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Pattern and rate of post-20 ka vertical tectonic motion around the Capo Vaticano Promontory (W Calabria, Italy) based on offshore geomorphological indicators

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A R T I C L E I N F O

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A B S T R A C T

The magnitude and rate of Late Pleistocene–Holocene vertical tectonic movements offshore of the Capo Vaticano Promontory (western Calabria, southern Italy) have been measured on the basis of the present-day depth variations of the edges of submerged depositional terraces (and associated abrasion platforms) that formed below the storm-wave base, during the sea level stillstand of the Last Glacial Maximum (LGM). These depositional features, represented by submerged prograding wedges and an associated terrace-shaped upper boundary, have been identified in high-resolution seismic reflection profiles acquired along the continental shelf and the upper slope of the promontory, and are referred to in this study as "Lowstand Infralittoral Prograding Wedges (LIPWs)". Our new data and methods provide evidence that LIPWs can be used as geomorphological indicators of vertical movements in offshore settings with well controlled uncertainty. Removal of the non-tectonic component of vertical changes using an ice-volume equivalent eustatic sea level compilation indicates ~11 (±3.2) m of uplift and ~25 (±3.2) m of subsidence, from southwest to northeast, along the promontory, over a distance of ~22 km, during the post-LGM. The resulting uplift and subsidence rates (including both regional and local components) for the last 20.350 (±1.35) years are 0.54 (±0.2) mm/y and 1.23 (±0.25) mm/y, respectively. These results are consistent with longer-term estimates based on uplifted 215–82 ka old coastal terraces and Late Holocene shorelines. This integration of offshore and coastal markers indicates a pattern of vertical movements characterized by a marked asymmetry associated with a northeast down tilt of the Capo Vaticano Promontory. The calculated tilt rate increases by one order of magnitude during the post-LGM in respect to the time interval from 215 to 82 BP. Displacement associated with the NW–SE striking normal fault that bound the Capo Vaticano Promontory to the Gioia Tauro Basin ended in the (?) Pleistocene, and thus does not contribute to the tilt of the promontory at least during the last 215 ka.

1. Introduction

The Capo Vaticano Promontory is a structural high located on the western (Tyrrhenian) side of the Calabrian Arc orogenic wedge (Fig. 1a), and makes up part of the upper plate of the Ionian subduction zone in the central Mediterranean (Fig. 1b). Following the south-eastward emplacement, the Calabrian Arc has undergone sustained Quaternary uplift reflected by elevated flights of Pleistocene coastal terraces (i.e. Westaway, 1993) and by Holocene terraces and beach deposits (i.e. Antonioli et al., 2006; Ferranti et al., 2010 and references therein). Uplifted Pleistocene coastal terraces are found at the Capo Vaticano Promontory (Tortorici et al., 2003; Cucci and Tertulliani, 2006, 2010; Bianca et al., 2011 and references therein) and are particularly suitable for the reconstruction of the long-term (>10^2 ky) uplift. The NE-ward elevation of the Pleistocene terraces documents an asymmetric uplift of the promontory with a marked northeast down tilt. Raised Holocene shorelines (terraced deposits, abrasion

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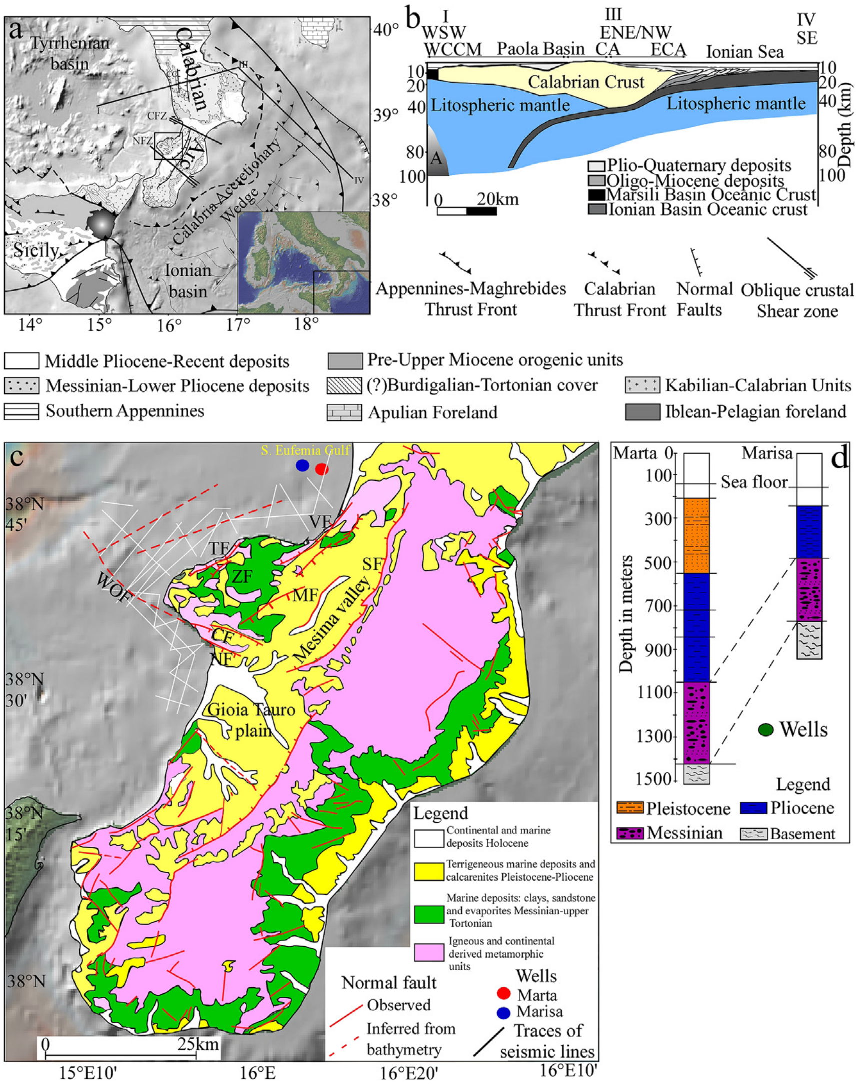


Fig. 1. (a) Topography, bathymetry and main tectonic features of southern Italy (square: Capo Vaticano Promontory). (b) Cross section from the Marsili ocean crust (southern Tyrrhenian) to the Ionian foreland displaying the lithospheric setting of the "Ionian Subduction zone". No vertical exaggeration. I–III–IV, trace of the cross section. WCCM = Western Calabria continental margin; CA, Calabrian Arc; ECA, External Calabria Arc; A, Astenosphere. (c) Simplified geologic map of southern Calabria. WOF, Western Offshore Fault; CF, Coccorino Fault; NF, Nicotera Fault; TF, Tropea Fault, ZF; Zaccanopoli Fault, MF, Mileto Fault; SF, Serre Fault; VF, Vibo Fault; CNZ and NFZ, NW–SE, left-lateral, crustal shear zones. (d) Core log indicating the lithostratigraphic units drilled at Marta and Marisa holes; Data from ViDEPI project (http://unmig.sviluppoeconomico.gov.it/).

platforms, barnacle and algal rims, and notches: Ferranti et al., 2010) also indicate that uplift and that the northeast down tilt persisted during the Late Holocene. However, the significant time-gap between the younger (82 ka) and most continuous marine terrace, as well as the raised Holocene shorelines does not allow a straightforward correlation between the Pleistocene (10^3–10^2 ky) and the Holocene (1 ky) pattern and rate of uplift and tilting of the promontory.

The Quaternary uplift of Calabria including the area of Capo Vaticano is thought to result from a dominant deep-seated deformation, with a superposed effect of upper crustal faulting. Although the combination of the two processes has been well documented both over a long-term (10^3–10^2 ky: Westaway, 1993; Ferranti et al., 2007) and a short-term (1–5 ky: Ferranti et al., 2007, 2010) timescale, studies at an intermediate-age (10 ky) timescale have not been published so far.

The aims of this study are a) to assess if the submerged depositional terraces (and the associated abrasion platform) formed below the storm-wave base during the sea level still-stand of the Last Glacial Maximum (LGM), and referred to here as "Lowstand Infralittoral Prograding Wedges (LIPWs)", can be confidently used as geomorphological indicators of vertical movements with well controlled uncertainty, and b) to estimate the pattern and rate of vertical tectonic movements around the Capo Vaticano Promontory during the Late Pleistocene–Holocene over an intermediate time-period (10 ka).

LIPWs formed in the outer shelf of the Tyrrhenian and Ionian Sea have been previously described by several investigators (i.e. Chiocci and Orlando, 1996; Pepe et al., 2003; Firetto et al., 2013 and references therein) but few attempts have been made to quantify the amount and rate of vertical motion using the edge of associated terraced areas as markers (Firetto et al., 2013; Fraccascia et al., 2013; Sulli et al., 2013). Furthermore, previous estimates have not been associated with error bars, and, consequently, the inferred values of magnitude and rate of vertical movements are not easily compared with those obtained by uplifted Quaternary marine terraces.

The new results from offshore geomorphological indicators integrated with published data on coastal terraces formed during the

Marine Isotopic Stage (MIS) 7.3 (215 ka), MIS 5.5 (124 ka), MIS 5.1 (82 ka) and Late Holocene have allowed a link to be established between the 10^2 ky- and the 1 ky-scale tectonic processes, and thus a gap to be bridged between the underwater and the exposed domains of this part of the western Calabria margin. As a corollary, this study provides new constraints on the geometry and kinematics of faults that are relevant for the earthquake hazard analysis of the Calabria region.

2. Regional setting

The backbone of the Calabrian Arc is formed by crystalline rocks of the Calabria-Peloritani domain, which was located adjacent to Corsica–Sardinia until Early Miocene times, after which it drifted south-eastward and was juxtaposed against the Southern Apennine–Maghrebide orogenic system (Bonardi et al., 2001; Mattei et al., 2002). The south-eastward emplacement of the Calabrian Arc was coeval with the northwest-ward Neogene subduction and roll-back of the Ionian slab beneath western Calabria and the south-eastern Tyrrhenian basin (Malinverno and Ryan, 1986; Pepe et al., 2010 and references therein, Fig. 1a and b), which today are inferred through deep earthquakes and imaged through tomography (Selvaggi and Chiarabba, 1995; Wortel and Spakman, 2000; Chiarabba et al., 2008). Offshore, the western Calabria continental margin is characterized by substantial crustal thinning which, however, is not solely associated with extensional faults (Pepe et al., 2010, Fig. 1b). Rather, since the Miocene the western Calabria continental margin experienced regional shortening accommodated by west-vergent thrusts. Shortening continued through the Pliocene to the present but was accommodated by a limited number of west-vergent thrust faults located in the western part of the margin (Pepe et al., 2010).

According to several investigators (Van Dijk et al., 2000; Tansi et al., 2007 and references therein) the Late Neogene upper crustal evolution of the Calabrian Arc was controlled by NW–SE, left-lateral, crustal shear zones (i.e. CFZ, NFZ, Fig. 1a) which dissected the Oligocene–Early Miocene orogenic belt and controlled the evolution of thrust belt basins. During the Late Pliocene and Quaternary, the Arc was dissected by longitudinal and transversal normal faults, which form the currently active tectonic belt along the mountain ridge and the western margin of Calabria (Ghisetti, 1981). Active NW–SE extension is documented by field mapping and structural analysis (Tortorici et al., 1995; Monaco and Tortorici, 2000; Ferranti et al., 2008; Faccenna et al., 2011), focal mechanisms of crustal earthquakes (Vannucci et al., 2004; Pondrelli et al., 2011; Presti et al., 2013), and geodetic velocities (D'Agostino and Selvaggi, 2004; Serpelloni et al., 2010; Devoti et al., 2011; Palano et al., 2012).

The Calabrian Arc was affected by uplift since the Late Pliocene, and at a faster rate after ~0.8 Ma (Dumas et al., 1982, 1988, 1999; Ghisetti, 1984, 1992; Westaway, 1993; Miyauchi et al., 1994; Monaco and Tortorici, 2000; Olivetti et al., 2012). Regional uplift is interpreted as an isostatic response to slab break-off (Westaway, 1993; Wortel and Spakman, 2000), or as a result of the convective removal of deep roots and decoupling of the Calabria forearc from the subducting plate (Doglioni, 1991; Gvirtzman and Nur, 2001). Whereas regional uplift is estimated at a maximum of 1 mm/y during the last 125 ka, footwall uplift along individual faults was typically ~0.2 mm/y (Westaway, 1993; Catalano and De Guidi, 2003), but might have peaked to 1 mm/y during limited time intervals (Tortorici et al., 2003; Ferranti et al., 2007). Late Holocene (1 ky) uplift rates are consistently higher (64–124%) than longer-term (10^3–10^2 ky) uplift rates, although the fastest Pleistocene and Holocene uplift rates are spatially related (Antonioli et al., 2006).

2.1. Structural framework of the Capo Vaticano Promontory and offshore area

The Capo Vaticano Promontory and its NW offshore prolongation is essentially a coherent block of predominantly pre-Triassic metamorphic and plutonic basement rocks. A swarm of extensional faults on the eastern side accommodates the structural separation of the block from the main mountain ridge of Calabria across the Mesima valley (Tortorici et al., 2003 and references therein, Fig. 1c), a basin filled by a thick Upper Pliocene–Lower Pleistocene marine succession (Ghisetti, 1981). Towards the SW, the Nicotera (normal) Fault separates the Capo Vaticano Promontory from the Gioia Tauro Plain (Fig. 1c), which overlies a basin filled by a ~600 m thick Upper Pliocene–Quaternary sedimentary succession (Ghisetti, 1981). A few km NE of the Nicotera Fault, the Coccorino Fault is found, which is clearly visible in the field (Fig. 1c). However, the offshore continuation of these structures and, therefore, the nature of the SW boundary of the Capo Vaticano Promontory, are unclear. Tortorici et al., 2003 suggest that the Coccorino Fault continues offshore towards the NW, along the morphological scarp which has been vaguely defined by low-resolution bathymetric maps (Fig. 1c). Cucci and Tertulliani (2010), from analyses of marine terraces found that the offshore part of the Coccorino fault (there called the Western Offshore Fault, Fig. 1c) could not be responsible for the M7, 1905 earthquake because of the negligible surface deformation induced onland, and suggest that the Coccorino Fault (*sensu* Tortorici et al., 2003) is only the onshore part of this tectonic lineament. Some of these faults are supposed to be active. The Coccorino Fault for instance (Cucci and Tertulliani, 2006, 2010), or one of the faults limiting the NW coast of the promontory (Piatanesi and Tinti, 2002) have been proposed as possible sources of the M7, 1905 earthquake and ensuing tsunami.

Several studies have been carried out on the raised Pleistocene terraces exposed in the Capo Vaticano Promontory (Ghisetti, 1981; Dumas et al., 1982, 1987; Barrier et al., 1988; Bonfiglio et al., 1988; Dai Pra et al., 1993; Westaway, 1993; Miyauchi et al., 1994; Tortorici et al., 2003; Cucci and Tertulliani, 2006, 2010; Bianca et al., 2011). A literature review indicates that there is general consensus in the following: (a) uplift rates have not been constant in time; (b) the northeast down tilt of the promontory; (c) fault activity alone does not fully explain the total magnitude of uplift. However, in the area close to the village of Capo Vaticano there is disagreement about the uplift rates with estimates ranging from less than 1 mm/y (e.g. Miyauchi et al., 1994; Cucci and Tertulliani, 2006, 2010) up to 2 mm/y (Tortorici et al., 2003; Bianca et al., 2011).

Vertical slip rates have been computed in the onland part of the Coccorino Fault which truncate the terrace flight. Based on the terrace's offset position, Cucci and Tertulliani (2010) calculate an average vertical slip rate of 0.2–0.3 mm/y for the Coccorino Fault, during the last 215 ka. Bianca et al. (2011), by using an alternative chronological scheme for the terraces, based on "Optically Stimulated Luminescence" dating, estimate a vertical slip rates ranging from ~0.25 to ~2.5 mm/y during the same time span. Short-term geoarcheological markers of sea level changes indicate that the uplift rate at Briatico, in the northern part of the promontory, is ~0.65 mm/y for the last 1806 ± 50 BP (Anzidei et al., 2013).

3. Material and methods

3.1. Seismic data acquisition, processing

A dense grid of very high-resolution seismic reflection profiles was recorded along the continental shelf and the upper slope of the Capo Vaticano Promontory, on board the R/V Urania, during October 2012, partly overlapping with a more limited seismic reflection survey conducted in December 2010 (Fig. 1c). The acoustic source used during seismic prospecting was a 1 kJ Sparker power supply with a multi-tips Sparker array, which lacks ringing and has a base frequency of around 800 Hz, fired at a time interval of 1.5 s. Data was recorded using a single-channel streamer with an active section of 2.8 m, containing seven high-resolution hydrophones, for 1.3 s two way time (t.w.t.) at a 10 kHz (0.1 ms) sampling rate. Positioning was controlled by a Differential Global Positioning System.

Data processing was performed using the Geo-Suite AllWorks software package, running the following mathematical operators: spherical divergence correction, de-ghosting, migration, band-pass (300–2000 Hz) filter, swell filter, trace mixing, time variant gain, and mute of water column. Signal penetration was found to exceed 500 ms t.w.t. The vertical resolution is ~1 m near the seafloor.

3.1.1. *Depth conversion*

The seismic lines were depth-converted following the seismostratigraphic analysis (see Section 4.1). In the study area, the average value of 1515 m/s for the sound speed on the water column was calculated using data recorded between the sea level and −180 m by the "RESON SVP20" sound velocity profiler. As no information is available on the velocities of seismic units, we have adopted average velocities from litho-stratigraphy and sonic log data available for coeval deposits in 7 wells drilled offshore in southern and western Sicily (also see Pepe et al., 2010 for details). The values we have used are 1700, 2000 and 3300 m/s for the Quaternary, Pliocene, Messinian evaporites and Upper Miocene sedimentary rocks, respectively. The uncertainties implicit in our approach to the velocities of seismic units have no consequences on the reconstructions of the pattern and rate of vertical movements we present because they are only based on the depth variations of the edges of the LIPWs that were computed using the average sound velocity speed measured in the water column. The obtained depth-converted sections are displayed with vertical exaggeration (V.E.) = 1:2 or 1:3 to better illustrate the architecture and the internal geometries of the sedimentary units.

3.2. *"Lowstand Infralittoral Prograding Wedges" as vertical movement indicators in offshore settings*

In the Mediterranean, "Infralittoral Prograding Wedges (IPWs)" have been described as shore-parallel, progradational sedimentary bodies developing along the inner shelf, between the mean fair-weather wave-base and the storm-wave-base levels, during the Late Holocene (Hernández-Molina et al., 2000; Fernández-Salas et al., 2009 and references therein). IPWs are generally formed seaward of the lower edge of abrasion platforms, which in turn are flat areas formed at and/or just above the intertidal zone. Above this zone of frequent wet/dry cycling, rock is weakened by subaerial weathering resulting in the formation of silty sands and sometimes coarse sand or gravel sediments (Retallack et al., 2012 and references therein). During storms, sediments are shed downslope to below the storm-wave base. The latter controls the accommodation space and, therefore, the depositional equilibrium profile and depositional shoreline break (Hernández-Molina et al., 2000).

Prograding sedimentary wedges bounded upwards by terrace-shaped surfaces developed over many continental margins of the Mediterranean, during the sea level stillstand of the LGM (Davis, 1985; Swift et al., 1991; Carter and Woodroffe, 1994; Reading and Collinson, 1996). These bodies typically formed under the combined action of waves and across-shore currents, which redistribute littoral sediments, and have been referred to as "Lowstand Submerged Depositional Terraces" (i.e. Chiocci and Orlando, 1996). Recently, these morphologic/sedimentary features have been considered as proxies for the position of the sea level at eustatic minima (i.e. during the LGM), and used to reconstruct the tectonic evolution of the northern Latium shelf (Fraccascia et al., 2013).

The terms "Lowstand Submerged Depositional Terraces" (sensu Chiocci and Orlando, 1996) and "Infralittoral Prograding Wedges" (sensu Hernández-Molina et al., 2000) essentially refer to depositional bodies formed by the same processes (i.e. redistribution of littoral deposits below the storm-wave base-level) under a different still-standing position of the sea level during a eustatic cycle. Therefore, in this paper we adopt the term "Lowstand Infralittoral Prograding Wedges (LIPWs) to indicate progradational sedimentary bodies sensu Hernández-Molina et al., 2000 developed during the sea level stillstand of the LGM.

3.2.1. *Paleo sea level indicators*

We have used the definitions proposed by Chiocci and Orlando (1996) to identify in seismic profiles the main morphological breaks, i.e. out-break, edge and lap-out (Fig. 2), that can be used as paleo sea level indicators. The former is the point where the terrace scarp intersects the continental slope, generally marked by a sharp break in slope. The terrace edge is placed where the seafloor breaks away from the straight line that approximates the terrace top's surface, which has a gradient generally less than 3°. The terrace lap out is the downslope end of the prograding wedge (Fig. 2). Among the features relevant as geomorphological indicators for the position of the sea level during the sea level stillstand of the LGM, in this study we have selected the seaward convex-upward edge of the depositional surface bounding the upper part of the LIPWs because it can be easily recognised on seismic profiles, and its depth is controlled by the storm-wave base levels.

3.2.2. *Paleo bathymetry*

Offshore the Capo Vaticano Promontory, LIPWs sometimes formed seaward of the lower edge of well-developed abrasion platforms. When it occurred, the depth difference between the edge of the LIPWs and the top of the abrasion platform is typically ~20 m (Fig. 2). This value is similar to that recorded by IPWs formed offshore the Ventotene Island (Chiocci and Orlando, 1996) as well as along the Spanish coast (Hernández-Molina et al., 2000), during the Late Holocene. Thus, the above mentioned depth difference can be considered as an average vertical datum in the Mediterranean Sea, not only for those IPWs developed under present-day depositional processes but also for those LIPWs formed during the sea level stillstand of the LGM.

Assuming that the erosional surface that makes the upward limit of the abrasion platforms formed between and/or just above the tide elevation range, which in the Mediterranean is between 50 and 70 cm, and thus is negligible for our reconstruction, and that the sea stood ~125 m below the present sea level around the Capo Vaticano Promontory at 20 ka (Lambeck et al., 2011), we assume in this work that the paleo-water depth for the edge of LIPWs was ~145 m. In the SW sector of the promontory, the average value for the depth of the edges of the IPWs (from 1 to 6, see Section 4.4) is 134.8 m; the standard deviation is 2.73 m while the absolute value of the maximum deviation is 3.2 m. Because we cannot exclude that the abrasion platforms developed not only in response to differential weathering but also in combination with wave erosion, in our quantitative analysis of vertical movements (uplift/subsidence) we assume an error bar of ±3.2 m (Fig. 2), coinciding with the maximum deviation.

3.2.3. *Age of youngest sediments*

Based on the most recent data on the absolute minimum sea level during the MIS 2, the LGM began ~30,000 BP (Orombrelli

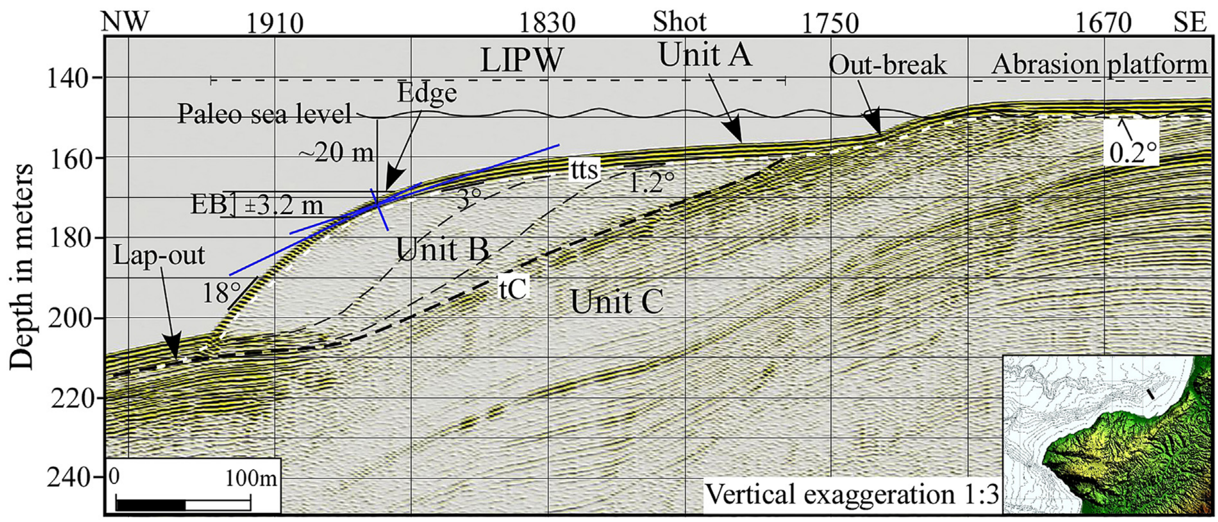


Fig. 2. Geological cross section across an LIPW formed seaward of the lower edge of the abrasion platform. EB, Error bar; tts, terrace top surface; tC, top of Unit C. Depth in meters. Vertical exaggeration 1:3.

et al., 2005 and references therein) and in the Alborean Sea (western Mediterranean) culminated at ~21,700 BP, with the sea level in its deeper position (Cacho et al., 1999; Peltier and Fairbanks, 2006; Clark et al., 2009; Oba and Irino, 2012). After this time, the sea level began to rise and at ~19,000 BP was at least 6 m above the eustatic minima reached during the sea level stillstand of the LGM (Lambeck et al., 2011). As sediment supply did not keep up with the rate of accommodation space creation, the seaward progradation of deposits ended, and the sediments avalanched onto the upper part of the continental slope during the sea level stillstand of the LGM were preserved as stable ("relict") deposits (Catuneanu, 2006). Therefore, we infer that the most recent sediments deposited on the edges of the LIPWs range in age between ~21,700 and ~19,000 BP, and in this study we assume the average value of 20,350 (±1350) BP as a nominal age for our quantitative analyses (Fig. 2).

4. Results

4.1. Seismostratigraphic analysis

Five seismic units were identified in the shallow subsurface offshore Capo Vaticano Promontory based on the internal configuration and external shape of the seismic units. These units are labelled A, B, C, D and E from youngest to oldest. Seismic characteristics such as amplitude, reflection continuity, external shape, and frequency allow us to infer depositional processes operating in the study area (Damuth, 1980). The seismic facies were also calibrated with data coming from the Marta and Marisa wells drilled a few kilometres north of the promontory (see Fig. 1 for location). These wells document a stratigraphic architecture characterised by a metamorphic basement covered by an Upper Miocene sedimentary succession (which includes Messinian evaporites), in turn overlain by Pliocene fine-grained deposits (mudstones and claystones) and by Pleistocene coarser deposits (sandstones and siltstones).

Unit A exhibits slightly seaward dipping, well-defined, high-amplitude and laterally continuous reflections with parallel geometry. The top of Unit A is defined by the seafloor (Figs. 2, 3a and b). Based on its stratigraphic position, we associate Unit A with the Upper Pleistocene–Holocene deposits formed during the transgressive and highstand stages of the last sea level rise.

Unit B is internally transparent or characterised by an outward-prograding sedimentary wedge with variable amplitude, high-frequency and sigmoid progradational configuration of reflections, with partial lateral continuity downlapping on top of Unit C (tC in Fig. 2). Unit B is wedge-shaped with a well-defined edge (Figs. 2 and 3a). The upper bounding surface is upwardly convex

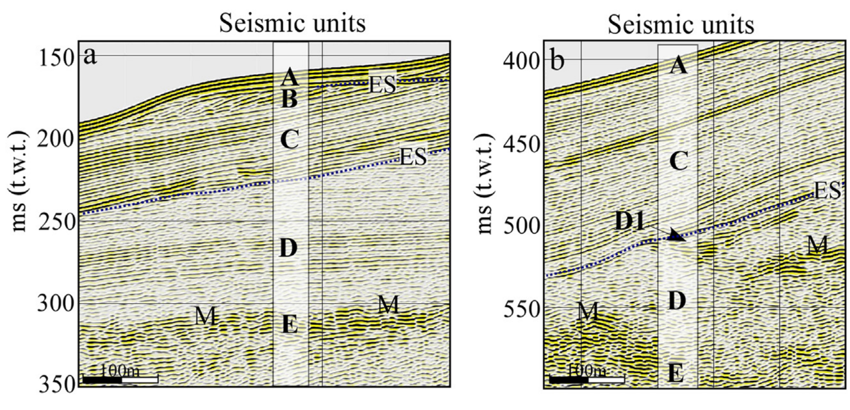


Fig. 3. Seismostratigraphic scheme of the MSK_91 seismic line. A, B, C, D, and E, Seismic Units (see Section 4.1 for description); ES, erosional surfaces; M, Top of Messinian horizon.

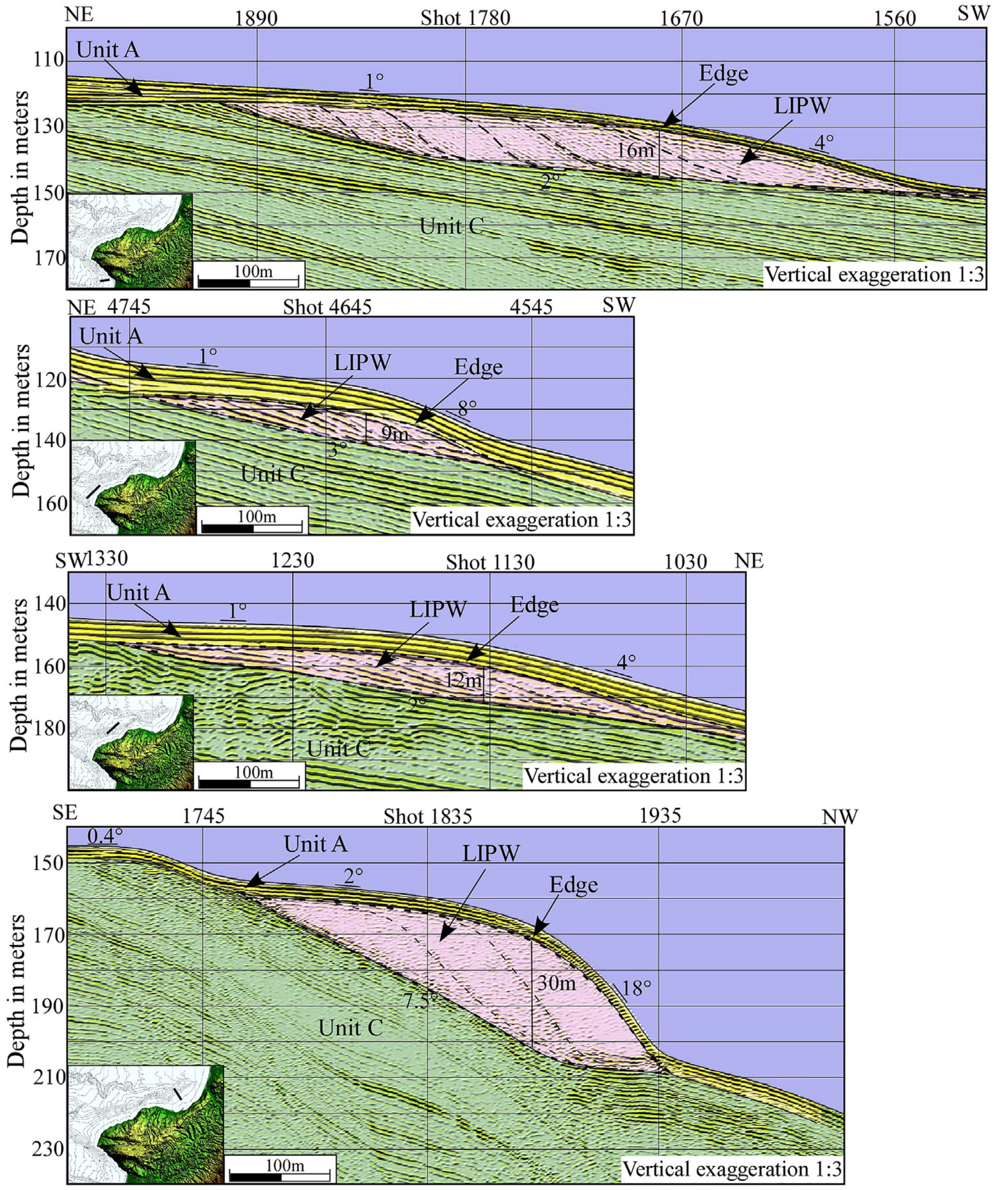


Fig. 4. Example of the LIPWs formed offshore of the Capo Vaticano Promontory and their morphological description. See Section 4.1 for description of seismic units. Depths are in meters. All lines have a threefold vertical exaggeration.

and marked by a toplap termination of internal reflections, which landward becomes an erosional surface (ES in Fig. 3a). One remarkable feature of the stratal terminations of Unit B's downlapping onto the top of Unit C is the systematic basinward increase of amplitudes of individual seismic reflectors (Fig. 2). We have interpreted Unit B as representative of the LIPWs formed during the sea level stillstand associated with the LGM.

Unit C is characterised by a succession of well-stratified, seaward dipping, high-frequency, and medium- to high-amplitude reflections of good lateral continuity, with parallel internal configuration (Figs. 2, 3a and b). This seismic facies is interpreted as representative of the Pleistocene coarser deposits (sandstone and siltstones) drilled by the Marta and Marisa wells.

Unit D is characterised by a succession of stratified, high-frequency, low- to medium-amplitude, discontinuous to local-continuous reflections, with a parallel internal configuration (Fig 3a), which can be correlated to the Pliocene fine-grained deposits (mudstones and claystones) drilled by the Marta and Marisa wells. A wedge-shaped, sub-unit (D1) is recognised in the upper part (Fig. 3b). Because of the overall appearance and their position at the foot of normal faults, the unit is interpreted as sediments deposited during normal fault activity. The upper bounding surface is an erosional surface (ES in Fig 3a and b). This unit represents a part of the Pliocene deposits.

Unit E is seismically characterized by discontinuous but sub-parallel reflections of moderate to high amplitude. It is bounded at the top by reflector "M" (Fig. 3a and b), a horizon of regional importance associated with the top of evaporites deposited during the late Messinian salinity crisis or with an erosional unconformity formed during the late Messinian sea level fall (Malinverno, 1981 and references therein).

4.2. *Stratal architecture and spatial distribution of the "Lowstand Infralittoral Prograding Wedges"*

The dense grid of seismic lines has allowed the mapping of fourteen, well-developed, shore-parallel LIPWs along the continental shelf and upper slope, some of which are illustrated in Fig. 4.

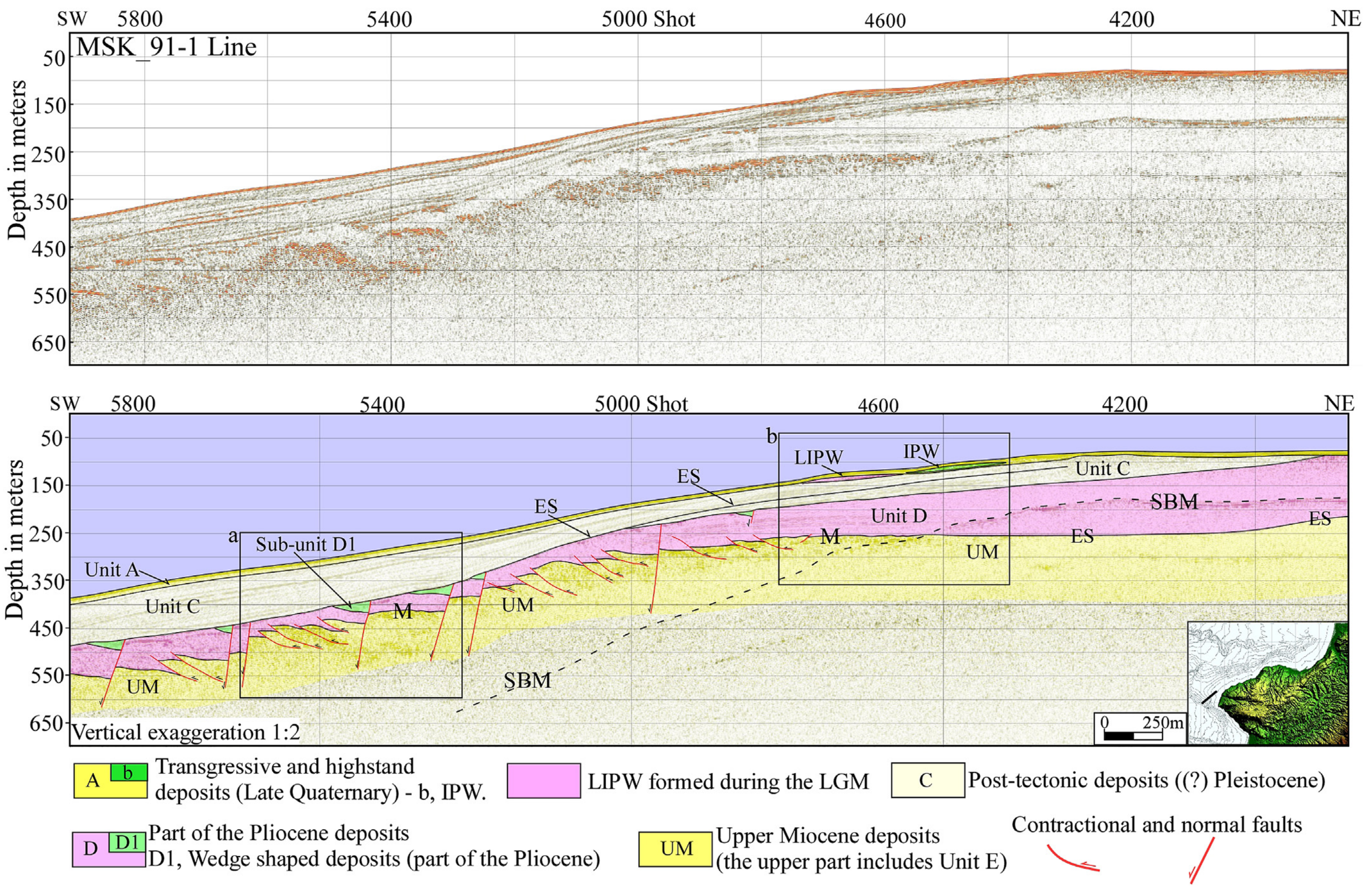


Fig. 5. The SW offshore sector of the Capo Vaticano Promontory as imaged in the MSK_91 line and its seismic facies interpretation. SBM, sea-bottom multiple; ES, erosional surface; M, Top of Messinian horizon. LIPW, Lowstand Infralittoral Prograding Wedges; IPW, Infralittoral Prograding Wedges. Boxes a and b are parts of the line displayed at higher scale in Figs. 7 and 8, respectively. See Section 4.1 for description of seismic units. Depths are in meters. Vertical exaggeration 1:2.

When detectable, the internal reflector configuration of the LIPWs is progradational with a foreset slope that varies from 9° to 13°. The lower boundary of the LIPWs is generally a seaward, gently dipping (~2°–3°) downlap surface, which locally reaches values up to 7.5°. Reflections of the LIPW's downlap on an erosional surface that can be found in the southwest sector of the promontory. The upper boundary is a toplap surface, with a gradient varying from 1° to 3° over a distance of 3–400 m. Seaward, the slope increases rapidly and reaches values up to ~18° in the frontal sector or the IPW. Along the dip section, the LIPWs range in length from ~200 to ~800 m (Fig. 4). The maximum length was detected in correspondence with the mouths of the Mesima River and in the S. Eufemia Gulf (Fig. 4). The thickness of the LIPWs varies between ~10 and ~30 m.

The LIPWs extend several kilometres along the continental shelf and upper slope of the promontory whereas their lateral continuity is locally interrupted by the headscarps of canyon that breach the shelf-edge. These features range in width from ~500 to ~600 m and form part of the erosional systems that extend from the shelf along the continental slope to the basins developed just a few kilometres offshore from the promontory.

4.3. The Late Neogene to Quaternary tectono-sedimentary evolution of the offshore Capo Vaticano area

In the following, the Late Neogene to Quaternary tectonic framework and evolution of the offshore area of Capo Vaticano Promontory is briefly illustrated using two depth-converted seismic sections, roughly orthogonally (MSK_91 line, Fig. 5) and parallel (MSK_91 Ext. line, Fig. 6) to the coastline, respectively.

Messinian evaporites and associated deposits are the deepest sediment imaged by our lines along the continental slope, connecting the south-west continental shelf of the Capo Vaticano Promontory to the Gioia Tauro basin (Fig. 5, shots 4350–5900), at depths larger than 550 m below sea level (b.s.l). Towards the NE, Messinian evaporites are missing and replaced by an erosional surface (ES).

Pliocene (?) deposits (Unit D) display substantial variations in thickness and tectonic style. They are ~140 m thick at the north-east termination of the MSK_91 line, thinning to ~35 m along the continental slope and then increase rapidly reaching ~75 m at the foot of the slope (Fig. 5). In more detail, Unit D displays a lower part ~30 m thick that conformably covers the Messinian evaporites and an upper part (sub-unit D1) locally characterised by a wedge-shaped geometry (e.g. Fig. 5, shots 4800–5900). The erosional surface (ES in Fig. 5) that makes up the upper limit of Unit D is observed from the continental shelf to the foot of the continental slope, at water depths greater than 500 m.

Pleistocene (?) deposits (Unit C) are found throughout the whole study area. Their thickness is ~50 m along the shelf and increases gradually moving south-westward, reaching ~100 m at the foot of the slope. In the SW sector of the study area, these deposits display a number of erosional surfaces (Fig. 5, Shots 4400–5000). In the north-western sector of the Capo Vaticano Promontory, Unit C deposits are incised by a number of canyons (Fig. 6). Buried paleo-valleys overlain by sediments that dip beneath the Upper Pleistocene–Holocene deposits (Unit A) were observed (Fig. 6a).

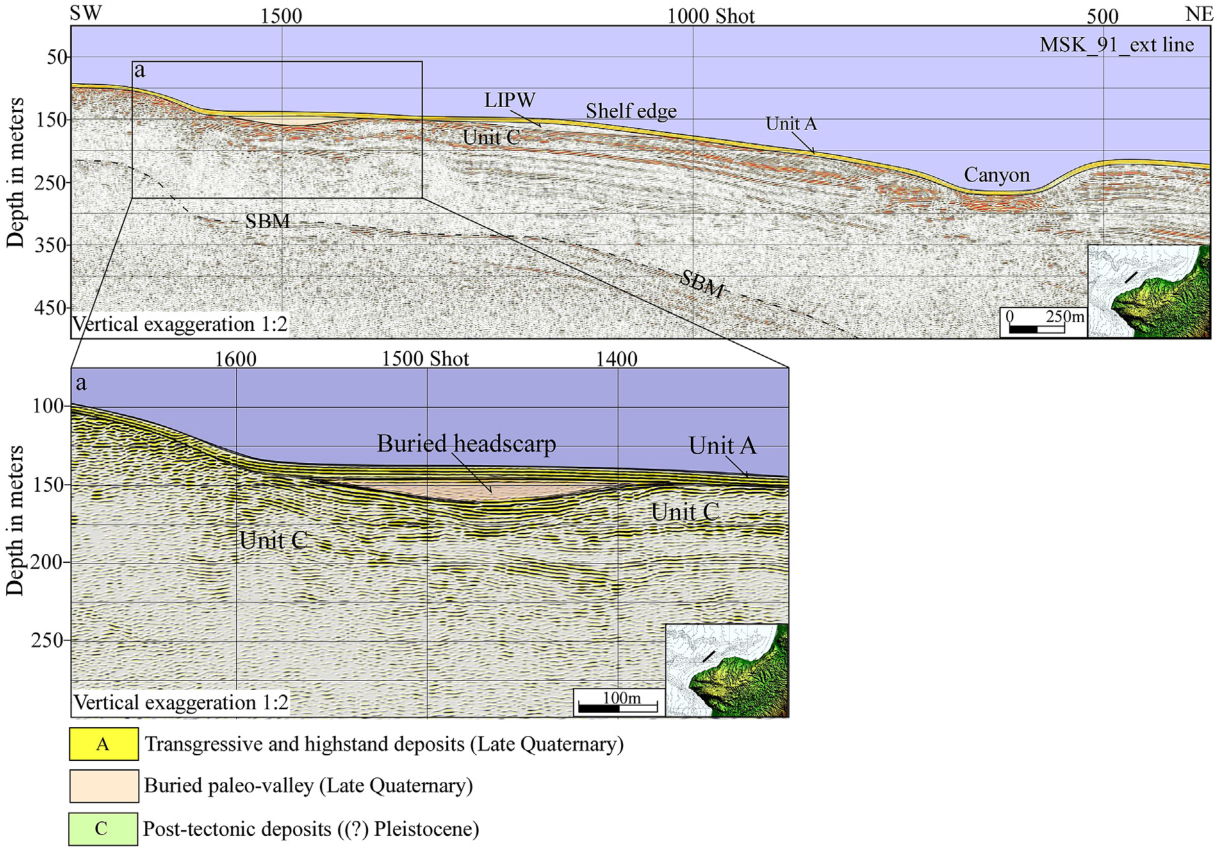


Fig. 6. The western offshore sector of the Capo Vaticano Promontory as imaged in the MSK_91_ext profile and its seismic facies interpretation. SBM, sea-bottom multiple. LIPW, Lowstand Infralittoral Prograding Wedges; Boxes a, is part of the line displayed at higher scale where is visible a buried head scarp formed in the upper slope. See Section 4.1 for description of seismic units. Depths are in meters. Vertical exaggeration 1:2.

Unit B is composed of the LIPW's deposits, which appear as ~1 to 3 km long, shore-parallel depositional bodies, ~200 to 800 m wide, with thicknesses that vary from a few meters up to 30 m, developed along the edge of the continental shelf and upper slope, around the Capo Vaticano Promontory (Fig. 5). Upper Pleistocene–Holocene deposits (Unit A) exhibit a slightly prograding, wedge-shaped geometry. Their thickness varies slightly from ~10 m on the continental shelf to less then ~8 m in the upper slope and reaches ~13 m at the foot of the slope, close to the Gioia Tauro basin (Fig. 5). On the whole, Units A and B pertain to the Late Quaternary depositional sequence corresponding to the last eustatic cycle.

4.3.1. Fault pattern

Contractional and extensional faults are mainly observed along the continental slope connecting the south-west continental shelf of the Capo Vaticano Promontory to the Gioia Tauro basin (Fig. 5). Although they rarely have displacements larger than a few tens of meters they document tectonic regimes that have remained active in the region through time. Southwest-verging thrust faults affect Messinian evaporites and associated deposits as well as the lowermost Pliocene layers (present-day dips between 14° and 20°, Fig. 7).

High-angle normal faults, dipping 70°–77° to the southwest also formed (Figs. 5 and 7). Normal faults generally have small displacements up to 40 m and are sealed by Unit C (Figs. 5 and 7), thus demonstrating that fault displacement nearly ceased along the continental slope before the (?) Pleistocene.

4.4. The post-20 ka vertical motion in the offshore Capo Vaticano area

In order to quantify the amount and rate of vertical motion offshore of the Capo Vaticano Promontory, we have focused on the depth variation of the present-day edges of the LIPWs that are used for local to regional correlation (Fig. 4). The LIPWs were chosen according to the criteria: a) the water depth of the upper bounding surface of the LIPWs must be greater than 130 m b.s.l., in order to exclude those IPWs developed during the transgressive and highstand stages of the last sea level rise (i.e. IPW(TH) in Fig. 8); b) we chose the deepest LIPWs when more than one was found vertically staked at different but nearby depths (i.e. IPW(TH) in Fig. 8); c) the LIPW must be only topped by the Unit A, that is, the Upper Pleistocene–Holocene deposits (Unit A in Section 4.1). The values for the paleobathymetry and age of younger sediments deposited at the edge of the LIPWs that we used in the quantitative analysis are those indicated in Sections 3.2.2 and 3.2.3.

Fourteen clearly expressed edge points of the LIPWs distributed around the Capo Vaticano Promontory were recognised (Fig. 9a). Their present-day depth projected onto a NE-trending line roughly perpendicular to the Coccorino and Nicotera faults as well as their possible continuation offshore, the "Western Offshore Fault" (WOF, Fig. 9b), illustrates the pattern of upper crustal movements of the promontory. The average value for the depth of the edge of the LIPWs deepens, from southwest to northwest, from ~134 m (offshore the village of Capo Vaticano) to ~158 m (offshore Tropea) and reaches ~170 m b.s.l. (offshore

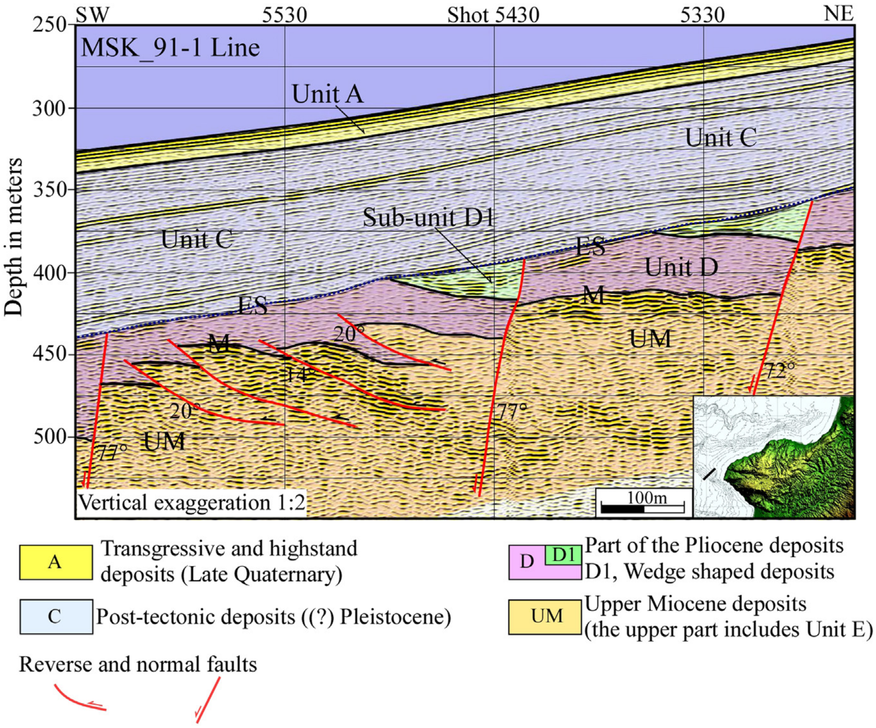


Fig. 7. Fault patterns along the MSK_91 seismic line. The lower part shows closely spaced, southwest-vergent reverse, and high-angle, NW–SE trending, southwest-dipping normal faults affecting the Messinian and younger deposits in the SW sector of the study area. ES, erosional surface; M, Top of Messinian horizon. See Section 4.1 for description of seismic units. Depths are in meters. Vertical exaggeration 1:2.

Briatico), over a distance of ~28 km. The regression curve for the LIPWs (LRL in Fig. 9b) intersects the horizontal line of 145 m b.s.l. (corresponding to the paleo-water depth for the edge of the LIPWs) in the area between Capo Vaticano and Tropea (Fig. 9a and b) suggesting that this sector served as a pivot for vertical movements during the post-LGM. The difference between the present-day depth of the edge of the LIPWs and the paleo-water depth estimated during their formation indicates ~11 (±3.2) m of net uplift and ~25 (±3.2) m of net subsidence for the southern and northern offshore sectors of the promontory, respectively, during the post-LGM. The resulting absolute uplift and subsidence rates (including both regional and local components) are 0.54 (±0.2) mm/y and 1.23 (±0.25) mm/y, respectively, for the last 20,350 (±135) years.

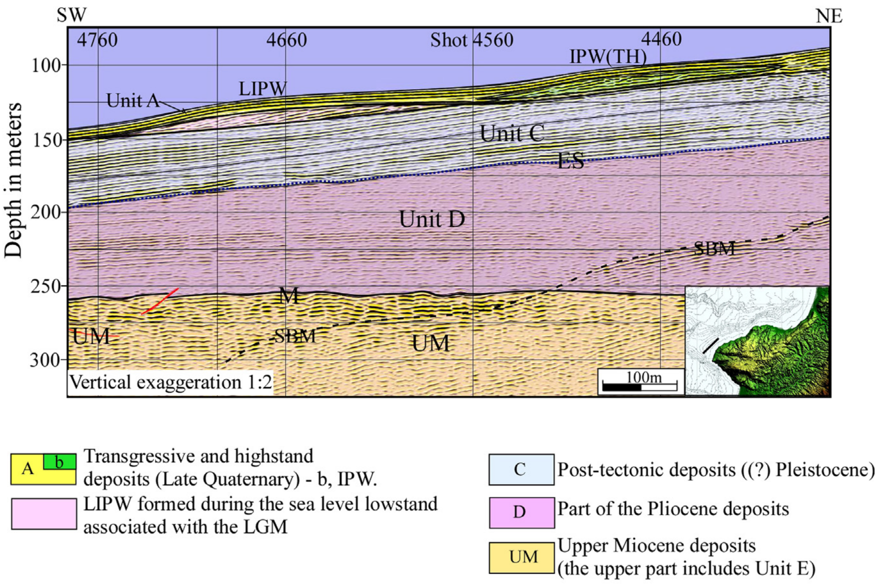


Fig. 8. IPWs formed on the upper slope at different but nearby depths in the study area. The lower one (LIPW) formed during the still-stand of the LGM. The IPW (TH) formed during the transgressive and highstand stages of the last sea level rise. SBM, sea-bottom multiple; ES, erosional surface; M, Top of Messinian horizon. See Section 4.1 for description of seismic units. Depths are in meters. Vertical exaggeration 1:2.

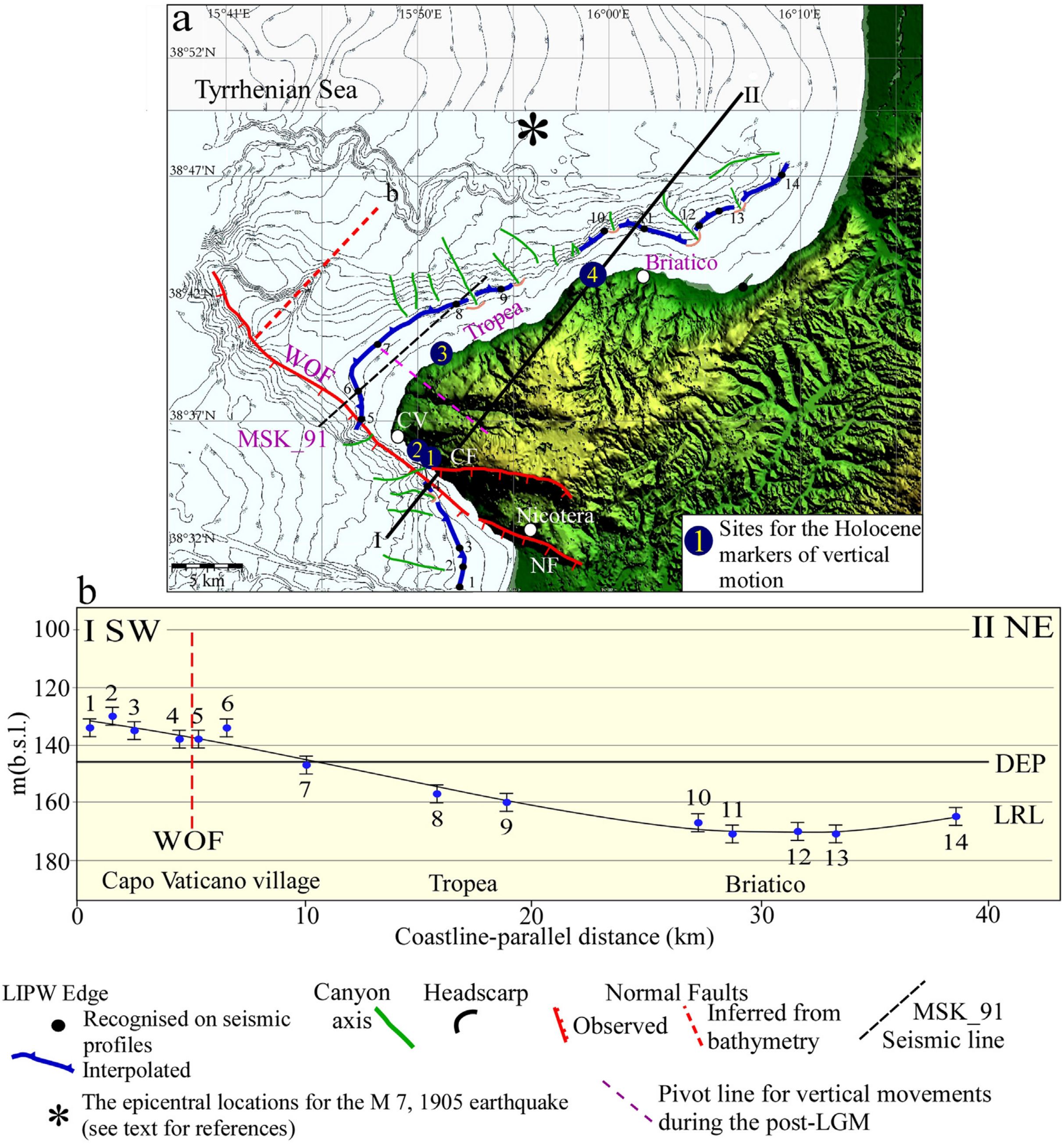


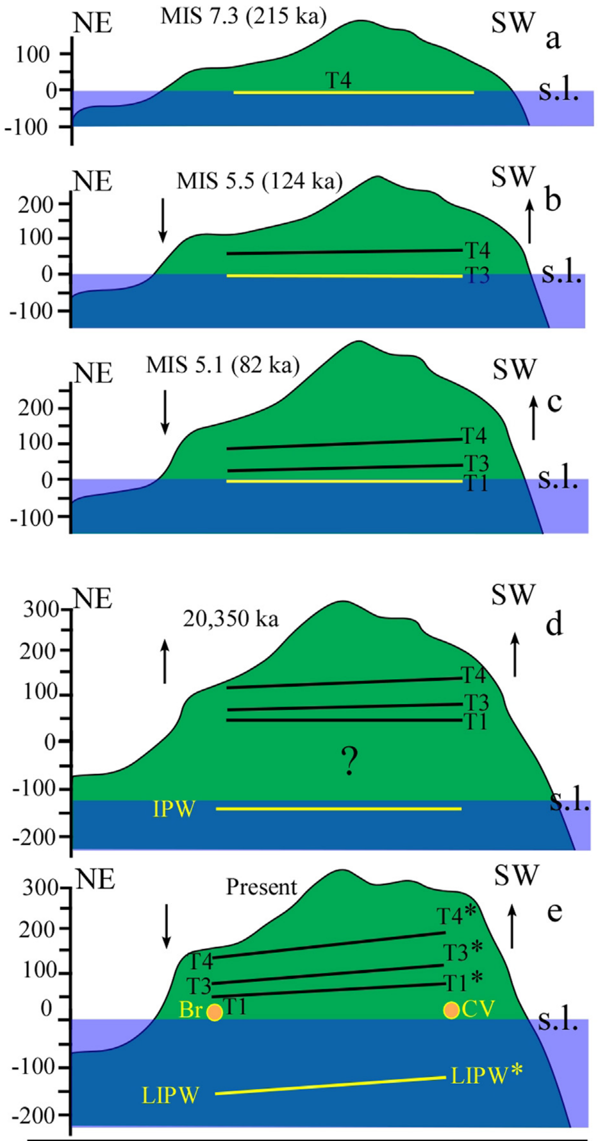
Fig. 9. (a) Map showing the position of slope breaks of the LIPWs edge formed offshore of the Capo Vaticano Promontory during the LGM, (b) NE-trending, coastline-parallel section of the depth of LIPWs. CV, Capo Vaticano village, CF, Coccorino normal fault; NF, Nicotera normal fault; WOF, Western Offshore Fault (see text for references). LRL, linear regression line; DEP, depositional equilibrium profile. Star indicates the epicentral locations for the September 8, 1905 earthquake (CPTI Working Group, 2011).

Noticeably, the present day depths of the edges of the LIPWs formed on the hanging wall (edges points 1, 2, 3 and 4) and footwall (edges points 5 and 6) of the WOF (Fig. 9a), whose geometry was accurately mapped in this study using the new seismic dataset, do not show a significant difference (Fig. 9b), thus suggesting that fault displacement decreased dramatically during the post-LGM.

5. Discussion

5.1. 10^2–10 ky-scale quantitative kinematic evolution

To provide a quantitative kinematic analysis of the longer-term (215 ka to present) pattern and rate of vertical tectonic motion around the Capo Vaticano Promontory, we have plotted along a NE-trending section parallel to the coastline, the average depth of the edges of LIPWs calculated in the SW and NE sectors of the promontory, and the elevation of the inner-edges of coastal terraces outcropping close to the village of Capo Vaticano and Briatico, formed during the peak of MIS 5.1, MIS 5.5 and MIS 7.3 (Fig. 10). We used data from these marine terraces because they are the three most continuous and best age-constrained Pleistocene marine terraces, as reconstructed by Cucci and Tertulliani (2006, 2010). Data shown in Fig 10 are then palinspatically restored for the last 215 ka, and relevant kinematic factors, i.e. uplift, subsidence and rotation rates, were derived and discussed.



Point	MIS-Age (ka)	Elevation/depht (m)	
LIPW*	20,35	-134	Subsidence ↓
LIPW		-170	
T1*	MIS 5.1 (82)	75	
T1		50-55	
T3*	MIS 5.5 (124)	115	Uplift ↑
T3		75	
T4*	MIS 7.3 (215)	185-190	
T4		135	

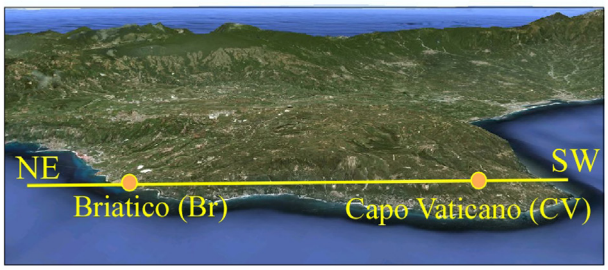


Fig. 10. Simplified palinspastic reconstruction of the vertical movements in the Capo Vaticano Promontory since 215 ka. Br, Briatico; CV, village of Capo Vaticano; T1, T3, T4, marine terraces formed during MIS 5.1, 5.5 and 7.3 respectively. Data on the elevation of the inner-edges of coastal terraces from Cucci and Tertulliani (2006, 2010).

During MIS 7.3 a continuous marine terrace (T4) formed around the promontory (Fig. 10a). From MIS 7.3 to MIS 5.5, when terrace T3 was formed, the promontory experienced differential vertical uplift, indicated by the northeast down tilt of T4 (Fig. 10b). During this time-interval, the uplift rates at the village of Capo Vaticano and Briatico were 0.79 (±0.03) mm/y and 0.66 (±0.04) mm/y (Fig. 11a and b), respectively, resulting in a tilt rate of ~0.2 × 10^{-6} degree/y (Fig. 11c). From MIS 5.5 to MIS 5.1 (Fig. 10c), the uplift rate increased up to 0.95 (±0.07) mm/y at the village of Capo Vaticano (Fig. 11a), and was 0.53 (±0.07) at Briatico (Fig. 11b), resulting in a tilt rate of ~0.4 × 10^{-6} degree/y (Fig. 11c).

A number of LIPWs formed during the stillstand associated with the LGM (Fig. 10d). At this time, no information on the net vertical movements of the edges for the MIS 5.1 marine terrace T1 can be derived. Consequently, the estimation of the rate of vertical movements during this time interval has not been possible so far. The parallelism of lines connecting the inner edges of the terrace formed during MIS 5.1 and the break in slope of the LIPWs simply suggests that the promontory did not experience a significant northeast down tilt from ~82 to ~20 ka (Fig. 10d).

During the post-LGM, the uplift rate offshore the village of Capo Vaticano was 0.54 (±0.2) mm/y (Fig. 11a) while the subsidence rate offshore Briatico was 1.23 (±0.25) mm/y (Fig. 11b). This differential vertical movement resulted in a northeast down tilt of the Capo Vaticano block at a rate of ~4.6 × 10^{-6} degree/a (Fig. 11c).

5.1.1. 10–1 ky-scale quantitative kinematic evolution

To establish a correlation between the 10–1 ky scale, we used data and constraints derived from three raised shorelines recognized around the Capo Vaticano Promontory (Antonioli et al., 2009; Ferranti et al., 2011; Spampinato et al., 2011), coupled with predicted sea level changes at the S. Eufemia Gulf (Lambeck et al., 2011). Calibrated radiocarbon ages indicated that the shorelines formed during the Late Holocene, with the lowermost belonging to the post-Roman age. On the SW side of the promontory, between the villages of Capo Vaticano and Nicotera, all of the terraces are higher than those on the NE side (Tropea and Briatico).

The Late Holocene uplift rate is 1.3 mm/y on the SW coast and steadily decreases to 1 mm/y at Tropea, and to 0.6 mm/y at Briatico, respectively, over distances of 10 and 22 km (Fig. 11d). This pattern is similar to that recorded by both Pleistocene marine terrace (>10^2 ky) and LIPW (10 ky) markers. The resulting tilt rate of ~0.52 × 10^{-6} degree/a indicates a persistent tilting, and coincides with the tilt rate established at the coast between 124 and 82 ka (Fig. 11), although the uplift rate on the SW coast was slightly larger during the Late Holocene compared to previous times.

5.2. Role of the “Western Offshore Fault” in the vertical tectonic movements of the Capo Vaticano Promontory over time

The present-day elevation of raised Pleistocene terraces outcropping along the Capo Vaticano Promontory results from a poorly constrained combination of regional vertical uplift and/or local uplift/subsidence associated with seismogenic faults (Cucci and Tertulliani, 2010 and references therein). The quantitative kinematic analysis presented above highlights that values of post-215 ka and of longer-term (10^2–10^3 ky) Pleistocene uplift rates calculated by Cucci and Tertulliani (2010) are quite similar in the area close to the village of Capo Vaticano (Fig. 11a). Towards the SW, our new seismic data demonstrate that the displacement along the extensional faults connecting the south-west continental shelf of the Capo Vaticano Promontory to the Gioia Tauro basin (WOF in Fig. 9a) ended before the (?) Pleistocene. The absence of significant tectonic movements on the southwest side of the shelf promontory during the post-LGM is also indicated by the similar values of the

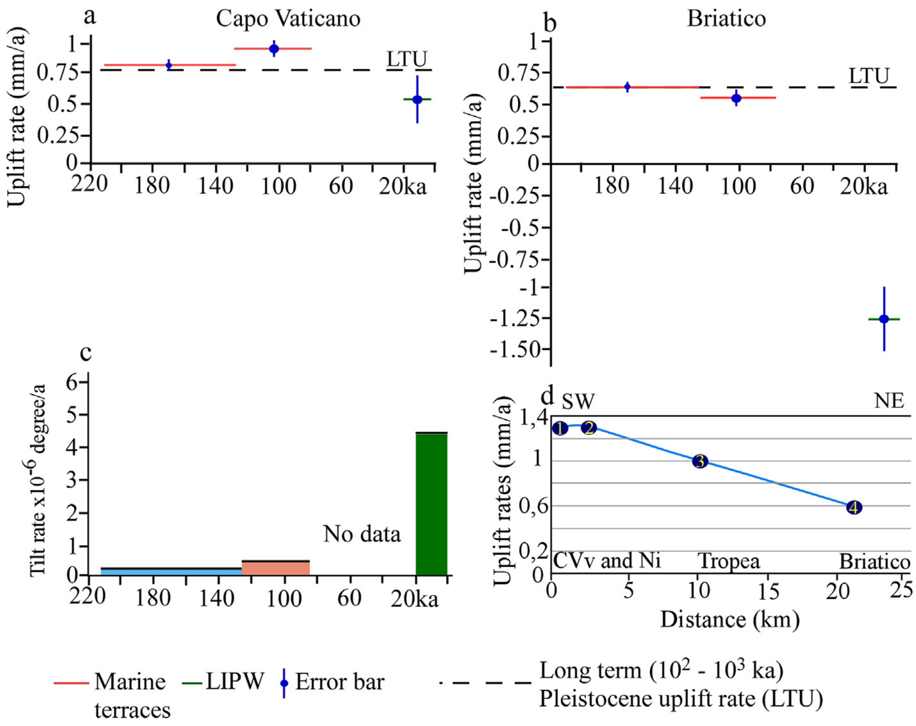


Fig. 11. (a) and (b) Summary of the most relevant kinematic parameters (uplift, subsidence) derived for the Capo Vaticano Promontory since 215 ka. (c) Tilt rate derived for the Capo Vaticano Promontory and its offshore prolongation since 215 ka. LTU, long term (10^2 to 10^3 ka) Pleistocene uplift rate (see text for references). (d) NE-trending, coastline-parallel section of the trend of Holocene uplift rates. See Fig. 9 for a location map of the site for the Holocene markers of vertical motion. CVv, Village of Capo Vaticano, Ni, Nicotera.

present-day depth of the edges of the LIPWs developed on the hanging wall and footwall of this fault system (Fig. 9b). Therefore, it is reasonable to assume that the driving mechanism for the post-215 ka uplift of the SW sector of the Capo Vaticano Promontory must be deep-seated and probably connected to deep and large-wavelength geodynamic process (Cucci and Tertulliani, 2010; Ferranti et al., 2010; Faccenna et al., 2011).

We are aware that this inference contrasts with previous studies (i.e. Tortorici et al., 2003) in which the Late Quaternary northeast down tilt of the Capo Vaticano Promontory has been related to the activity of both the NE–SW and WNW–ESE striking normal fault systems (i.e. the Coccorino fault and its offshore prolongation), as well as the regional raising component. However, the tectonic reconstruction presented here using constraints derived from unpublished seismic reflection profiles coupled with on- and off-shore geomorphological indicators of vertical movements outlines a different scenario, at least for the last 215 ka. This does not preclude more recent deformation along the onshore segment of the Coccorino Fault (*sensu* Cucci and Tertulliani, 2010).

6. Conclusions

Seismically detected LIPWs and their associated abrasion platform, developed during the sea level still-stand of the LGM, are reliable indicators of the paleo sea level, and can therefore be used to quantify the pattern and rate of vertical tectonic movements over an intermediate time period (10 ky). This finding is particularly significant because vertical tectonic motions (uplift/subsidence) are typically difficult to estimate in offshore settings at a scale of 10 ky.

The present-day depth variation of the edges of LIPWs indicates a difference in the vertical movements between the SW and NE offshore sectors of the Capo Vaticano Promontory, during the post-LGM. This is consistent with that recorded onshore by Pleistocene coastal terraces that were widely used by several investigators as markers to reconstruct the vertical movements along the coastal area at 10^2 ka timescale. Thus, the new data and interpretation we are presenting here fill an information gap between the underwater and exposed domains of Capo Vaticano Promontory, and reconcile independent observations on the pattern and rate of vertical motion between the 10^2 ka to the 1 ka timescale.

A northeast down tilt of the Capo Vaticano block is recorded post-215 ka, both by coastal terraces formed during MIS 7.3, 5.5 and 5.1 and by LIPWs. Nevertheless, the data we are presenting highlight that the value for the tilt rate increases by one order of magnitude in the post-LGM in respect to the 215–82 ka time intervals.

The extensional faults system connecting the south-west continental shelf of the Capo Vaticano Promontory to the Gioia Tauro basin (namely Coccorino Fault for Tortorici et al., 2003 and Western Offshore Fault for Cucci and Tertulliani, 2010) was inactive during the (?) Pleistocene and, thus, cannot be responsible for the northeast down tilt of the Capo Vaticano block, at least during the last 215 ka.

Finally, the analysis of the pattern and rate of post-20 ka vertical motion around the Capo Vaticano Promontory we present represent a quantitative contribution towards the understanding of the process responsible for the Late Quaternary uplift of the Calabrian Arc. Moreover, the new structural information derived from interpretation of seismic profiles recorded in the offshore area of Capo Vaticano Promontory represents a further necessary step towards the earthquake hazard analysis of the Calabria region.

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