit geometry was further analysed through both internal reflection configurations (e.g., aggradational, progradational, chaotic) and external morphologies (e.g., tabular, mounded, lens-shaped, wedge-shaped) to support the interpretation of depositional environments.

All seismic units rest on an irregular, laterally continuous, high-amplitude reflector interpreted as an erosional unconformity (LGM-u; Figures 4–7). It truncates underlying oblique reflections and locally exhibits flat-to-gently-dipping geometries. LGM-u is traceable across the seismic profiles to a depth of ~138 m bpsl.

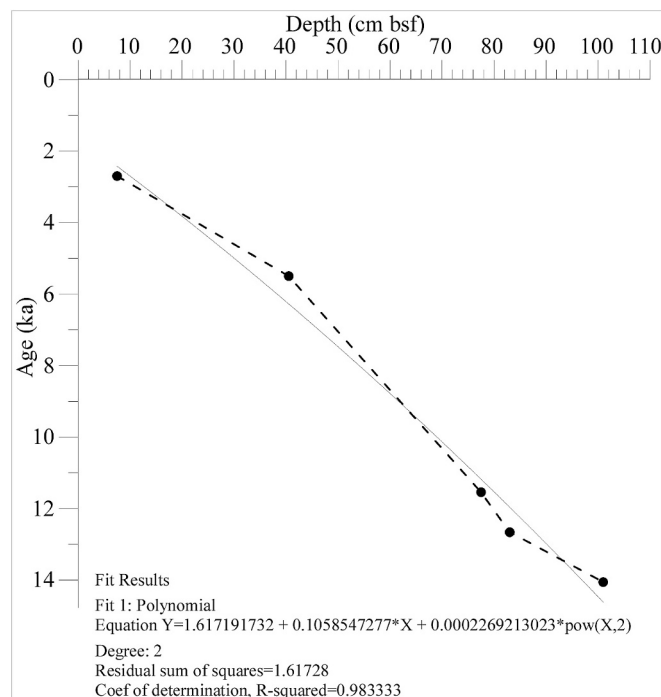
Along the continental shelf of the southern Tyrrhenian Sea, previous studies (e.g., Peltier, 2004; Caruso et al., 2011; Sulli et al., 2013; Martorelli et al., 2016; Pepe et al., 2018; Ferranti et al., 2019; Morelli et al., 2022; Martorelli et al., 2023; Casalbore et al., 2024, and references therein) recognise this surface as a shelf-wide unconformity formed during subaerial exposure of the continental shelf between ~26 and 20 ka. In agreement with this regional framework, and supported by chronostratigraphic constraints from core GEO14-C3, the LGM-u is interpreted as having developed during the LGM sea-level stillstand.

The principal seismic-stratigraphic characteristics of the identified



(caption on next page)

**Fig. 2.** Characterisation of gravity core G01-2019 (see Figure 1b for location). Sedimentary units are defined based on grain-size parameters (granulometry, sorting, skewness, and mean grain size). Paleoeological interpretation and benthic foraminiferal zonation are shown. SSW = sum of squares within groups (intervals). Foraminiferal abundances are plotted against calibrated age (cal ka BP). The star marks the position of a *Turritella* sp. specimen dated to 12,708 cal yr BP by AMS  $^{14}\text{C}$  (see Table 1). Black solid squares indicate additional tie points identified from ecostratigraphic constraints (see Table 2).



**Fig. 3.** Age–depth model for core G01-2019 constructed by linear interpolation between five chronostratigraphic tie points defined by planktonic foraminiferal and coccolithophore eco-biostratigraphic events (Table 2), supplemented by a calibrated radiocarbon age (12,708 ka BP; Table 1).

**Table 2**

Chronostratigraphic tie points identified in core G01-2019 based on planktonic foraminiferal and coccolithophore eco-biostratigraphic events.

| Core | Depth (cm) | bioevent                                         | age (cal BP) | Taxonomic group         | Reference                |
|------|------------|--------------------------------------------------|--------------|-------------------------|--------------------------|
| G01  | 7–8        | <i>Trilobatus sacculifer</i> acme end            | 2,700        | Planktonic foraminifera | Lirer et al. (2013)      |
| G01  | 40–41      | <i>Globorotalia truncatulinoides</i> re-entrance | 5,500        | Planktonic foraminifera | Lirer et al. (2013)      |
| G01  | 77–78      | Top <i>Gephyrocapsa oceanica</i>                 | 11,600       | Calcareous nannofossils | Di Stefano et al. (2015) |
| G01  | 100–101    | <i>Gephyrocapsa muelleri</i> peak                | 14,100       | Calcareous nannofossils | Sprovieri et al. (2003)  |

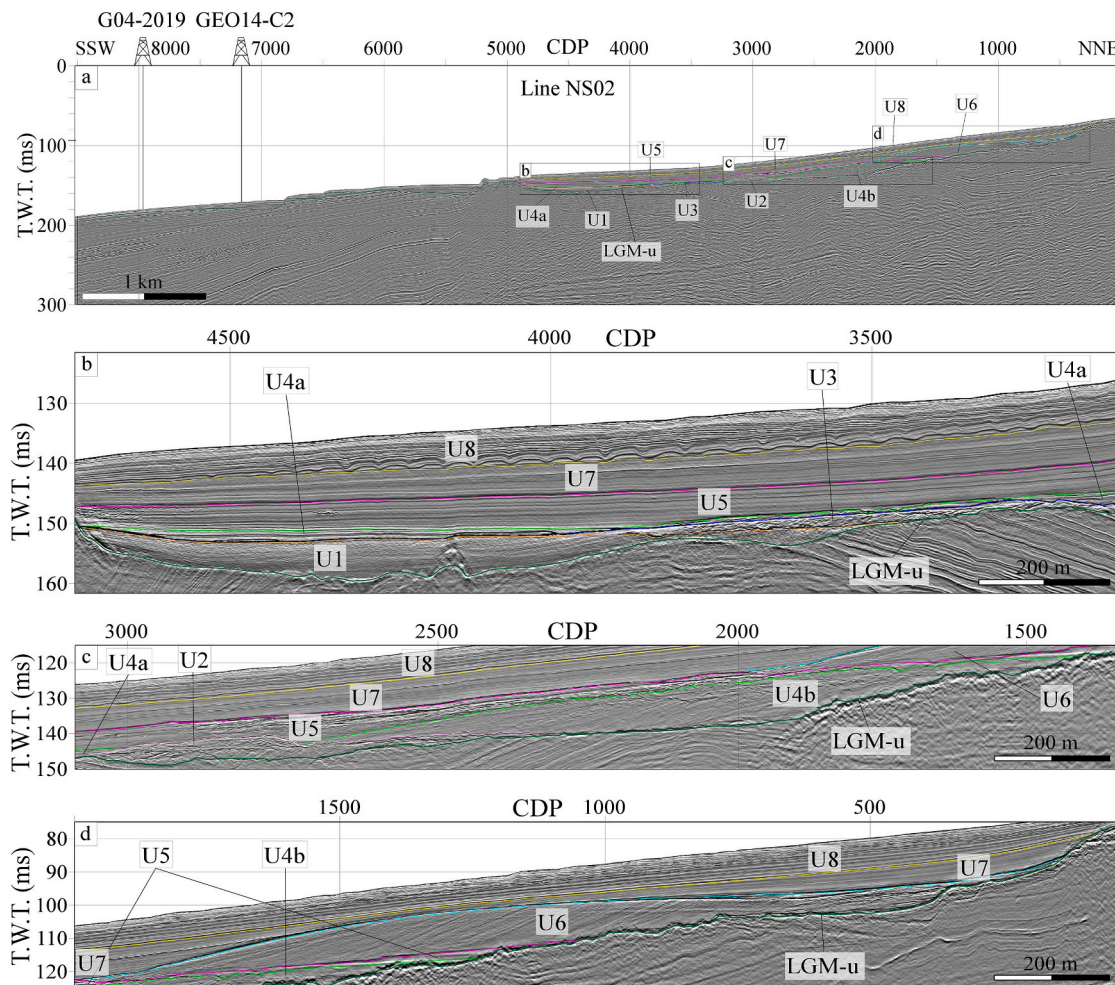
units are summarised below.

- **Unit U1** is characterised by subparallel, very low-amplitude reflectors (Figures 4a and b). It is bounded above and below by irregular reflectors interpreted as erosion surfaces (green and orange lines, respectively, in Figure 4b). The unit infills a topographic depression formed during the LGM, with deposits largely confined to the available accommodation space and reaching a maximum thickness of ~ 6 m (Figure 5c). The unit displays an overall aggradational stacking pattern, with reflectors onlapping the basal surface in the southern sector and draping the irregular substrate toward the

north. Unit U1 reaches a maximum thickness of approximately 6 m and extends laterally for ~1220 m.

- **Unit U2** comprises two seismic facies. The lower facies is defined by seaward-dipping clinoforms that grade landward into chaotic to acoustically transparent reflections (Figures 4c, 5d, 6a and b). The upper facies forms a mound-shaped body, with asymmetric internal architecture, characterised by landward-dipping reflectors on the landward (upwind) flank and seaward-prograding clinoforms on the seaward (leeward) flank (Figures 4c and 5d). This geometry indicates bidirectional sediment transport and supports deposition in an outer-bar setting. Landward, Unit 2 includes a chaotic facies truncated by an erosional surface, interpreted as a relict inner bar. This facies likely reflects variable hydrodynamic conditions, promoting sediment reworking and incomplete preservation. Collectively, these facies define a nearshore bar system consistent with the model of Sitkiewicz et al. (2020). The unit reaches a maximum thickness of approximately 6 m and extends laterally for ~630 m.
- **Unit U3** exhibits high-frequency, high-amplitude reflectors with a progradational configuration. It overlies the LGM-u and locally, toward the southwest, Unit U1 (Figures 4b, 6c and d). The unit is bounded by erosion surfaces at both its base (green and orange lines in Figure 4b) and top (blue line in Figure 4b). The progradational architecture indicates deposition during a relative sea-level stillstand. In contrast, the upper bounding unconformity reflects a subsequent relative sea-level fall that promoted wave-driven reworking of the upper deposits. The unit attains a maximum thickness of approximately 2 m and exhibits a lateral extent of ~700 m.
- **Unit U4** is subdivided into subunits U4a and U4b (Figure 4b and c). Subunit U4a comprises continuous, high-frequency, high-amplitude reflectors arranged in an aggradational stacking pattern and overlies Unit U1. In contrast, subunit U4b consists of low-amplitude, oblique-tangential reflectors that downlap onto the LGM-u and are truncated upward by an erosional surface. Subunit U4b is interpreted as a prograding wedge (Figures 5d, 6c and d) formed during a relative sea-level stillstand, followed by a relative sea-level fall responsible for the upper erosional surface. The unit reaches a maximum thickness of approximately 12 m and extends laterally for ~1300 m.
- **Unit U5** is characterised by parallel, laterally continuous, high-frequency, low-amplitude reflectors (Figures 4b, c), forming a tabular body with an overall aggradational stacking pattern. Reflectors onlap onto Units U2 and U4b. In the northeastern sector of profile NS02, Unit U5 locally displays high-amplitude chaotic reflections (Figure 4c). The unit is interpreted as recording deposition during a relative sea-level rise. The unit attains a maximum thickness of approximately 5 m and extends laterally for ~2100 m.
- **Unit U6** is characterised by continuous, moderate- to high-frequency, medium-amplitude reflectors arranged in an oblique configuration, with toplap terminations and a wedge-shaped geometry (Figures 4d, 5e). From east to west, reflectors downlap onto both the LGM-u and the upper surface of Unit U5 (Figure 4d). This architecture supports interpretation as a prograding wedge formed during a relative sea-level stillstand. The unit is interpreted as recording deposition during a relative sea-level rise. The unit reaches a maximum thickness of approximately 11 m and exhibits a lateral extent of ~1460 m.
- **Unit U7** comprises laterally continuous reflectors with upward-increasing frequency and amplitude (Figures 4b–d). It displays an aggradational stacking pattern, with onlap terminations onto Unit U6 (Figure 4d) and overlying Unit U5 toward the SSW (Figures 4b, c). The upper boundary is defined by an undulating erosional surface





**Fig. 4.** (a) Seismic profile NS02 showing the seismo-stratigraphic units identified in the SEG since the LGM (see Figure 1b for location). A green line indicates the LGM-u. The vertical scale is in two-way travel time (TWT, ms). (b–d) Enlarged sections of profile NS02 highlighting internal reflection configurations and bounding surfaces of the seismo-stratigraphic units and subunits.

(Figure 4b). The unit is interpreted as recording deposition during relative sea-level rise. The unit reaches a maximum thickness of approximately 10 m.

- **Unit U8** comprises high-frequency, medium-high amplitude, laterally continuous reflectors (Figures 4b and c), with the present-day seafloor as its upper boundary. Locally, its lower portion exhibits undulating, high-amplitude reflectors (Figure 4b) with wavelengths of 46–60 m and an amplitude of  $\sim 1$  m. These features can be interpreted as generated by gravity-driven processes (e.g., sediment slumping or creeping), or, less plausibly, upper-flow-regime bed-forms by sediment-laden gravity flows. The unit attains a maximum thickness of approximately 5 m.

Lithostratigraphic and radiocarbon data from sediment core G01-2019 (location shown in Figure 1b), integrated with results from cores GEO14-C3 and GEO14-C2 (Loreto et al., 2023), provide key lithological and chronological constraints, placing the LGM-u surface at 20.337 ka and the uppermost sand layer to 10.75 ka (Figure 7 - Table 1).

## 5. Discussion

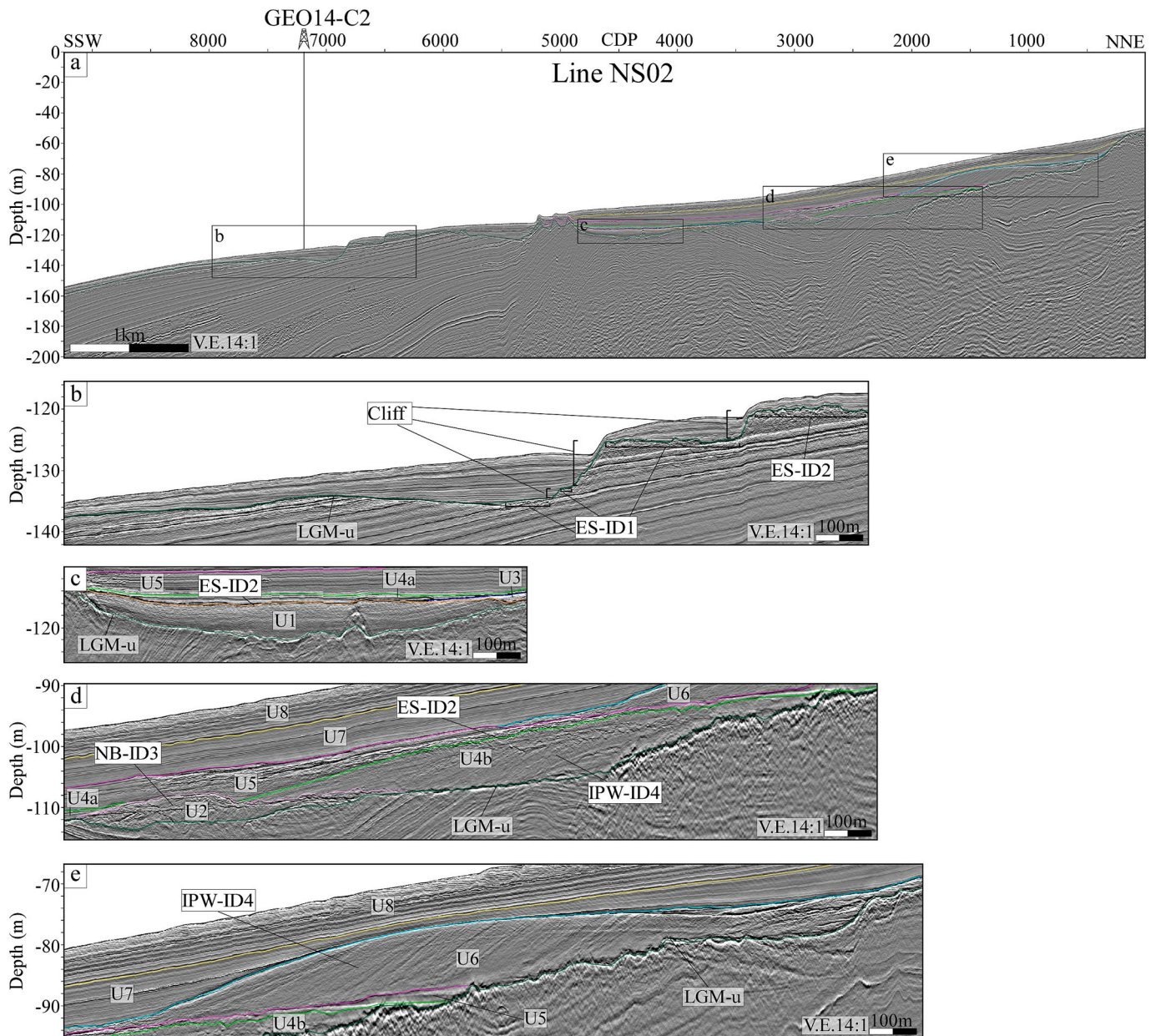
We present an RSL curve for the southeastern Tyrrhenian region spanning from the Last Glacial Maximum to the early Holocene, derived from a multi-proxy dataset. This reconstruction is then compared with a suite of published synthetic RSL curves produced by different GIA models. Finally, we examine the spatial variability of RSL across the

central Mediterranean as predicted by the best-fitting ANU14-HV GIA model at three selected time slices.

### 5.1. Methodological approach for the RSL reconstruction from the LGM to the early Holocene

To reconstruct the RSL curve for the SEG from the LGM to the early Holocene, we integrated newly identified palaeobathymetric indicators derived from a multi-proxy approach combining seismic stratigraphic interpretation, sediment core analysis, AMS radiocarbon chronological constraints, and published data. However, it is important to note that calibrated ages from AMS  $^{14}\text{C}$  measurements, together with the age-depth model of gravity core G01 (Figure 3), constrain the chronology of only two key stratigraphic horizons. The older horizon, corresponding to the LGM unconformity (LGM-u), is dated approximately 20.337 ka, whereas the younger horizon is represented by the uppermost sandy layer in core GEO14-C3, dated at 10.75 ka. Consequently, the proposed RSL reconstruction should be regarded as qualitative, since the available chronological framework does not permit a robust definition of the precise timing and duration of individual sea-level phases. Nevertheless, the identified palaeobathymetric indicators provide reliable vertical constraints on former sea-level positions, allowing reconstruction of the overall trend and oscillatory behaviour of relative sea-level changes throughout the investigated interval.

Palaeo-sea-level indicators are characterised by variable uncertainty ranges; therefore, depth uncertainties were assigned to each indicator to



**Fig. 5.** (a) Time–depth converted seismic profile NS02 (see Figure 1b for the location). (b–d) Enlarged sections of profile NS02 showing erosional surfaces and depositional nearshore features. ES = erosion surface; IPW = infralittoral prograding wedge; NB = nearshore bar; ID = identification number of paleo-sea-level indicators (see Table 1, Section 5.2); LGM-u = Last Glacial Maximum unconformity; V.E. = vertical exaggeration.

account for inherent errors (see Section 5.2). After defining depth values and associated error bars, the RSL curve was temporally constrained between 20.337 and 10.75 ka. The precise age and duration of individual phases (i.e., relative sea-level rise, stillstand, or fall) cannot be robustly constrained by the present dataset, nor by other currently available regional records. Consequently, their chronological placement is based exclusively on the timing of major palaeoclimatic events known to have exerted a primary control on Mediterranean sea-level variability: (1) Heinrich Stadial 1 (H1; 18–14.7 ka BP; Hodell et al., 2017), associated with cold conditions and enhanced meltwater input; (2) the Bølling–Allerød interstadial (GI-1; 14.642–12.846 ka BP; Rasmussen and Thomsen, 2014), a warm phase encompassing the sea-level rise of Meltwater Pulse 1A (MWP-1A; 14.2–13.8 ka; Weaver et al., 2003; Lin et al., 2021; Blanchon and Chutcharavan, 2023); (3) the Younger Dryas stadial (GS-1; 12.846–11.643 ka BP; Rasmussen and Thomsen, 2014), marking a return to near-glacial conditions; and (4) Meltwater

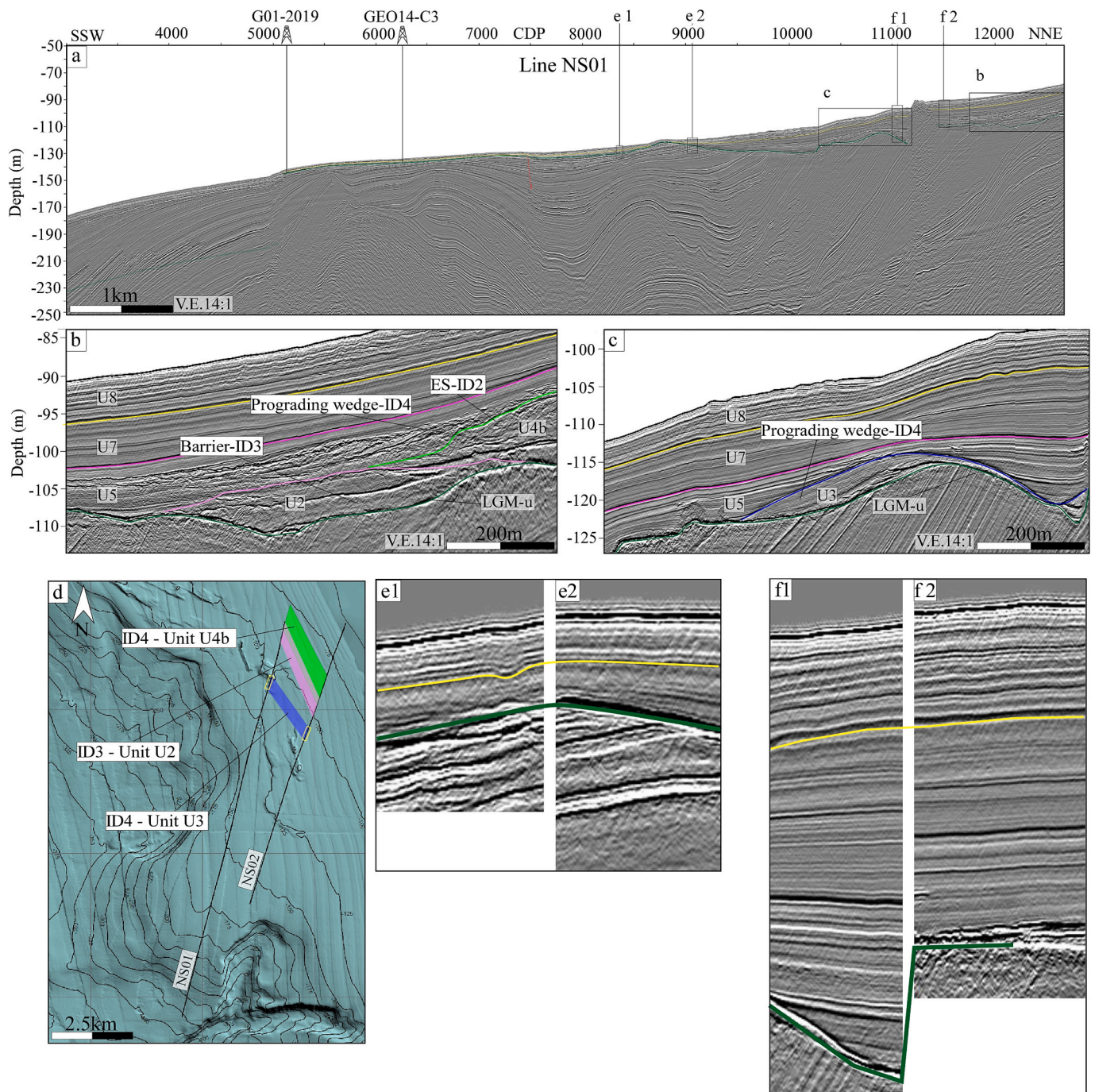
Pulse 1B (MWP-1B; 11.5–11.1 ka; Fairbanks, 1989; Bard et al., 2010; Abdul et al., 2016), associated with renewed sea-level rise under warming conditions.

Following construction of the RSL curve (Section 5.2), vertical adjustments (depth corrections) were applied to account for the influence of local tectonics on relative sea-level change. The resulting curve was subsequently evaluated against independent sedimentological evidence and benthic foraminiferal assemblages from core G01-2019 (Section 5.2.1).

## 5.2. Sea-level markers for reconstructing past sea-level changes

Four palaeo-sea-level indicators were identified on the seismic profiles (Table 3) and are described below, together with their estimated depth ranges and associated uncertainties:

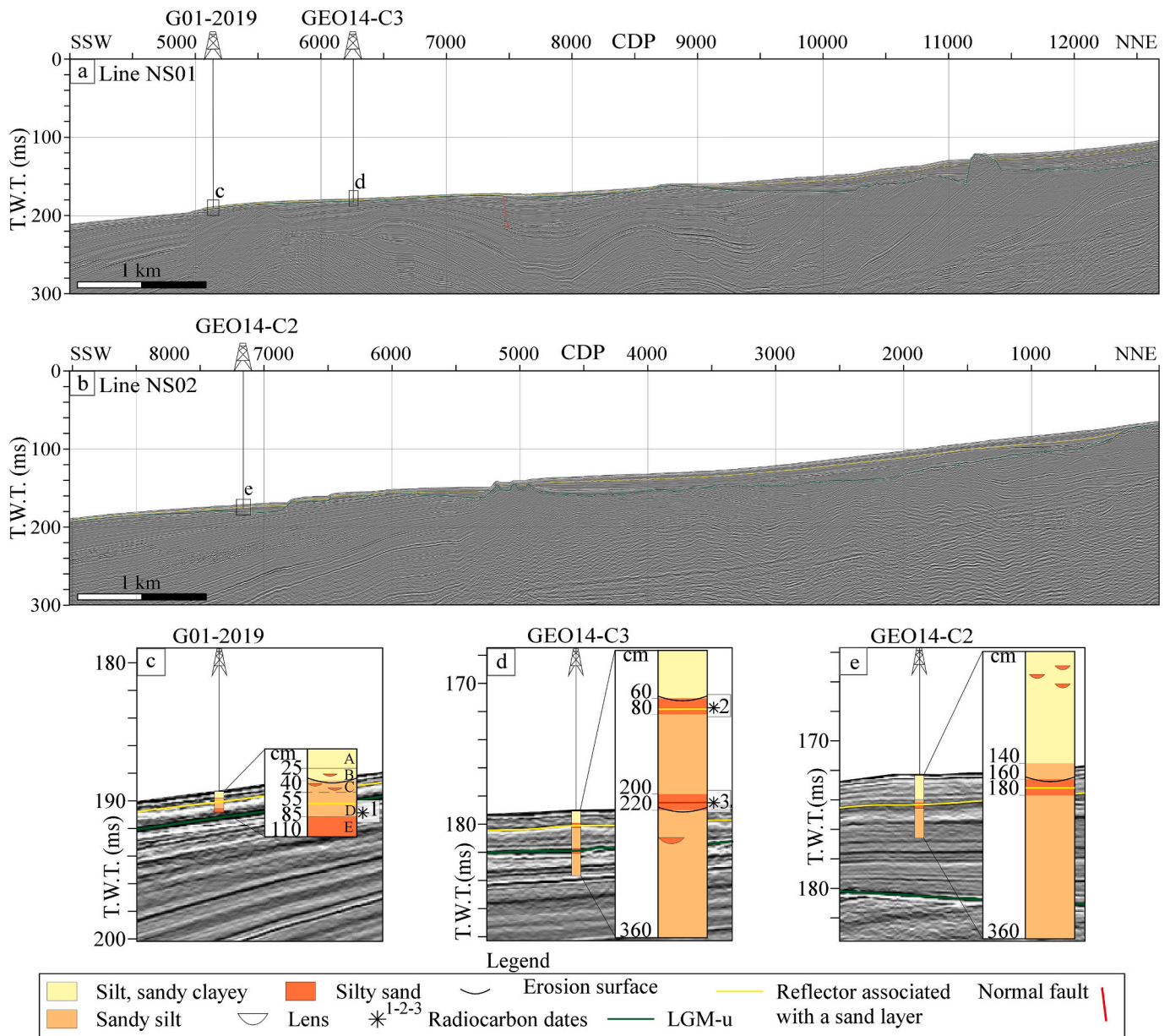




**Fig. 6.** (a) Time–depth converted seismic profile NS01 (see Figure 1b for location). (b–c) Enlarged panels of profile NS01 highlighting nearshore features identified in the SEG. (d) Interpretative map showing the location of nearshore features and associated stratigraphic units in the SEG, including correlations between seismic profiles NS01 and NS02. ID = identification number of palaeo–sea-level indicators (see Table 3); (e1–e2) and (f1–f2) Enlarged panels of profile NS02 illustrating the seismic facies used to correlate the LGM-u surface and the uppermost sand unit dated to 10.75 ka. LGM-u = Last Glacial Maximum unconformity (~20 ka). V.E. = vertical exaggeration.

- **Cliff-overstep erosion surface (ID 1 in Table 3):** an erosional surface associated with a “cliff-overstep” transgressive model (sensu Zecchin et al., 2011, 2015), interpreted to have formed at a water depth of  $2 \pm 1$  m.
- **Fairweather wave-base erosion surface (ID 2 in Table 3):** an erosional surface interpreted to have developed at a water depth of  $10 \pm 5$  m, corresponding to the maximum depth of frequent wave-driven sediment agitation under average conditions (Cattaneo and Steel, 2003). We adopt the lower-bound estimate of 5 m because SEG is interpreted as a moderate-energy setting.
- **Nearshore bar (ID 3 in Table 3):** a sedimentary body formed within the shoaling and wave-breaking zone (Davidson-Arnott, 2013; Ribas et al., 2017; Van Enkevort et al., 2004). In the northwestern Mediterranean and central Tyrrhenian Sea, such features typically occur at water depths of 1–5.5 m (Aleman et al., 2017; Feyssat et al., 2024; Ojeda et al., 2011; Melito et al., 2020; Taramelli et al., 2020).
- **Edge of infralittoral prograding wedge (IPW; ID 4 in Table 3):** the seaward, convex-upward limit of a depositional surface corresponding to the topset–foreset rollover. This feature is readily identifiable on seismic profiles due to its terraced wedge morphology,





**Fig. 7.** Seismic profiles (a) NS01 and (b) NS02 showing the projection of the gravity cores used in this study onto the seismic lines. (c, d) Stratigraphic correlation of gravity cores in the SEG, with lithology and depth indicated. The blue line marks a seismic reflector correlated with a sandy layer dated at 10.75 ka.

with its depth primarily controlled by storm wave-base levels (Chiocci and Orlando, 1996; Casalbone et al., 2017). Reported depths vary with local oceanographic and climatic conditions and methodological approaches:  $\sim 20 \pm 3$  m near the Capo Vaticano promontory (Pepe et al., 2014) and  $\sim 20 \pm 10$  m in the southeastern Tyrrhenian Sea (Casalbone et al., 2017).

Uncertainties in palaeo-water depth were evaluated for all indicators used in the time-to-depth conversion of the seismic profiles. This assessment accounts for variability in seismic-wave velocities, assuming minimum values of 1490 m/s in the water column and 1600 m/s in sediments, and maximum values of 1535 m/s and 1750 m/s, respectively. Depth uncertainty for each indicator was calculated as half the difference between maximum and minimum depth estimates, i.e.,  $(\Delta\text{depth}_{\text{max}} - \Delta\text{depth}_{\text{min}})/2$ . These uncertainties were subsequently combined with literature-derived error ranges associated with each palaeo-sea-level indicator.

### 5.3. Sant'Eufemia Gulf: RSL change from the LGM to the early Holocene

Within the SEG, eight sectors of the seismic profiles preserve geomorphological and stratigraphic markers indicative of former RSL, including erosional surfaces, cliff-overstep geometries, nearshore bars, and infralittoral prograding wedges. These features record successive phases of RSL rise, stillstand, and fall.

#### Phase 1: Onset of post-LGM sea-level rise

Three erosional surfaces (ID 1 in Table 3) and associated “cliff-overstep” morphologies (sensu Zecchin et al., 2011, 2015), each comprising a subvertical escarpment fronted by a basal wave-cut platform, are identified along the seismic profile NS02 (Figure 8a). The lowermost surface, at  $\sim 137$  m bpsl, truncates pre-LGM deposits and records the initiation of coastal cliff formation followed by landward retreat. A second surface at  $\sim 135$  m bpsl reflects continued reworking during ongoing RSL change, partially truncating the pre-existing morphology. A third surface at  $\sim 126$  m bpsl marks renewed cliff retreat and the development of the uppermost escarpment (the highest

**Table 3**

Palaeo-sea-level indicators, including identification number (ID), indicative depth ranges with associated uncertainties, and references. bsl = below sea level.

| ID indicator | Past sea-level indicators                           | Water depth of formation (m bsl) | References                                                                                                 |
|--------------|-----------------------------------------------------|----------------------------------|------------------------------------------------------------------------------------------------------------|
| 1            | Erosion surface of the "cliff-overstep"             | 2 ± 1                            | Zecchin et al., 2011, 2015                                                                                 |
| 2            | Erosion surface formed at the fairweather wave base | 10 ± 5                           | Cattaneo and Steel, 2003                                                                                   |
| 3            | Nearshore bar                                       | 3 ± 2                            | Aleman et al., 2017; Feyssat et al., 2024; Ojeda et al., 2011; Melito et al., 2020; Taramelli et al., 2020 |
| 4            | Edge of the infralittoral prograding wedge          | 20 ± 3<br>20 ± 10                | Pepe et al., 2014<br>Casalbore et al., 2017                                                                |

morphological element in Figure 8a).

If the erosional surfaces are assumed to have formed at water depths of  $\sim 2 \pm 1$  m (Zecchin et al., 2011, 2015), they would indicate relative sea-level positions of  $\sim 135$ ,  $\sim 133$ , and  $\sim 124$  m bpsl, respectively. Nevertheless, an alternative interpretation remains possible, whereby the second and third erosional surfaces formed during the final stage of MIS 3, under falling sea-level conditions, rather than during the subsequent MIS 2 transgression.

#### Phase 2: Rapid sea-level rise and erosional reworking

An erosional surface attributed to the fair-weather wave base (sensu Cattaneo and Steel, 2003; ID 2 in Table 3) truncates the crest of the uppermost cliff at  $\sim 121$  m bpsl (Figure 8b). Assuming a minimum of  $\sim 5$  m of overlying water, this surface constrains RSL to  $\sim 116$  m bpsl. As in Phase 1, formation during late-stage sea-level fall rather than early transgression remains a viable alternative interpretation.

#### Phase 3: Sediment infill and nearshore bar development

Continued RSL rise, promoted sediment infill within topographic depressions (Unit U1; Figure 8c). In the landward sector, a nearshore bar system (Unit U2; Figure 8c) constrains RSL to  $\sim 3$  m above the bar crest (ID 3 in Table 3), consistent with analogous from the NW Mediterranean and central Tyrrhenian Sea (e.g., Aleman et al., 2017; Feyssat et al., 2024; Ojeda et al., 2011; Melito et al., 2020; Taramelli et al., 2020). These sedimentary bodies are confidently interpreted as post-LGM in age, as they are underlain and delimited at their base by the LGM-u erosional surface.

Using the present-day bar crest depth ( $\sim 108$  m bpsl), RSL is estimated at  $\sim 105$  m bpsl (solid line in Figure 8c). This stillstand is further supported by an erosional surface truncating Unit U1 (ID 2 in Figure 8c). Reconstructed water depths ( $< 15$  m) are consistent with fair-weather wave-base processes.

#### Phase 4: Progradation and minor sea-level fall

A relative stillstand favoured the formation of an IPW (Unit U3; Figure 8d; ID 4 in Table 3). The rollover depth ( $\sim 115$  m bpsl) implies an RSL position of  $\sim 95$  m bpsl (dashed line in Figure 8d), assuming  $\sim 20$  m of overlying water (Casalbore et al., 2017; Pepe et al., 2014).

This phase is followed by a minor RSL fall ( $\sim 5$  m), which increases water depths over the wedge and promotes wave reworking, as evidenced by an erosional surface at its top (ID 2 in Table 3). RSL subsequently rose again to  $\sim 100$  m bpsl by the end of this phase (solid line in Figure 8d).

#### Phase 5: MWP-1A rise and subsequent fall

Phase 5 corresponds to the rapid rise in RSL associated with Meltwater Pulse 1A (MWP-1A), during which sea level increased by  $\sim 24$  m (Fairbanks, 1989). This rise caused RSL to shift from  $\sim 100$  m bpsl at the end of Phase 4 to  $\sim 76$  m bpsl (Figure 8e), driving aggradational

deposition (subunit U4a). A subsequent stillstand is indicated by IPW development (subunit U4b, Figure 8e; ID 4 in Table 3). The estimated water depth of  $\sim 76$  m bpsl is consistent with the IPW development, with the rollover depth at  $\sim 96$  m bpsl. The stillstand is followed by a relative fall of  $\sim 5$  m (to  $\sim 81$  m bpsl), marked by an erosional surface truncating the wedge.

#### Phase 6: Younger Dryas RSL rise and stillstand

Renewed RSL rise led to aggradation of Unit U5, followed by a pronounced stillstand during the Younger Dryas stadial (12,846–11,643 ka), favouring formation of IPW Unit U6 (Figure 8f; ID 4 in Table 3). The absence of erosional truncation suggests relatively stable RSL conditions, with water depths of  $\sim 20$  m consistent with IPW development (Casalbore et al., 2017; Pepe et al., 2014). Based on the rollover depth ( $\sim 79$  m bpsl), RSL is estimated at  $\sim 59$  m bpsl at  $\sim 11.7$  ka.

#### Phases 7–8: Post-MWP-1B rise and early Holocene

Phase 7 records a renewed RSL rise associated with MWP-1B ( $\sim 11.5$ – $11.1$  ka), reflected in aggradational deposition of Unit U7 (Figure 8g). This phase is temporally correlated with Meltwater Pulse 1B (MWP-1B;  $\sim 11.5$ – $11.1$  ka), a warm interval associated with accelerated sea-level rise. Beyond 10.75 ka (base of Unit U8, see Table 1), local constraints are lacking. Eustatic curves reported in the literature, after correction using GIA models, indicate a sea-level rise ranging from  $\sim 4.5$  m (Lambeck and Purcell, 2005; ANU04-MED) to  $\sim 11.5$  m (Roy and Peltier, 2015, 2017; ICE-7G(VM7)). Higher estimates of up to  $\sim 18$  m have been proposed for MWP-1B based on data from the Sicily Channel (Civile et al., 2015). In the absence of direct constraints, a mean estimate of  $\sim 11.3$  m is adopted here as a representative value, while retaining the full range as uncertainty. This yields an RSL position of  $\sim 48$  m bpsl (Figure 8g). Subsequent Holocene RSL rise led to the formation of Unit U8 (Figure 8h). No diagnostic seismic geometries within the dataset further constrain the trajectory of sea-level rise during this interval.

Following the construction of the RSL curve, palaeo-sea-level marker depths were corrected to account for vertical tectonic movements. The wider Catanzaro Strait region is characterised by long-term uplift of  $\sim 40$  m over  $\sim 770$  kyr ( $\sim 0.05$  mm yr $^{-1}$ ; Longhitano et al., 2014), whereas the continental shelf has undergone  $\sim 5$  m of subsidence over the last  $\sim 20$  ka ( $\sim 0.25$  mm yr $^{-1}$ ; Martorelli et al., 2023).

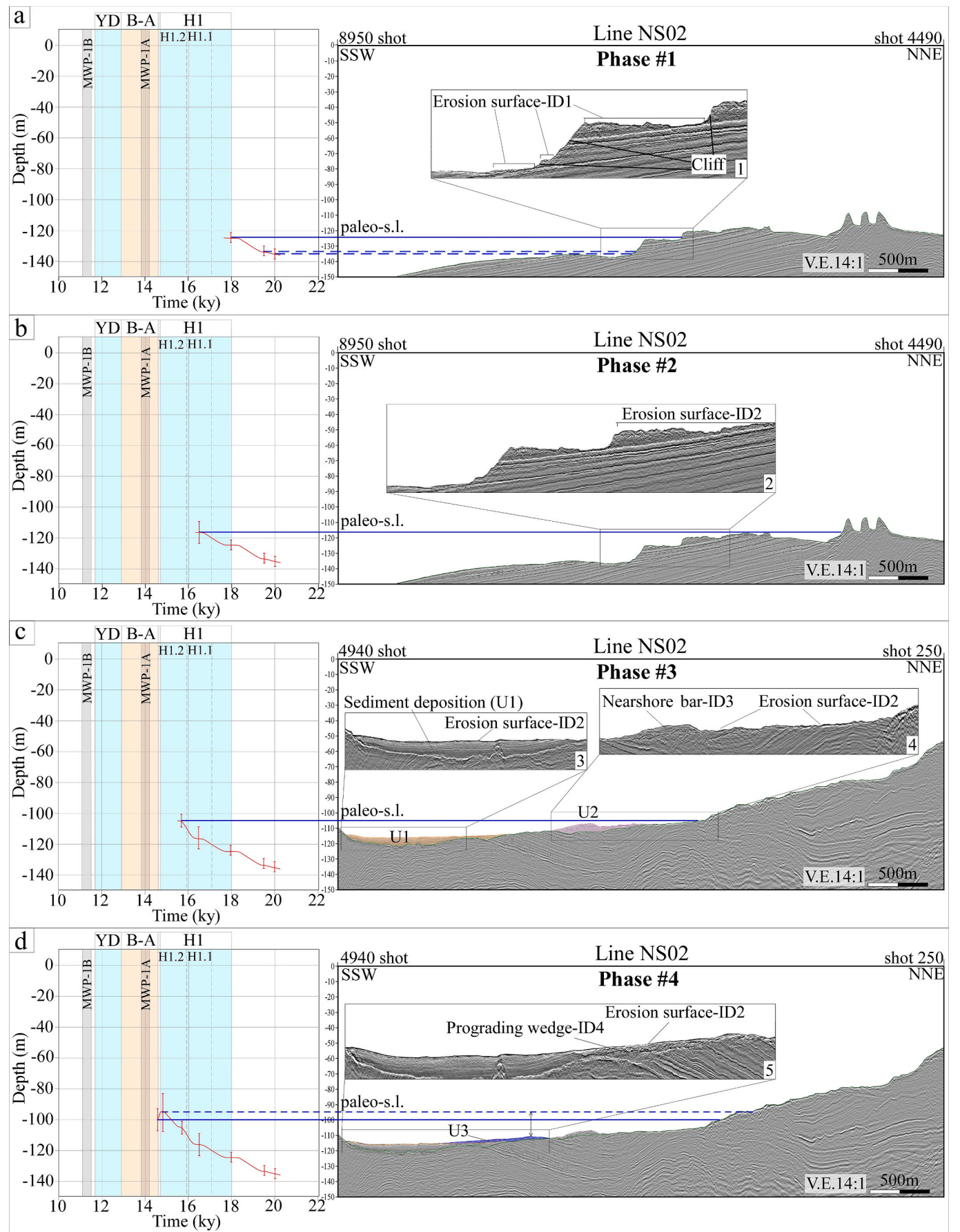
To reconcile these contrasting trends—regional uplift and local, fault-controlled subsidence—a net vertical displacement rate of  $\sim 0.2$  mm yr $^{-1}$  was adopted, reflecting the dominant subsidence signal over the Late Quaternary interval considered in this study. This linear correction was applied to the RSL curve to account for cumulative vertical ground movement over the past 20 ka (Figure 9).

#### 5.3.1. RSL Curve Validation via Grain-Size Analysis and Benthic Foraminifera

The RSL reconstruction between  $\sim 14.5$  ka and the early Holocene is independently supported by benthic foraminiferal assemblages (BF5–BF3) and granulometric trends observed in Units D and E from the lower portion of core G01-2019 (Figure 2). The *Gephyrocapsa muelleriae* peak bioevent, recognised within Unit E and dated to 14.1 ka cal BP (Table 2; Sections 4.1 and 4.2), corresponds to a palaeo-water depth of  $\sim 48$  m (146–98 m) on the reconstructed RSL curve (red rectangle in the curve of Figure 9). This estimated palaeo-water depth is consistent with an outer infralittoral depositional setting, as indicated by the occurrence of gravelly muddy sands and the benthic foraminiferal assemblage (BF5) within Unit E, dominated by shallow-water taxa such as *Elphidium*, *Miliolidae*, and epiphytic species. Within Unit E, progressive deepening is inferred from the upward decline in shallow-water benthic foraminiferal taxa (transition from BF5 to BF4), accompanied by a decrease in the sand-to-silt ratio. Sediments are predominantly fine-skewed and contain abraded, reddened mollusc and foraminiferal remains, indicative of reworking and prolonged residence under low-energy marine conditions.

A subsequent phase of sea-level rise, reconstructed between  $\sim 12.9$  and 11.5 ka BP, corresponds to the lower portion of Unit D in core G01-





**Fig. 8.** (a–h) Depth-converted cross-sections from seismic profile NS02 illustrating reconstructed relative sea-level (RSL) positions associated with the development of key palaeo-sea-level indicators (ID 1–4; see Table 3) during successive phases of RSL rise, stillstand, and fall (Phases 1–8; see Section 5.3). For each phase, stratigraphic units younger than the considered time slice have been removed to isolate the preserved depositional and erosional record. Phase 1 (~20 ka) marks the onset of post-LGM sea-level rise, whereas Phase 7 (~10.75 ka) represents the youngest chronologically constrained stage based on core GEO14-C3 (Loreto et al., 2023). Phase 8 corresponds to the subsequent early Holocene interval, for which RSL estimates rely on published data. Each panel includes the reconstructed RSL curve from the LGM to the corresponding time slice. Dashed and solid blue lines denote earlier and later RSL positions within each phase. B-A, Bølling–Allerød; YD, Younger Dryas; H1, Heinrich Stadial 1; MWP-1A and 1B, Meltwater Pulse 1A and 1B.

2019. This unit displays a clear fining-upward trend, particularly reflected in the reduction of the gravel fraction. In parallel, benthic foraminiferal assemblages (BF4–BF3) record a shift from infralittoral to circalittoral environment. This transition is marked by a continued decline in shallow-water taxa (e.g., *Elphidium* spp., epiphytic species) and an increase in taxa such as *Bulimina spathulata*, *B. aculeata*, and *Cassidulina carinata*, which are characteristic of circalittoral environments in the Mediterranean Sea (Sgarrella and Moncharmont Zei, 1993). The *Gephyrocapsa* oceanic peak bioevent, identified within Unit D and dated to 11.6 ka cal BP (Table 2; Sections 4.1 and 4.2), corresponds to a palaeo-water depth of ~88 m on the reconstructed RSL curve (red circle in the curve of Figure 9), consistent with the circalittoral environment.

Overall, the combined granulometric fining and faunal turnover provide independent evidence for progressive deepening, supporting the RSL rise inferred from the seismic-stratigraphic framework.

### 5.3.2. Qualitative comparison with GIA-derived RSL curves

The RSL curve reconstructed in this study was qualitatively compared with a suite of synthetic RSL curves derived from different GIA models (Figure 10), computed from numerical solutions of the SLE (see Section 3.3). The comparison includes models from the ICE-X suite (Tushingham and Peltier, 1991; Peltier, 2004; Argus et al., 2014; Peltier et al., 2015; Roy and Peltier, 2015, 2017), the ANU models (Lambeck and Purcell, 2005; Lambeck et al., 2014), and the PaleoMIST model (Gowan et al., 2021).

All models predict RSL values between approximately -40 and -60 m at ~11 ka BP (Figure 10). Up to ~13.5 ka BP, model outputs remain within a relatively narrow range (-40 to -80 m). For earlier intervals, the ICE-X suite and ANU models yield a range of RSL predictions of 10–20 m, with a predicted RSL of -110 m to -120 m at ~20 ka. In contrast, the PaleoMIST model predicts a significantly higher sea level, with an RSL above 100 m bpsl at ~20 ka.

The RSL reconstruction presented here indicates a systematically lower sea-level position at ~20 ka compared to most model predictions. Specifically, our estimate is ~7 m lower than that of Lambeck et al. (2011) and ~4 m lower when uncertainties on RSL observations are accounted for. Among the evaluated models, the Lambeck et al. (2011) curve provides the closest agreement for this time slice. From ~18.5 ka onward, the reconstructed curve broadly converges with modelled trends within uncertainty bounds, with the notable exception of the PaleoMIST and ICE-3G (VM1) models, which show persistent deviations in both absolute depth and temporal evolution.

Overall, the comparison indicates that existing GIA-based RSL predictions do not fully reproduce the reconstructed RSL trajectory, particularly between ~20 and 11 ka. Model outputs generally exhibit more subdued sea-level variability than that inferred from the record we present. Given that these models are based on independent implementations of the SLE, the systematic nature of this mismatch suggests that current GIA frameworks—particularly those based on laterally homogeneous (1-D) Earth models—may not adequately capture the spatial and temporal complexity of post-LGM RSL evolution in the southeastern Tyrrhenian region. This discrepancy highlights the importance of integrating multiple independent palaeo-sea-level indicators to constrain RSL reconstructions.

To further assess model performance, a qualitative comparison was conducted using 11 RSL data points from this study (hereafter, “reference depth points”). Palaeo-sea-level estimates from each model were extracted at corresponding ages (Table 4) and evaluated against the

uncertainty envelopes of the reconstructed values. The PaleoMIST and ICE-3G (VM1) models were excluded from this analysis due to their substantial deviations from the reconstructed curve. Among the remaining models, the ANU14-HV and ANU14-LV Earth–ice solutions (Lambeck et al., 2014), together with the ANU04-MED solution (Lambeck and Purcell, 2005), show the highest level of agreement, matching 7 of the 11 reference depth points (Table 4).

It is important to note that the differences among the ANU14-HV, ANU14-LV, and ANU04-MED solutions do not reflect fundamentally distinct physical models, but rather represent alternative realisations within a common modelling framework, defining an envelope of plausible RSL projections (e.g., percentile-based bounds). At the same time, other models, such as ICE-5G (VM2a), ICE-7G (VM7), and the Lambeck et al. (2011) reconstruction, demonstrate comparable performance, each matching 6 of the 11 reference points. This indicates that, although ANU-based solutions provide the closest overall agreement, no single model fully reproduces the reconstructed RSL evolution.

### 5.4. Spatial distribution of RSL in the central Mediterranean

In this study, the ANU14-HV solution is used to generate contour maps of RSL distribution across the central Mediterranean at three key time slices (11, 15, and 20 ka), corresponding to the temporal range constrained by the available data (Figure 11). As shown in Figure 10, this model provides the closest overall agreement with the reconstructed RSL curve, predicting sea-level positions within a few metres of those derived for the SEG along large sectors of the central and southern Tyrrhenian margins, the Ionian Sea, and much of the Sicilian shelf. This agreement suggests that the reconstructed RSL curve may be considered broadly representative, at least in a first-order, qualitative sense, of regional sea-level variability between ~11 and 20 ka across these sectors of the central Mediterranean. However, spatial deviations evident in the model outputs indicate that local departures from this generalised trend are significant. Accordingly, the application of the Sant’Eufemia RSL curve to other areas requires spatial corrections derived from GIA-based contour maps to account for regional variability.

## 6. Conclusion

The integration of high-resolution multichannel seismic profiles with sedimentological, micropalaeontological, and calibrated radiocarbon data from gravity cores has enabled the identification of multiple morpho-stratigraphic markers spanning several millennia, including erosional surfaces, infralittoral prograding wedges, and a nearshore bar, along the continental shelf of the SEG from the LGM.

These markers provide robust constraints on past sea-level positions, allowing reconstruction of an RSL curve from the LGM to the early Holocene. The resulting curve exhibits a non-linear, step-like architecture, characterised by alternating phases of sea-level rise and intervals of relative stillstand or minor falls. The vertical resolution achieved in this study reveals low-amplitude sea-level oscillations superimposed on the overall transgressive trend, which were not well resolved in previous reconstructions. Independent sedimentological and micropalaeontological evidence, particularly grain-size variations and benthic foraminiferal assemblages, closely track these phases, providing strong, process-based validation of the reconstructed RSL signal.

Comparison with synthetic RSL curves derived from published GIA models indicates that the ANU14-HV, ANU04-MED, and ANU14-LV



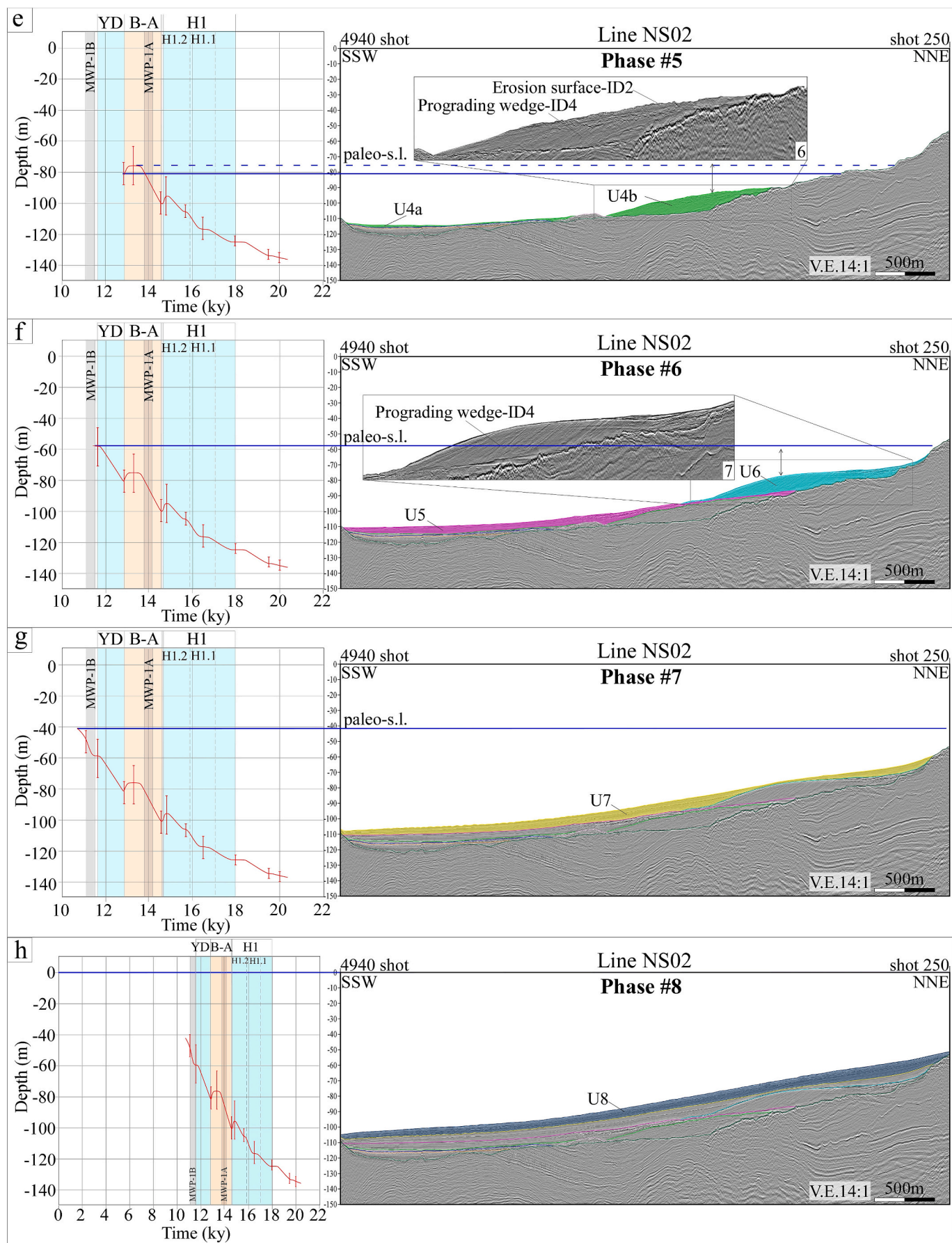
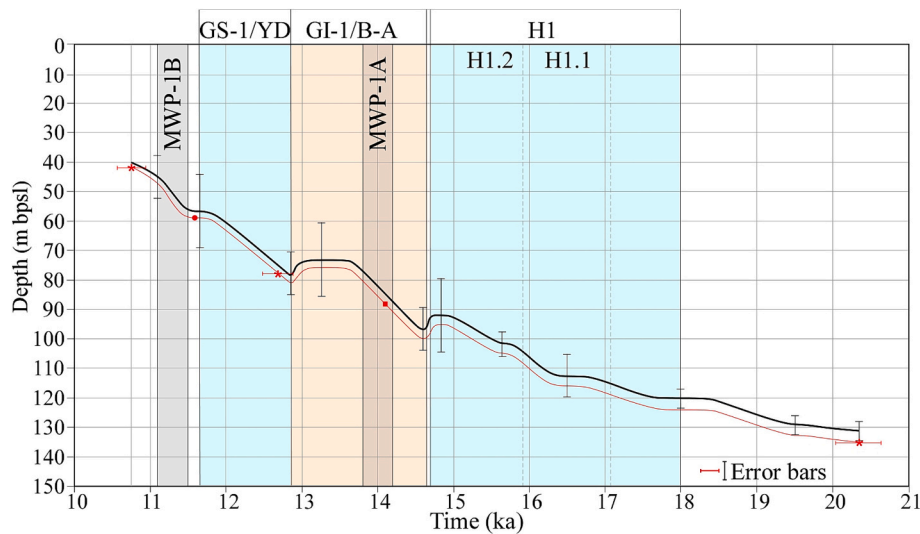
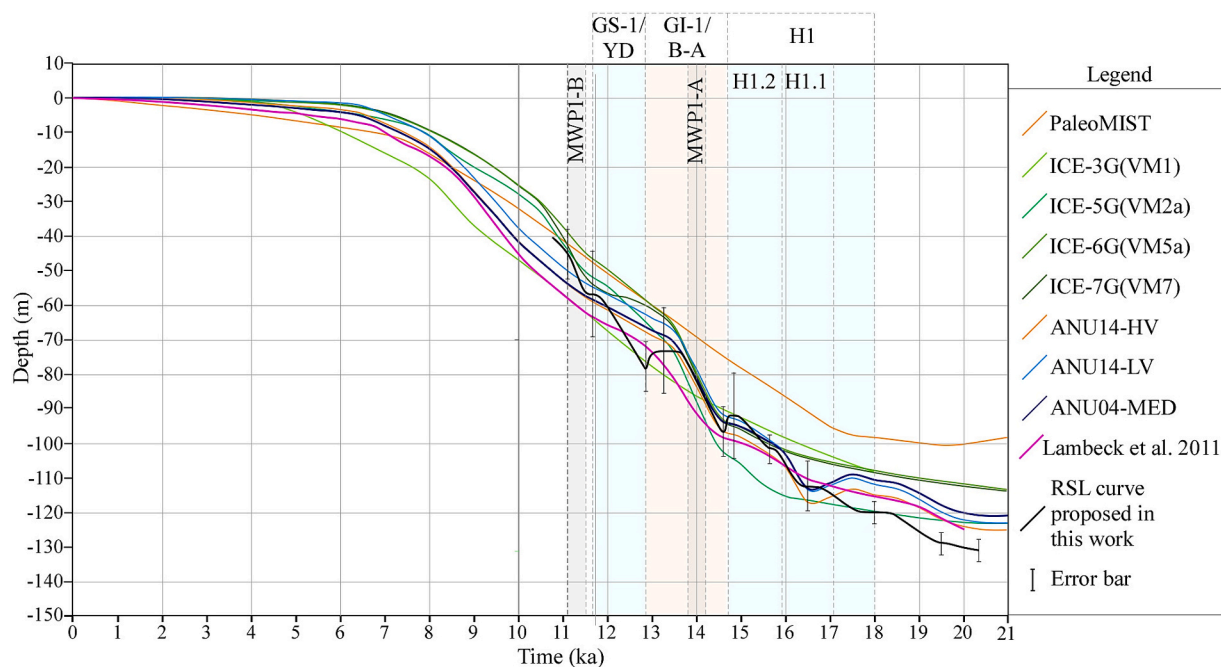


Fig. 8. (continued).



**Fig. 9.** RSL curve for the SEG from the LGM to 10.75 ka. The red line represents the RSL reconstruction derived from nearshore geomorphic features, seismic-stratigraphic markers, AMS  $^{14}\text{C}$  ages (Table 1; red stars on the curve), and bioevents (Table 2; red rectangle and circle on the curve indicating the *Gephyrocapsa muelleri* peak and the top *Gephyrocapsa oceanica*, respectively). This reconstruction integrates the effects of global sea level, glacial isostatic adjustment, and local tectonics. The black line shows the RSL curve corrected for regional uplift and fault-related deformation, assuming a net vertical displacement rate of  $0.2 \text{ mm yr}^{-1}$ . GI-1/B-A, Greenland Interstadial-1/Bølling-Allerød; GS-1/YD, Greenland Stadial-1/Younger Dryas; H1, Heinrich Stadial 1; MWP-1A and 1B, Meltwater Pulse 1A and 1B.



**Fig. 10.** Comparison between the RSL curve proposed in this study and modelled RSL predictions derived from a range of glacial isostatic adjustment (GIA) models available in the literature.

solutions provide the closest agreement across multiple time slices, although no single model fully reproduces the observed RSL trajectory. This result highlights both the robustness of the geological reconstruction and the current limitations of GIA models, particularly in capturing short-term variability and region-specific responses. Nevertheless, the overall agreement supports the use of the reconstructed curve as a first-order approximation of RSL evolution across large sectors of the central Mediterranean, provided that spatial corrections are applied.

More broadly, this study demonstrates that integrating high-resolution seismic stratigraphy with sedimentological and micro-palaeontological proxies significantly enhances the resolution and reliability of RSL reconstructions. The methodological framework

developed here is transferable and provides a reproducible basis for future investigations of sea-level change in coastal systems characterised by complex interactions among eustasy, tectonics, and sediment dynamics. These results also emphasise the need for improved GIA modelling approaches, potentially incorporating three-dimensional Earth structure and better regional constraints, to more accurately resolve post-LGM sea-level evolution.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.margeo.2026.107810>.



Table 4

Comparative analysis of the RSL curve for the SEG, reconstructed from the LGM to the early Holocene, and GIA-corrected model outputs from the ICE-X class (see Section 3.3), together with the RSL curve for Briatico proposed by Lambeck et al. (2011). Modelled RSL values were extracted at the ages corresponding to the reconstructed data points using linear interpolation between adjacent time steps. Best-fit depth values (in bold) indicate modelled RSL estimates that fall within the uncertainty bounds of the reconstructed data.

| Time (ky)               | RSL in the Sant'Eufemia Gulf |     | ANU14-HV    | ANU14-LV | ANU04-MED | ICE-5G (VM2a) | ICE-6G (VM5a) | ICE-7G (VM7) | Lambeck et al., 2011 |
|-------------------------|------------------------------|-----|-------------|----------|-----------|---------------|---------------|--------------|----------------------|
|                         | RSL (m)                      | u   | RSL (m)     | RSL (m)  | RSL (m)   | RSL (m)       | RSL (m)       | RSL (m)      | RSL (m)              |
| 20.0                    | -131                         | ±3  | -124        | -122     | -120      | -123          | -112          | -112         | -125                 |
| 19.5                    | -129                         | ±3  | -122        | -120     | -118      | -122          | -111          | -112         | -122                 |
| 18.0                    | -120                         | ±3  | -116        | -113     | -112      | <b>-121</b>   | -109          | -110         | -117                 |
| 16.5                    | -113                         | ±7  | <b>-116</b> | -112     | -111      | <b>-117</b>   | -105          | <b>-106</b>  | <b>-112</b>          |
| 15.7                    | -102                         | ±4  | <b>-102</b> | -98      | -99       | -112          | <b>-99</b>    | <b>-99</b>   | <b>-103</b>          |
| 14.8                    | -92                          | ±12 | <b>-98</b>  | -94      | -95       | -106          | <b>-95</b>    | <b>-96</b>   | <b>-100</b>          |
| 14.6                    | -97                          | ±7  | <b>-95</b>  | -90      | -93       | <b>-101</b>   | <b>-92</b>    | <b>-93</b>   | <b>-98</b>           |
| 13.3                    | -73                          | ±12 | <b>-73</b>  | -68      | -71       | <b>-74</b>    | <b>-66</b>    | <b>-67</b>   | <b>-81</b>           |
| 12.9                    | -79                          | ±7  | -69         | -64      | -67       | -67           | -60           | -61          | <b>-71</b>           |
| 11.7                    | -57                          | ±12 | <b>-61</b>  | -57      | -61       | <b>-55</b>    | <b>-50</b>    | <b>-57</b>   | <b>-66</b>           |
| 11.1                    | -48                          | ±7  | <b>-53</b>  | -49      | -53       | <b>-42</b>    | <b>-37</b>    | -40          | <b>-58</b>           |
| Number of intersections |                              |     | 7/10        | 7/10     | 7/10      | 6/10          | 5/10          | 6/10         | 6/10                 |

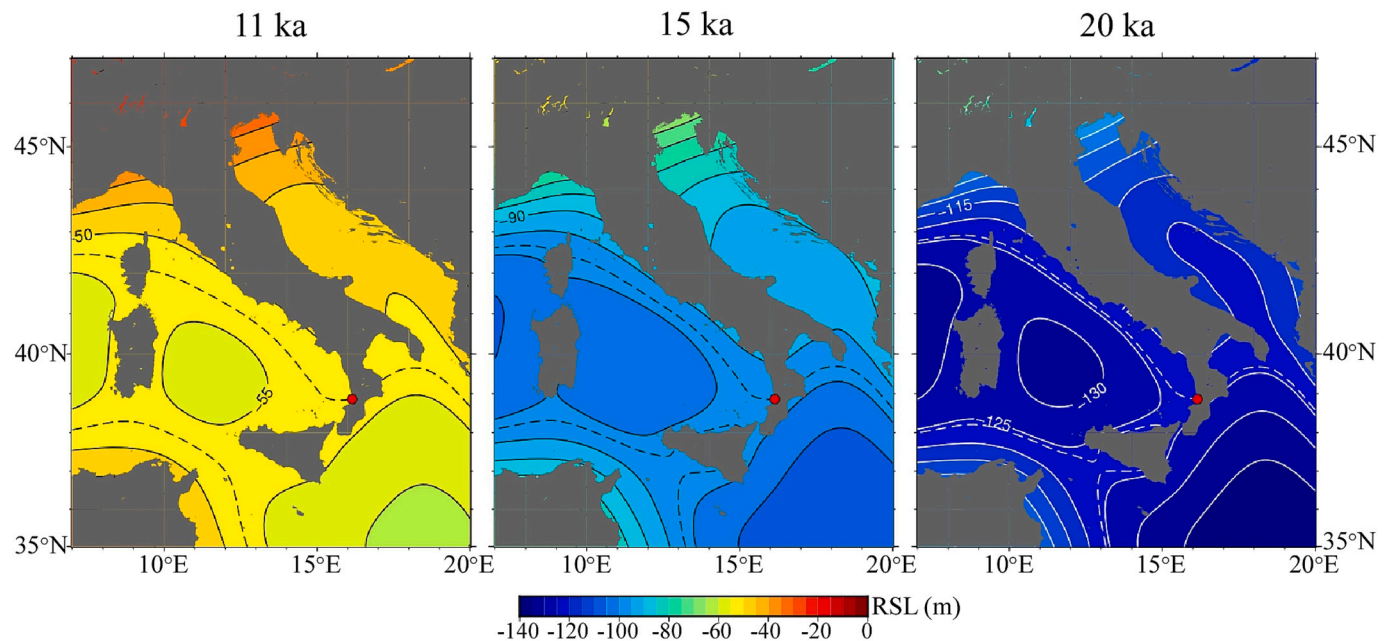


Fig. 11. Contour plots showing the spatial distribution of RSL in the central Mediterranean as predicted by the ANU14-HV GIA model at 20, 15, and 11 ka. Solid contour lines represent 5 m RSL intervals, whereas the dashed contour line marks locations where modelled RSL matches that of the SEG. The results indicate that RSL values in the vicinity of the SEG are broadly representative of those along the Italian coastlines of the central and southern Tyrrhenian Sea, the Ionian Sea, and most sectors of the Sicilian coastline. This interpretation implicitly assumes that the ANU14-HV model adequately captures the glacio-isostatic response across the entire study region. However, this assumption may be limited by model simplifications, including the adoption of laterally homogeneous (1-D) Earth structure and the neglect of spatial variations in mantle rheology. These limitations may lead to region-specific mismatches between modelled and actual RSL signals. Therefore, caution is required when extrapolating the reconstructed RSL curve beyond the SEG.

CRediT authorship contribution statement

M. Corradino: Methodology, Investigation, Formal analysis, Conceptualization. C. Cirelli: Data curation. V. Di Donato: Data curation. D. Melini: Data curation. F. Molisso: Data curation. G. Spada: Data curation. D. Casalbone: Data curation. F. Pepe: Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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framework for the RSL reconstruction. We also thank Sam Johnson (USGS Emeritus), one anonymous reviewer and the editor Michele Rebesco for their constructive comments, which significantly improved the clarity, scientific rigour, and overall quality of the manuscript.

## Data availability

The seismic profiles used in this study are available in the Data Availability section at

<https://www.dropbox.com/scl/fo/q9ushh0m0k09s1t74gzt/AEnX12PJWnwJjQqifP8e5W0?rlkey=0ym2dur8ck8m12hcn53xj0px&dl=0>

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