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GEOMORPHOLOGY OF SOFT CLASTIC ROCK COASTS IN THE MID-WESTERN ADRIATIC SEA (ABRUZZO, ITALY)

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Abstract

We present the first detailed overall study on the rock coasts in the central Adriatic Sea (Abruzzo, Italy), which is one of the few cases of a coast with clastic soft rocks in the entire Mediterranean area. The coast is composed of cliffs with small beaches, coastal slopes with or without a contiguous coastal plain and intervening low-lying coasts. It is developed on the eastern seaward side of a wide plateau and mesa landscape shaped on an Early-Middle Pleistocene clay-sand-sandstone-conglomerate marine sequence covered by Late Pleistocene – Holocene continental deposits.

The study focuses on the overall coast and on eight specific sites, combining: (i) DEM (2 m cell, LiDAR-derived) analysis and geological-geomorphological surveys of the emerged and submerged areas, for the cliff/coastal slope characterization, (ii) the results of U/Th, ^{14}C sediment dating and archaeological and palaeontological attributions, for constraining the coastal evolution, and (iii) aerial photo time-series (1954-2013 time span) analysis, for the recent cliff retreat assessment. The overall features of the cliffs and coastal slopes were defined in terms of their morphology, lithology, tectonic setting, landforms and geomorphological processes, whereas the analysis of Late Pleistocene – Holocene continental deposits and landform distribution defined and constrained the evolution of the coastal system. This enabled us to define eight different types of coastal cliffs/slopes meaningful for clastic soft rock coasts. The coastal types were defined in terms of: (i) lithology (15% cliffs on marine sandstone, 15% cliffs on marine conglomerate, 3% cliffs on continental deposits, 43% coastal slopes on clay-sand-sandstone-conglomerate sequences), (ii) morphostructural setting (i.e. clay/sandstone-conglomerate interface elevation), and (iii) of state of activity (3.8% active cliffs, 13.8% inactive cliffs, 15.9% palaeocliffs, 43% of inactive and locally reactivated landslides on coastal slopes). Variable retreat rates were also defined, from retreat measurements over a 60-year time span (ranging from 0.15 m/yr to ~1 m/yr), and were found to be induced by episodic and localized cliff recession processes and connected to combined wave-cut and gravity-induced slope processes. The assessment of coastal and gravity-induced geomorphological processes, combined with the analysis and dating of the continental deposits, allowed us to define the Late Pleistocene to present evolution and timing and the evolutionary mechanisms of the main coastal types of soft rock coasts. They are connected to wave-cut and gravity-induced erosion cycles on cliffs and to large rotational ancient landsliding with local recent reactivations on coastal slopes. For the different coastal types the expected hazard conditions were outlined.

Highlights:

- Geomorphological features of the coastal slopes and cliffs of the Central Adriatic area;
- Lithological features and chronological (U/Th and ^{14}C) and palaeontological (Mammal remains) constraints of the Late Quaternary continental deposits along the coast;
- Definition of eight types of coastal cliffs and slopes meaningful for soft rock coasts;
- Distribution of geomorphological processes and evolution mechanisms of coastal types.

Keywords: Rock coast, clastic rocks, cliffs and coastal slopes, Central Italy, Mediterranean Sea.

1. Introduction

The mid-Western Adriatic coast is one of the few examples of a coast on clastic soft rocks in the whole Mediterranean Sea region. Other cases are limited to short coastal segments, for example the western Bulgarian Black Sea, on sandstones, clays and limestones (Simeonova, 1985); the eastern Black Sea, Anapa (Russia) and Sukhumi (Georgia), on soft clays (Zenkovich, 1985); the Southern Crimea Peninsula, on steeply sloping flysch beds (Shuisky, 1985); Northern Marche, Adriatic Sea, on clay-sandstone (Colantoni et al., 2004); Southern Tuscany, Tyrrhenian Sea, on sand and sandstones (Bini et al., 2013); Trieste Gulf, Northern Adriatic sea, on flysch sediments (Biolchi et al., 2016a); and some larger sections that characterize the Mediterranean Iberia and Balearic Islands whose cliffs occur in conglomerate and/or soft rocks (Furlani et al., 2014). Mediterranean rock coasts are intimately related to the complex geological history of this area, controlling hard and soft rock types, vertical and horizontal tectonic movements and climate/sea-level fluctuations. They have been shaped during the Pleistocene and Holocene and strongly modelled over the last 6,000 years, when the sea level increased to or close to that at present (Bird, 2008; Antonioli, 2012). Although the Quaternary evolution of the Mediterranean coasts has been extensively studied, few studies have addressed defining the coastal types of the soft rock coasts and their evolution in relation to the regional geological setting, local tectonic and stratigraphic features, and ancient and present geomorphological processes (Furlani et al., 2014; Antonioli et al., 2017 and references therein).

The mid-Western Adriatic area is composed of a Pleistocene marine sequence, with different poorly consolidated clastic sediment and weak clastic rocks outcropping on the coastline (Cantalamessa and Di Celma, 2004; Chiocchini et al., 2006; ISPRA, 2012a,b,c; Di Celma et al., 2016). In a coastal section as short as 66 km, a homogeneous mesa-plateau morphostructural setting (D'Alessandro et al., 2003; Miccadei et al., 2017), a large morphological variability (ca. 22 km of coastal cliffs, ca. 28 km of coastal slopes and ca. 16 km of alluvial plains; D'Alessandro et al., 2001) and a complex Quaternary history are documented (ISPRA, 2012 a,b,c). This makes the area ideal for characterizing a rock coast system on soft clastic rocks in relation the Late Quaternary evolution and the influential coastal geomorphological processes.

This study analyses the geomorphologic, lithologic and structural-jointing features of the study area, focusing on the effects of inherited morphstructures on the landforms, processes and dynamics affecting coastal cliffs and slopes. It combines (i) field and scuba-dive geological and geomorphological mapping with geostructural analysis, (ii) a detailed characterization of the continental Quaternary succession improved with new radiometric and palaeontological chronological constraints, and (iii) interpretations of aerial photos and DEMs time series. The integrated detailed geological-geomorphological approach, with a focus on the Late Quaternary history, provides a contribution to defining: (i) the features and constraints of the Late Pleistocene-Holocene continental deposits developed on the rock coasts; (ii) the types of cliffs and coastal slopes, meaningful for rock coasts on soft clastic rocks, in terms of lithological, geomorphological, tectonic features, acting geomorphological processes, and retreat rates; and (iii) the distribution of competing geomorphological processes (mainly coastal and gravity-induced) leading to different mechanisms and timings of the morphostructural evolution of cliffs and coastal slopes and their inherent natural hazards. Finally, the study provides an effective approach for predicting the behaviour of the soft rock coasts, which is the basis for correctly assessing hazard distribution and managing coastal areas.

2. Soft rock coasts

Rock coasts represent the 75-80% of coasts worldwide (Emery and Kuhn, 1982; Trenhaile, 1987; Sunamura, 1992), and they comprise more than 50% of coasts in the Mediterranean area (Fig. 1, Furlani et al., 2014).

Furthermore, rock coasts composed of soft materials are a peculiar subgroup (Finkl, 2004; Sunamura, 2015). Although soft sediment coasts (e.g. beach/dune systems and mudflats) have been widely investigated given their high economic and social values, interest in rock coasts has grown rapidly in recent decades (Naylor et al., 2010), and many scientists have focused on the factors controlling their erosional processes (Sunamura, 1983, 1992, 2015; Trenhaile, 1987, 2014, 2015; Griggs and Trenhaile, 1994; Griggs, 1995; Andrade et al., 2002; Dickson et al., 2004; Antonioli et al., 2017). Their geomorphological features and dynamics, and therefore their safe management and development, remain a challenge, particularly for rock coasts on soft materials because they are the result of intricate combinations of many endogenous and exogenous factors, including lithology and structures of outcropping rock formations, climate, wave energy, tides, and long term sea-level changes (Sunamura, 1992, 2015). The diverse intensity and timing of interacting factors produces a complex combination of subaerial and coastal processes (Griggs and Trenhaile, 1994). These act over different temporal and spatial scales and spatial scales, influenced by the inherited morphostructural and stratigraphical setting resulting in a wide spectrum of cliff morphologies and retreat modes (Trenhaile, 1987; Sunamura, 1992; Griggs and Trenhaile, 1994; Sherman and Gares, 2002).

Most research activity, particularly in the Mediterranean area, has focused on hard rock coasts, investigating geomorphological processes and evolution, cliff stability and cliffs morphotypes (Andriani et al., 2005; Andriani and Walsh, 2007; De Pippo et al., 2007; Di Crescenzo and Santo, 2007; Budetta et al., 2008, 2015; Arnott, 2009; Furlani et al., 2011, 2014; Miccadei et al., 2011a, Thébaudeau et al., 2013; Farabollini et al., 2014; Kennedy et al., 2014; Biolchi et al., 2016a,b; Antonioli et al., 2017). Few works have outlined the geomorphology of coastal cliffs and slopes on soft (usually with uniaxial compressive strengths of <5 MPa, Sunamura, 2015) clastic rocks (Mortimore and Duperret, 2004; Collins and Sitar, 2008; Walkden and Dickson, 2008; Spagnolo et al., 2008; Trenhaile, 2009; Brooks and Spencer, 2010; Chelli et al., 2010; Walkden and Hall, 2011; Sunamura, 2015), which are poorly represented coastal types in the Mediterranean area (Furlani et al., 2014). However, soft rock coasts are of great interest due to: i) retreat rates of 10^{-2} to 10 m/yr, which are up to two orders of magnitude greater than hard rock cliffs (Davies et al., 1972; Griggs and Savoy, 1985; Sunamura, 1994; D'Alessandro et al., 2001; Colantoni et al., 2004; Quinn et al., 2009; Young, 2018); ii) the episodic and localized nature of cliff recession over a short time span, which tends to an almost parallel recession over a long time span (Richards and Lorriman, 1987; Dornbusch et al., 2008; Sunamura, 2015); iii) fast and scattered erosion cycles that include toe erosion, cliff instability, mass movements, talus deposits, and beach formation and erosion, and the resumption of toe erosion (Colantoni et al., 2004; Dornbusch et al., 2008; Brooks and Spencer, 2010; Sunamura, 2015), with a contradictory role of the talus and beach deposits accumulated at the bases of the cliffs.

These issues and a variable resilience to geomorphological processes have aroused the interest of geomorphologists, civil engineers, planners and environmental scientists working on hazard quantification and risk prevention and mitigation on coastal areas (according to the European and national recommendations and e.g. Pethick and Crooks, 2000; Mortimore et al., 2004; De Pippo et al., 2008; Nunes et al., 2009; Violante, 2009; Naylor et al., 2010; Bini et al., 2013; Pennetta et al., 2015; Sciarra et al., 2016; Audisio et al., 2017).

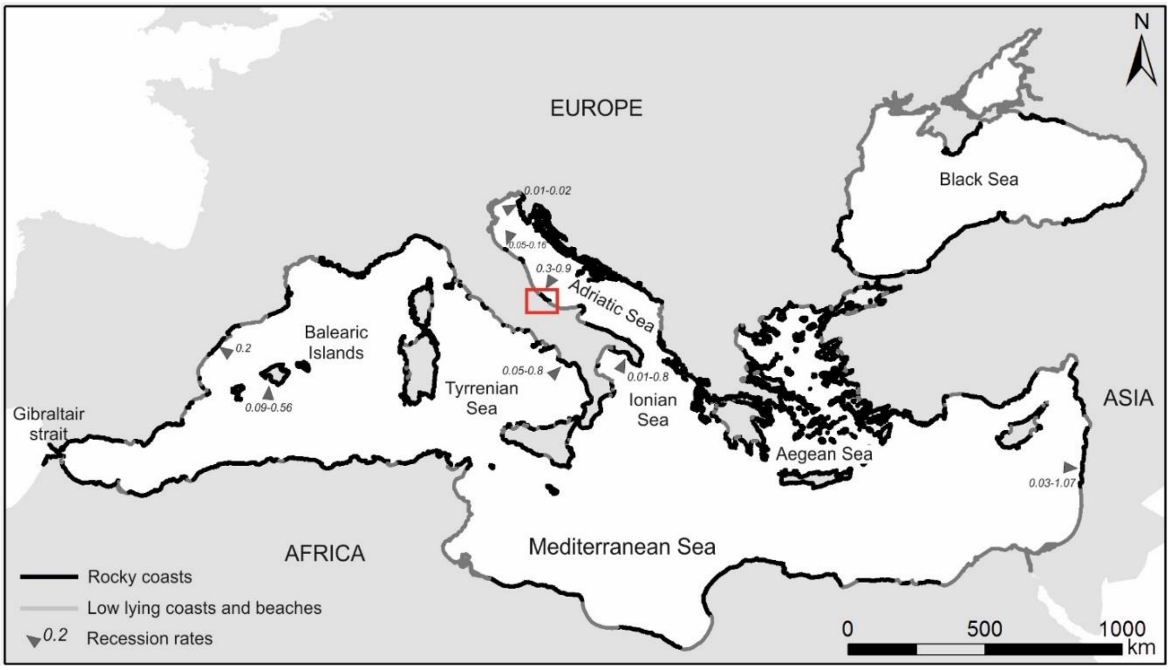

Fig. 1: Map of the Mediterranean and Black Sea area (modified from Furlani et al., 2014) showing rock coasts, low-lying coasts and beaches, sites of reported cliff recession rates (in m/yr). The red (black in the printed version) box indicates the location of the study area.

3. Study area

3.1 Regional setting

The study area is located along the Adriatic coast (Fig. 1) between the piedmont reliefs of the NE-verging Apennines orogen and the Adriatic continental shelf (Fig. 2a). The piedmont-coastal domain is characterized by the external fronts of the central Apennine fold-and-thrust belt that are buried under Late Miocene-Pleistocene clastic marine to transitional-continental sedimentary sequences. The area moved from a foredeep basin domain (Late Miocene-Pliocene) to a neritic regressive depositional domain (Early-Middle Pleistocene; e.g. Ori et al., 1986; Cantalamessa and Di Celma, 2004; Bigi et al., 2013 and references therein). Since the Middle Pleistocene, this sector has been uplifted up to 200 m above the present sea level (at a rate of ca. 0.2-

0.4 mm/yr). The landscape was shaped by fluvial, slope and coastal processes that have combined to produce a plateau and mesa relief (Demangeot, 1965; Ascione and Cinque, 1993; Cinque et al., 1993; Dramis, 1993; Ascione et al., 2008; D'Alessandro et al., 2003, 2008; Buccolini et al., 2010; Miccadei et al., 2018). This sector has been affected by Late Pleistocene-Holocene sea-level fluctuations (up to +7 a.s.l., MIS 5e, and down to -120 m b.s.l., MIS 2) and then up to the present sea level during the Holocene (ca. 6,000 BP), with a largely positive relative sea-level rise at the coast (Lambeck et al. 2004; Ferranti et al., 2006; Antonioli et al., 2009; Parlagreco et al., 2011; Antonioli, 2012). Taking into account the gentle gradient of the seabed bathymetry (<0.5%), these fluctuations led to a strong (some tens of km) NE-shifting of the coastline during the sea-level low-stands (Lambeck et al. 2004). Finally, this domain is characterized by a moderate seismicity generated by sources that may belong to the buried outer thrust fronts of the central Apennines and to other families of inherited structures reactivated within the present-day stress regime. According to the INGV and DISS database (http://diss.rm.ingv.it/diss/), CPTI15 Catalogue (Rovida et al., 2016), this area has been affected by moderate earthquakes (M_w ~4-5.5, Fig. 2a).

3.2 Geological features of the rock coast

The central Adriatic rock coast area (Abruzzo Region) is 66 km long (Fig. 2b), with ca. 22 km of clastic rock coast and cliffs with small rectilinear and pocket beaches, ca. 28 km of coastal slopes with or without adjacent coastal plains and 16 km of alluvial plains intersecting the coast (D'Alessandro et al., 2001, 2003; Miccadei et al., 2011b). The rock coast is developed on the eastern seaward side of a wide plateau and mesa landscape that is developed on Early-Middle Pleistocene marine to transitional clastic sediments and is covered by Late Pleistocene – Holocene continental deposits (Fig. 2b,c).

The lower part of the Pleistocene marine succession comprises several hundreds of metres of consolidated and stratified blue-grey clay. Upward, a gradual transition to stratified yellow sands occurs (up to 100 m thick), which consist of weakly consolidated marine sand with thin clay to clayey sand layers (lower part) and moderately cemented sandstone with sand and conglomerate lenses (upper part). A moderately- to well-cemented conglomerate layer, up to some tens of metres thick, with sandstone and grey-green clay levels and lenses, lies on an erosive contact over the sandstone layer. It closes the Early-Middle Pleistocene marine sequence passing to a transitional environment (Cantalamessa and Di Celma, 2004; Chiocchini et al., 2006; ISPRA, 2012a,b,c; Di Celma et al., 2016). A distinct erosional contact separates this sequence from the overlying Late Pleistocene-

Holocene continental deposits that consist of landslides, slope deposits, colluvial deposits and beach-dune systems, while fluvial deposits are present along the mouths and valleys of the main rivers (Miccadei et al., 2011b, 2013; ISPRA 2012a,b,c; Piacentini et al., 2015).

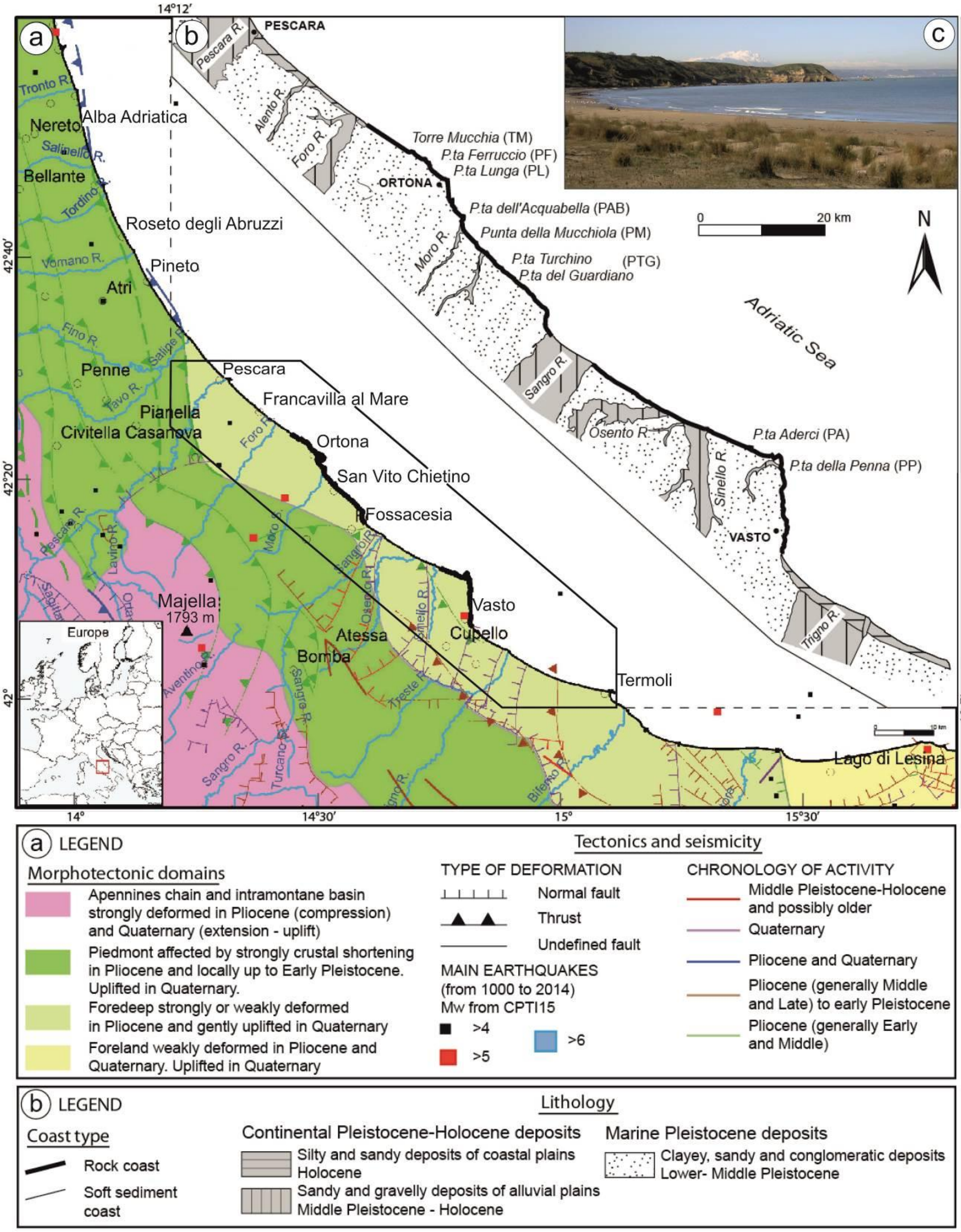

Fig. 2: **a**) Main structural domains, faults (modified form C.N.R., 1983) and historical earthquakes (Rovida et al., 2016) of Central Eastern Apennines. The black polygon indicates the study area. **b**) Physiographic and lithological scheme of the study area (modified from Miccadei et al., 2011b). **c**) Panoramic view of the study area from Punta Aderci to the north.

The structural setting is defined by sub-horizontal to very gently seaward-dipping layers. Two main tectonic discontinuity (low displacement faults and large joints) systems are present at surface: an ancient Pliocene-Early Pleistocene SW-NE to N-S system transverse to the coastline (D'Alessandro et al., 2008; ISPRA, 2012a,b,c) and a recent Middle-Late Pleistocene NNW-SSE to WNW-ESE system roughly parallel to the coastline (D'Alessandro et al., 2008). The structural setting is a result of Pleistocene uplift and NE-tilting, which caused the bedrock sequence to be at different structural elevations along the coast, with the top conglomerate level ranging from sea level to more than 100 m a.s.l. (Bigi et al., 1997; Chiocchini et al., 2006; ISPRA 2012a,b,c). From a hydrogeological point of view, the conglomerate, sandstone and sand layers in the upper parts of the mesa-plateau reliefs may host local aquifers, with small springs located at the contact over the clay unit on the cliffs and coastal slopes.

The geomorphological configuration is the result of marine, fluvial and gravity-induced slope processes operating over the variable lithological and structural features. The cliffs are affected by competing coastal erosion and landsliding, whereas the coastal slopes are mostly affected by large rotational and translational landslides (Cancelli et al., 1984; Buccolini et al., 1994; D'Alessandro et al., 2001; Fiorillo, 2003; Aringoli et al., 2002, 2013; Della Seta et al., 2013; Piacentini et al., 2015). Anthropogenic landforms are largely present all along the coastal area and are mostly represented by coastal infrastructure and tourist facilities. Remains of the old Adriatic coastal railway built at the end of the 1800s are located at the bases of the cliffs and coastal slopes and are protected by barriers. Hence, parts of the rock coast are armoured at the toe with protective materials. Moreover, two harbours (Ortona and Vasto) changed the coastal morphodynamics, inducing the formation of large beach-dune systems covering the cliffs (Miccadei et al., 2011b).

The coastal area is characterized by a Mediterranean climate (Peel et al., 2007) with maritime influences. The average annual precipitation amounts (data from Region Abruzzo Hydrographic Service) are 600-800 mm/yr, with occasional heavy rainfall (>100 mm/d and 30-40 mm/h; Miccadei et al., 2012b). The coastal climate is characterized by the most frequent and highest waves arriving from the NW and NE with moderate intensity (Ortona wavemeter according to GNRAC, 2006 and ISPRA, 2018). The majority of the significant waves (>0.5 m) are higher than 2 m, and the strongest waves, which are as high as 3.5-6 m, have a 5% probability. Finally, the area features a microtidal environment characterized by an overall range of ≤1 m (ISPRA, 2018).

4. Methods

We analysed a 66 km-long coastal section and eight specific sites on coastal cliffs and slopes, combining (1) the interpretation of aerial photos and DEMs, (2) geological-geomorphological field surveys and (3) the results of sediment dating.

The main physiographic features of the entire investigated sector and the morphology of the cliffs and coastal slopes, were derived from stereoscopic imaging analysis of aerial photos (2001-2002 Regione Abruzzo flight, provided by Abruzzo Region Cartographic Office) and from GIS processing (ArcMap 10.1 © Esri) of a LiDAR-derived DEM at a 2-m cell size (acquired in 2011, provided by the National Geoportal of the Italian Ministry of Environment, http://www.pcn.minambiente.it/). The analysis aimed to identify and map scarps, break-in-slopes, flat and counter slope areas, landslides deposits, as well as to a preliminary differentiation between continental and marine Quaternary deposits. The coastal indentation index was calculated as the ratio between the real length of the coastal sector and its rectified length (Mastronuzzi et al., 1992; Maracchione et al., 2001), based on the 1:5,000 topographic map of the Abruzzo Region, 2007 edition (provided by Abruzzo Region Opendata services).

Existing cliffs retreat rates, based on aerial photos from 1954, 1975 and 1985 (D'Alessandro et al., 2001), have been integrated with more recent data using a comparable methodology. The cliffs were mapped on Volo Italia 1999 orthophotos (provided by the National Geoportal), Abruzzo Region 2009 and 2013 orthophotos (provided by Abruzzo Region Opendata services), extending the estimation of retreat rates over the last ~60 years, from 1954 to 2013, and to cliffs on continental deposits, not investigated previously.

A detailed geological field survey was conducted over the area, at a scale of 1:5,000, and on eight cliffs and coastal slope sites, at a scale of 1:1,000. The survey was based on a litho-stratigraphic approach, keeping attention on the litho-stratigraphic features of bedrock and superficial deposits, coastal and slope landforms and tectonic features of marine bedrock. This survey aimed to detail the presence and spatial distribution of superficial Quaternary continental deposits, improve existing lithological and tectonic information about the clastic marine bedrock, and investigate the morpho-stratigraphic relationships between bedrock, slope deposits, landslide deposits and eluvium-colluvium covers. Detailed litho-stratigraphical profiles on cliffs were realized to map lithological features at cliffs base and upper edge, stratigraphy of deposits building the cliffs, and tectonic features and joints.

The stratigraphic interpretation of the Quaternary continental deposits was supported by chronological constraints. Ages of calcretes and calcareous concretions were obtained by alpha spectrometry U/Th dating, undertaken by the Environmental & Isotope Geochemistry Lab. of RomaTre University of Rome. Three calcretes outcrops were sampled, by collecting, at each location, four coeval subsamples at the same stratigraphic level. Subsamples were prepared by removing altered parts and any recrystallized fragments. About 20 g of selected carbonatic material was dissolved in 7 N HNO_3. Insoluble residue was removed by centrifugation and digested in a mixture of $HF+HClO_4+HNO_3$. The two solutions were mixed and spiked with a tracer containing ^{228}Th and ^{232}U in secular equilibrium. Hydrogen peroxide was added to remove organic matter present in the solution. Isotopic complexes of uranium and thorium were extracted according to the procedure described in Edwards et al. (1987) and alpha-counted using high-resolution ion-implanted Ortec silicon surface barrier detectors. Ages were determined adopting the total sample dissolution technique (TSD) elaborated by Bischoff and Fitzpatrick (1991) for dating isotopically dirty carbonates. In order to calculate the $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ activity ratios of the pure carbonate fraction, samples are plotted on a three-dimensional isochron, whereby the X, Y and Z axes are the $^{232}Th/^{238}U$, $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ activity ratios, respectively. The age of the sample was calculated by means of Isoplot/Ex 3.0, a plotting and regression program designed by Ludwig (2003) for radiogenic-isotope data. Errors are quoted as 1σ, as conventionally adopted with alpha-spectrometry. ^{14}C dating was undertaken on lignite remains by the Radiocarbon Dating Lab. of the La Sapienza University of Rome; standard chemical pre-treating were carried out (12% HCl leaching followed by diluted alkaline solution treating and exsiccation at 110°C) followed by conversion to benzene (combustion and purification, lithium carbide synthesis, hydrolysis, catalytic trimerization with Cr) and radiocarbon activity counting (LSC) beta multichannel spectrometers; the provided age is "conventional", since very ancient ages (~ 40,000 yrs) are not suitable for calibration. Archaeological remains (Usai et al., 2003) and new palaeontological attribution of mammal findings, analysed by the Palaeontological Lab of the La Sapienza University of Rome, provide further information for the stratigraphic attribution of continental deposits.

The geomorphological field survey was undertaken at scales of 1:5,000 – 1:1,000 to identify present and ancient landforms and the morphogenetic processes affecting the coast (Smith et al., 2011; Chelli et al., 2016). Periodic field observations were carried from 2004 to 2017 and used for the direct observation and photographic documentation of active processes of cliff landsliding and retreat. Scuba-diving surveys performed at a scale of 1:1,000 down to 15 m b.s.l. provided information on the submerged parts of cliffs, as shore platforms and the underwater extensions of deposits related to the cliffs' evolution. Scuba survey procedures and methods were applied according to the Geological Survey of Italy guidelines up-scaled for detailed mapping (Orrù and Ulzega, 1987; Miccadei et al., 2012a). The geostructural analysis of rock masses was carried out at seventeen locations along the main cliff areas to characterize the geometry, spatial distribution and density of jointing affecting the cliffs.

All the detailed mapping and data are summarized on the simplified geomorphological map and in the detailed block diagrams presented in the next section, as well as in the coastal types sections and schemes discussed later on.

5. Results

5.1 Morphological and lithological features

The planar geometry of the coastline ranges from rectilinear to sinuous, with an overall indentation index of 1.22, locally increasing up to 1.35. The profile morphology is quite heterogeneous (Fig. 3), and four main morphological types of cliffs and coastal slopes are identified: 1) vertical cliffs up to >25 m high, 2) vertical cliffs up to >25 m high with gentle concave-convex slopes at their bases, 3) undulated concave-convex slopes up to >100 m high, and 4) slope-over-wall profiles with slopes up to >100 m high and walls 5-10 m high.

Geological and geomorphological investigations outline a complex Late Pleistocene – Holocene continental succession made-up of landslide, slope, eluvium-colluvium, beach-dune, fluvial, calcrete and travertine deposits, overlaying the Early-Middle Pleistocene marine to transitional clastic (clay, sand, sandstone, and conglomerate) units through a distinct and irregular erosive contact (Fig. 4, Table 1).

The landslide and slope deposits are composed mainly of chaotic sands and calcareous pebbles, including conglomerate and sandstone blocks. They are present at the cliff bases, produced by translational landslides and rockfalls. Within the landslide deposits at the cliff toe between Punta Aderci and Punta Penna, a bone remain was sampled and attributed to a *Bos primigenius* femoral part, whose most probable stratigraphic attribution is the early Holocene (Fig. 5a, b, Table 2). Moreover, the most widespread landslide bodies consist of ancient >1km^2 large rotational sliding, made-up of tens to hundreds of metres wide blocks of conglomerate and sandstone. These blocks are strongly counterslope tilted, with strata dipping more than 35° towards the SW, covering most of the coastal slopes between the Moro and Salinello rivers (Fig. 4).

	Torre Mucchia (TM)	Punta Ferruccio (PF)	Punta Lunga (PL)	Punta dell'Acqua bella (PAB)	Punta della Mucchiola (PM)	Punta Turchino Punta del Guardiano (PTG)	Punta Aderci (PA)	Punta della Penna (PP)
Morphological features								
H_c	>25 m	>25 m	<25 m	>25m	5<H<10	5<H<10	>25m	>25m
H_s	60 m	60 m	60 m	70 m	120 m	120 m	---	---
Sty	Vertical	Vertical and Vertical+concave convex	Vertical	Vertical and Vertical+concave convex	Slope-over-wall Undulated concave-convex	Slope-over-wall Undulated concave-convex	Undulated concave-convex Vertical	Vertical
Lithological features								
L_f	Sand	Conglomerate Silty sands	Silty sands	Conglomerate Sandstone	Landslides deposits	Landslides deposits	Conglomerate	Sandstone
L_e	Sandstone	Conglomerate	Silty sands	Sandstone	Landslides deposits	Landslides deposits	Conglomerate	Conglomerate
Tectonic features								
G	Sub-horizontal	Sub-horizontal	Sub-horizontal	Sub-horizontal	Chaotic	Chaotic	Sub-horizontal	Sub-horizontal
Fr	N60°E, 75° NW N90°E, 75°N N40°W, 80°NE N50°W, 50°NE N10°E, 80°ESE	N20°E, 80°WNW N60°E, 80°NW N90°E, 90° N60°W, 85°SW N60°W, 85°NE N20°W, 80°NNE	N60°E, 90° N70°W, 70° NNE N20°W, 90°	N10°E, 70°ESE N45°E, 90° N10°W, 60°WSW N50°W, 90°	/	N10°E, 80°ESE N30°E, 90° N60°E, 80°NW N60°W, 90° N30°W, 70°NE	N60°W, 90° N50°W, 80°NE N20°W, 90°	N30°E, 80°SE N60°E, 90° N15°W, 80°ENE
Geomorphological features								
L	Rockfalls, translational sliding, wave erosion	Rockfalls, translational sliding, wave erosion, notch	Rockfalls, translational sliding, wave erosion	Rockfalls, translational sliding, notch, shore platform	Complex landslides, rockfalls	Complex landslides, rockfalls	Rockfalls, notch, shoreplatform	Rockfalls, shoreplatform
SP	--	--	--	Horizontal	--	--	Horizontal	Horizontal
N	--	On silty sand	--	On conglomerate	--	--	On conglomerate	--
Retreat rates								
R	0.63 m/yr	0.85 m/yr	0.76 m/yr	0.46 m/yr	0.25 m/yr	0.97 m/yr	0.15 m/yr	0.75 m/yr

Table 1 Lithological, tectonic and geomorphological features of the eight surveyed cliff-coastal slopes areas (locations in Fig. 2 and Fig. 4). Hc: cliff height; Hs: coastal slope height; Sty: slope type; Lf: lithotypes at the cliff foot.; Le: lithotypes at the cliff upper edge; G: structural strata setting; Fr: fracturing; L: landforms; SP: shore platform, following Sunamura's classification (1992); N: notch; R: retreat rate.

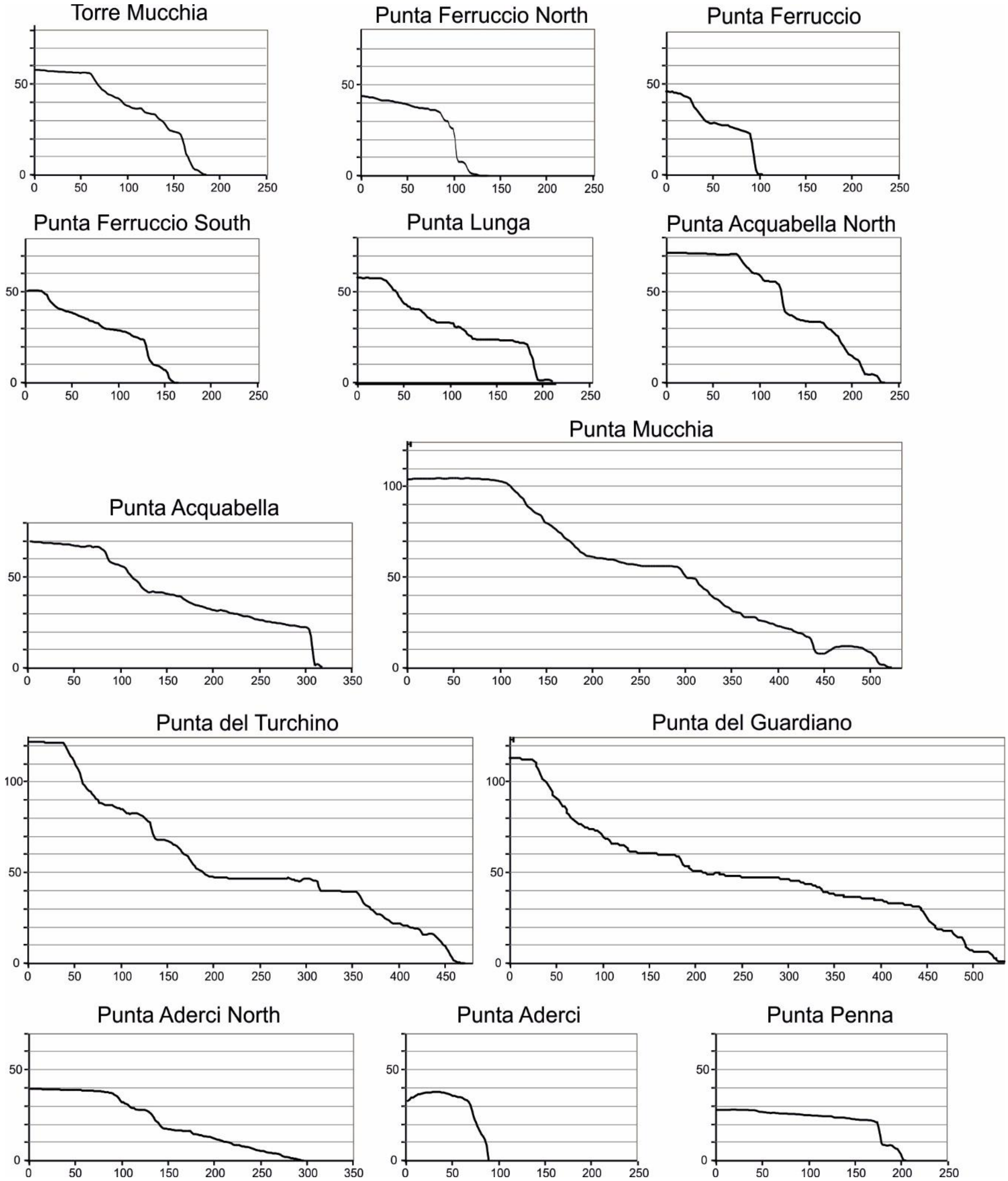

Fig. 3: Topographic profiles in the coastal areas from LiDAR data with a 2-m cell size resolution. Units of measurement are metres.

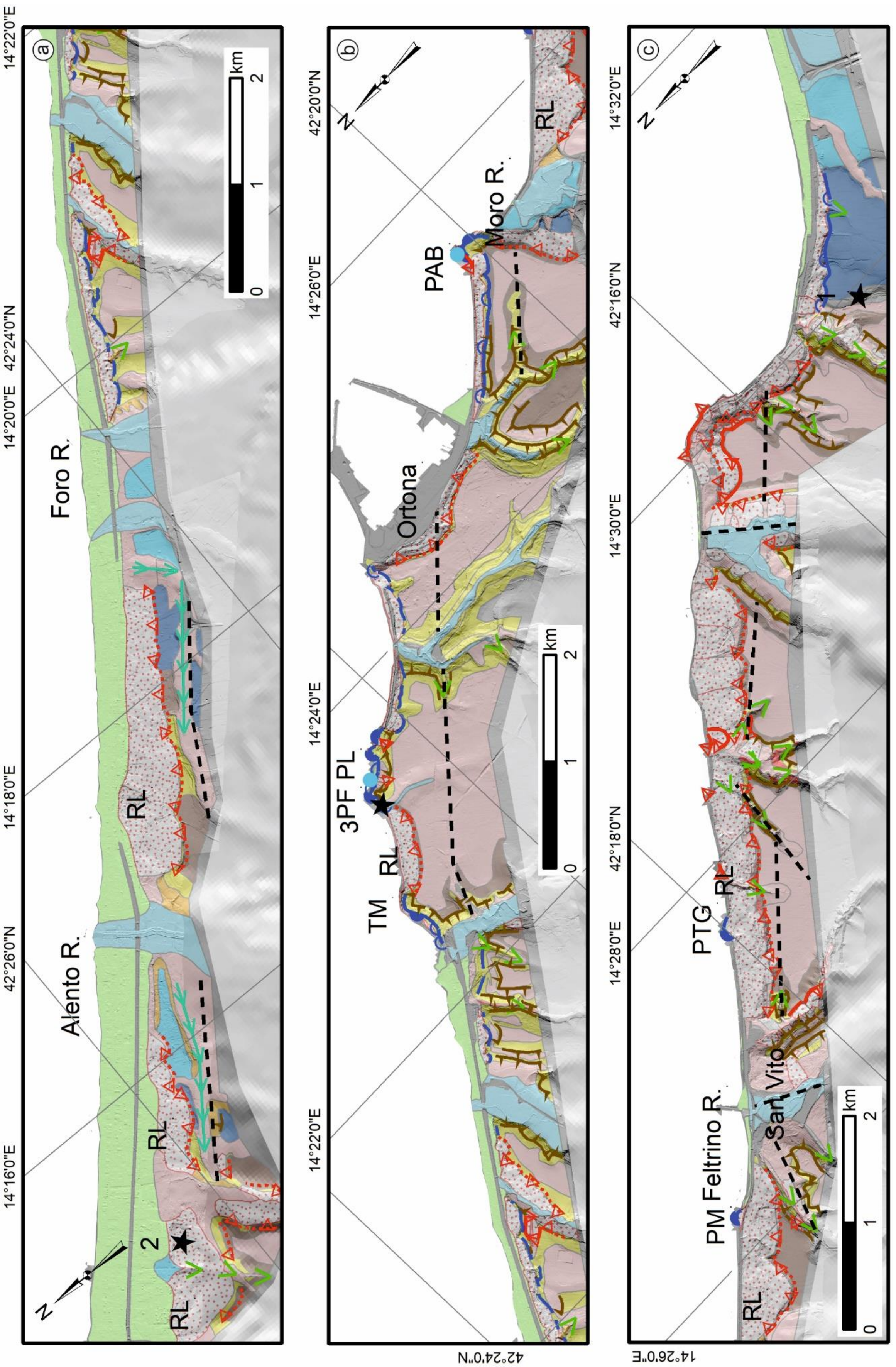

Fig. 4: Schematic geomorphological map of the rock coast area (over hill-shade image from the 2 m DEM). Location of a, b, c, d, e in Fig. 4f.

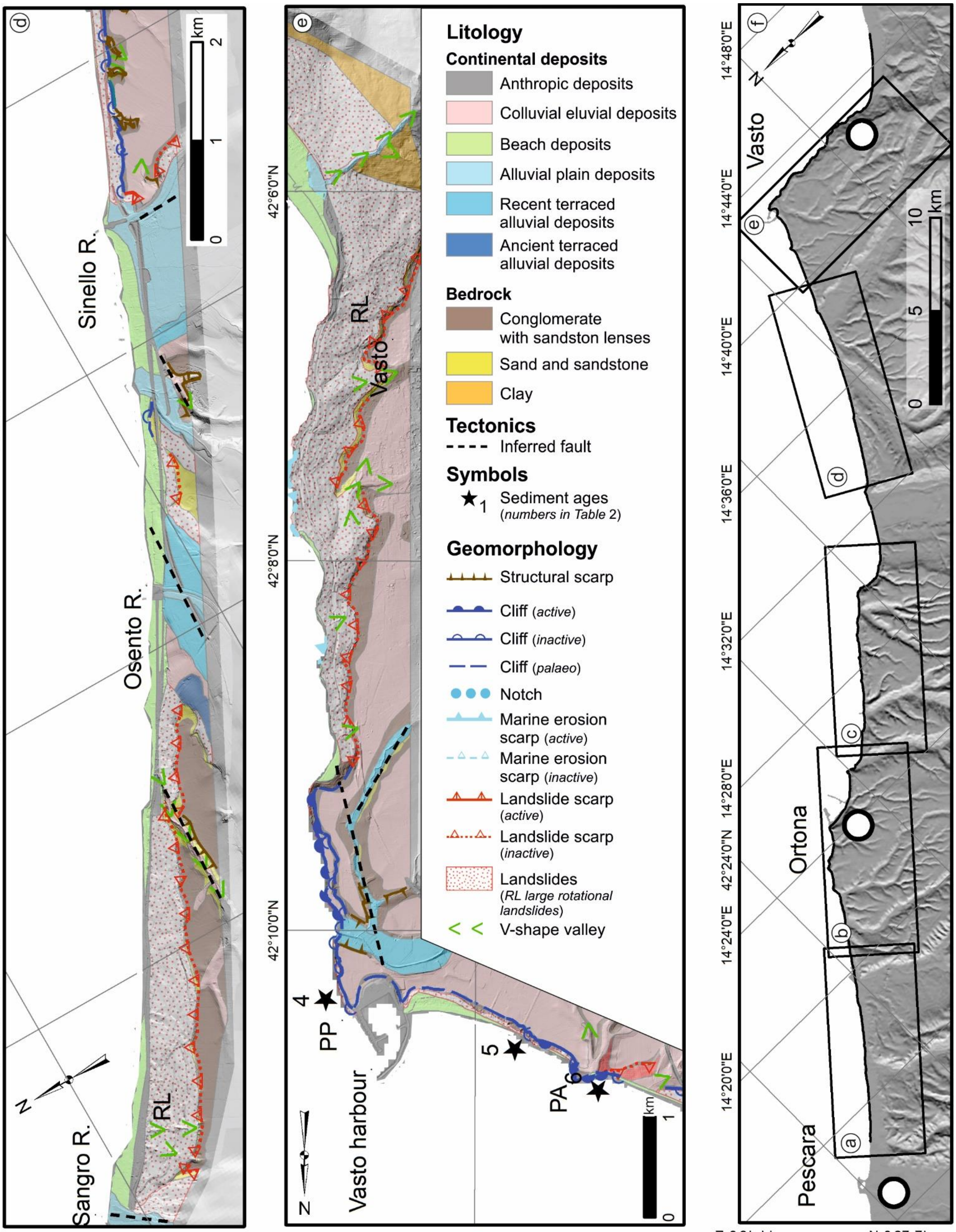

Fig. 4: (continue) Schematic geomorphological map of the rock coast area (over hill-shade image from the 2 m DEM). Location of a, b, c, d, e in Fig. 4f.

Eluvium-colluvium deposits comprise clay-sand-gravel chaotic to laminated assemblages. Extensive layers of eluvium-colluvium deposits cover the flat tops of the coastal slopes and cliffs overlying the conglomerate bedrock unit. They also cover flat areas and scarps along the coastal slopes, as well as the small valleys incising the cliffs. Clayey-sandy deposits are occasionally present at the bases of the coastal cliffs and are cut back by the present marine erosion, such as in the case of the Punta Penna cliff, where lignite remains were ^{14}C dated to 42 ± 8 ky (Fig. 5c, d, Table 2, location in Fig. 4).

Calcretes are made up of small patches (not represented in Fig. 4) of laminated calcareous concretions ranging from porous and soft to compact and hard, with horizontal undulated stratification. They generally fill the flat areas or counterslope depressions, overlaying ancient landslide deposits. U/Th dating of two different outcrops provide ages of 31 ± 4 ky and 52 ± 8 ky (Table 2, location in Fig. 4). Travertine deposits are characterized by small horizontal-growing, massive structure on some cliffs, with vertical stratification parallel to the cliff, and by encrusting massive convex bodies made-up of a sequence of millimetre-size undulated layers. They are built-up by carbonate precipitation on local springs and small waterfalls on the cliffs and in little pools at the cliff toe, overlying pre-existing forms and deposits related to cliff recession as conglomeratic blocks. The age of the travertines provided by U/Th dating is 9 ± 7 ky (Table 2, location in Fig. 4).

Gravelly to sandy beaches, locally associated to sand dunes, are scattered all along the bases of cliffs and fill in small to large pocket beaches. In some cases, they are backed by coastal plains that are up to hundreds of metres wide (Fig. 4).

Recent (Holocene) and terraced (Middle-Late Pleistocene) fluvial sand-gravel deposits with clay-silt lenses are present at the mouth of the main fluvial valleys intervening between the rock coast sectors (Fig. 4).

#N	Sample	Description	Method	Age
#1	Fossacesia (FC)	Calcrete	U/Th	52 ± 15 ky BP
#2	Francavilla al Mare (FNC)	Calcrete	U/Th	31 ± 3.3 ky BP
#3	Punta Ferruccio (PF)	Travertine concretion	U/Th	9 ± 7 ky BP
#4	Punta Penna (Roma 1889)	Lignite remains	^{14}C (conv. age)	42.8 ± 1.5 ky BP
#5	Punta Aderci	Mammal remain: femur of *Bos primigenius*	Palaeontological analysis	Early Holocene
#6	Punta Aderci	Archaeological findings	Archaeological analysis	*XI-VIII century BC (Usai et al., 2003) +* 1350 or 1817 AC

Table 2 Constraints on the Quaternary continental deposits.

Fig. 5: **a**) Sample location within the landslide deposits at the cliff base between Punta Aderci and Punta Penna. **b**) Bone remain attributed to a Bos *primigenius* femoral part dated to early Holocene (Table 2). **c**) Sample location within a clay-sand deposit at the base of the Punta Penna cliff. **d**) Lignite remains ^{14}C dated to the Late Pleistocene (42 ± 8 ky, conv. age, Table 2).

Lithological features indicate that the coastal slopes and cliffs are developed on different bedrock units, with variations between toes and tops, and were grouped into 1) cliffs on sandstone, 2) cliffs on conglomerate, 3) coastal slopes on ancient slide deposits, and 4) cliffs on late Quaternary slope continental deposits.

5.1.1 Cliffs on sandstone

Cliffs on sandstone constitute over the 15% of the study area and characterize the promontories of Torre Mucchia, Punta Lunga and Punta dell'Acquabella (Table 1, Fig. 4). They are primarily vertical to very steeply seaward-dipping and >25 m high, with locally gentle concave-convex base profiles (Fig. 3). These cliffs are formed when the bedrock clay/sandstone-conglomerate (referred to as c/scg hereon) interface is just below present sea level. The sandstone bedrock unit consists of moderately consolidated and weakly cemented sand at the lower part of the cliff (s, Fig. 6a). The upper part, is made of cemented sandstone, with strata ranging from 10 to 30 cm in thickness and poorly cemented sandstone strata interbedded (ss, Fig. 6a). Occasionally (i.e. promontory of Punta dell'Acquabella, Fig. 6b,c), the cliff toes are characterized by lenses of well to poorly cemented conglomerate, 2-5 m thick, with heterometric rounded pebbles (ø 5-10 cm). The cliff toes are partly covered by recent slope sand deposits, with embedded blocks of conglomerate and sandstone up to >10 m in size (c, Fig. 6a). Above the top of the cliffs a gentle slope is usually present, mostly covered by silt-sandy-gravelly eluvial-colluvial and slope deposits.

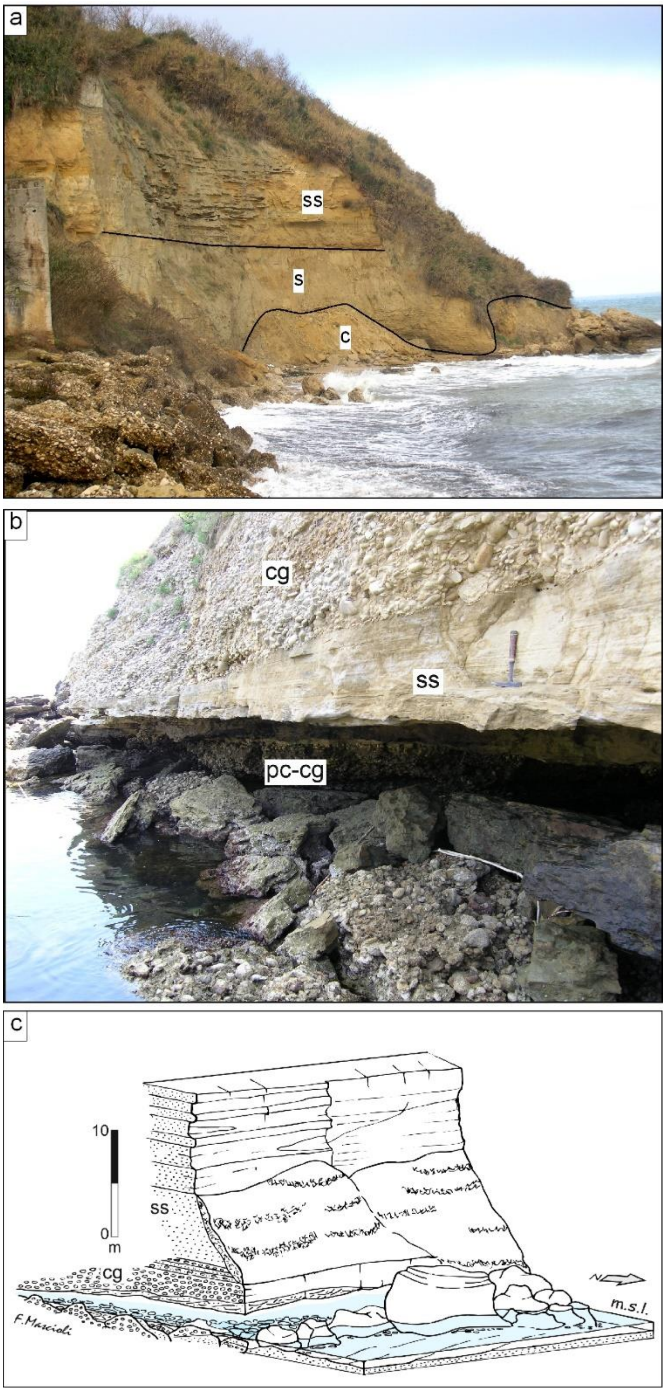

Fig. 6: Coastal cliffs on sandstone. **a**) Torre Mucchia cliff on marine sandstone (ss) and sands (s) and with rockfall deposits at the base (c). **b**) Punta dell'Acquabella, cliff on sandstone (ss) with conglomerate levels (cg), with basal notch in a poorly cemented conglomerate lens (pc-gc). **c**) Block diagram of the cliff on sandstone of Punta dell'Acquabella.

5.1.2 Cliffs on conglomerate

Cliffs on conglomerate extend over 15% of the area and characterize the promontories of Punta Ferruccio, Punta Aderci and Punta della Penna (Table 1, Fig. 4, 7). They are >25 m high with a sub-vertical and sometimes gentle concave-convex slopes at their bases (Fig. 3). In these cliffs, the bedrock c/scg interface is well below present sea level. The conglomerate is moderately to well cemented, made of heterometric calcareous pebbles and cobbles 1 to 20 cm in size (cg, Fig. 7). Levels and lenses of sandstone and silty-sand from 2 to 5 m thick are present, locally outcropping at the cliff toe. In some cases, the cliffs are covered by recent slope and landslide deposits, consisting of conglomerate blocks up to >10 m in size (e.g. Fig. 7b). The slopes above the cliffs are usually covered by silty-sandy-gravelly eluvium-colluvium and slope deposits. At Punta Ferruccio, the conglomerate along the cliff is encrusted by phytohermal travertine concretions (tr, Fig. 8), which, according to U/Th analysis, are dated to 9 ± 7 ky (Table 2).

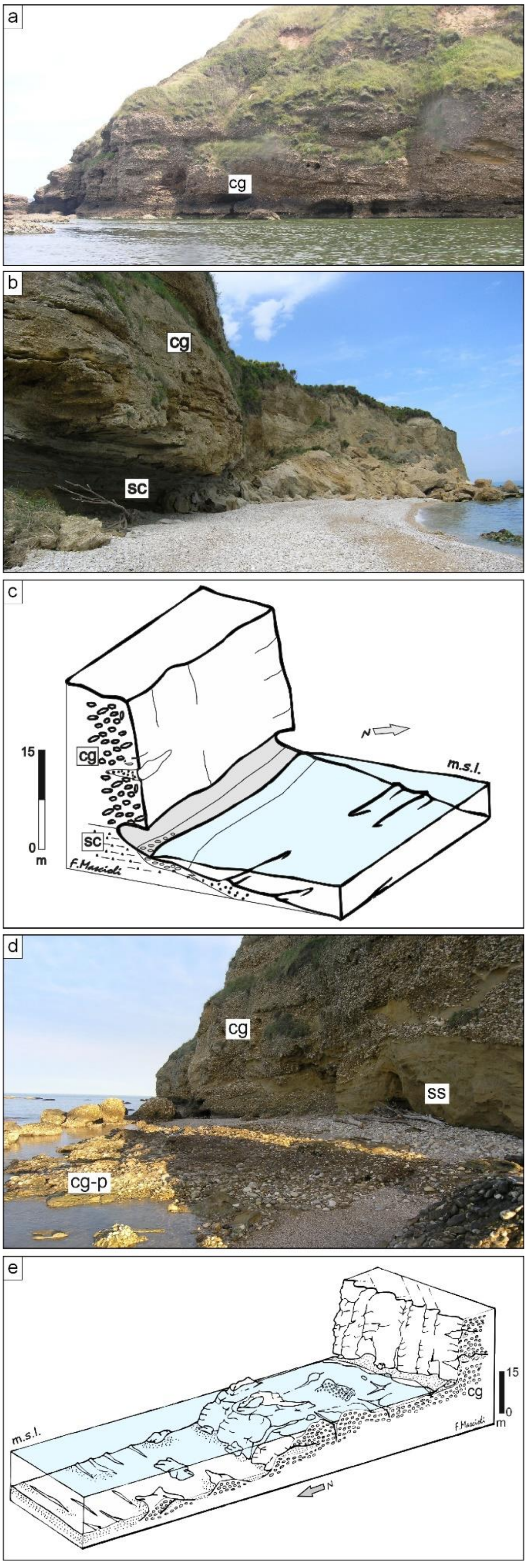

Fig. 7: Coastal cliffs on conglomerate. **a**) Punta Aderci cliff on marine conglomerate (cg). **b**) Punta Ferruccio, cliff on conglomerate (cg), with basal notch in sandy-clay (sc). **c**) Block diagram of the cliff on conglomerate of Punta Ferruccio. **d**) Punta Aderci, cliff on conglomerate (cg) at the internal margin of a horizontal shore platform developed on conglomerate (cg-p), with small discontinuous notches in the sandstone lenses (ss). **e**) Block diagram of the coastal cliff on conglomerate with shore platform at Punta Aderci.

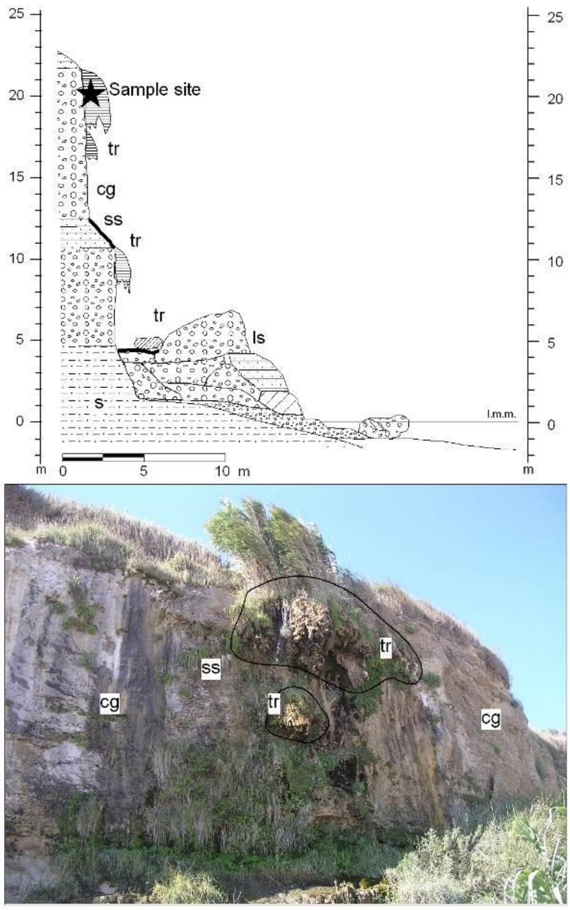

Fig. 8: Punta Ferruccio, stratigraphic log and photo of travertine formations and encrustations (tr and black thick surfaces) developed over a conglomerate cliff (cg) with sandstone lenses (ss) and sand (s). Travertine also encrusts rockfall deposits (ls) at the base of the cliff. The sample location refers to dated sample #3 (Table 2).

5.1.3 Coastal slopes on ancient landslide deposits

Coastal slopes are widespread and extend over 43% of the area (Table 1, Fig. 4). The profile morphology includes undulated concave-convex slopes up to >100 m high. Alternating steep scarps, flat areas and counterslopes, with no lateral continuity or height correlation (Fig. 9) that are occasionally contiguous with coastal plains occur. Slope-over-wall profiles are also common, with 5-10-m cliffs at the bases of the slopes. The marine conglomerate unit generally outcrops on the upper scarps, bounding the flat tops of the hills, whereas the underlying sand-sandstone deposits are just occasionally exposed. The bedrock c/scg interface is well above present sea level and the clayey marine deposits are generally buried under continental deposits consisting of large roto-translational landslides deposits covered by slope and eluvium-colluvium deposits. Landslide deposits consist of blocks of conglomerate and sandstone that are ten to hundreds of metres in size and strongly tilted counterslope, with strata dipping more than 35° towards the SW (Fig. 9), outlining steep scarps all along the coastal slopes down to the coastline. Slope deposits consist of chaotic sands and calcareous pebbles, including blocks of conglomerate and sandstone referable to the marine bedrock unit. Sandy eluvium-colluvium and small patches of calcretes overlay slope and landslide deposits, mostly in flat and countersloping areas. Calcretes are made of laminated calcareous concretions ranging from porous and soft to compact and hard, with horizontal undulated stratification. Two samples of calcretes over landslide deposits were U/Th dated to 31 ± 4 ky and 52 ± 8 ky (Table 2, location in Fig. 4), providing at least a Late Pleistocene age for the large landslides. Some of the coastal slopes are covered at their toes by beach and dune deposits and by anthropogenic deposits (e.g. railway and road embankments, harbour earth works).

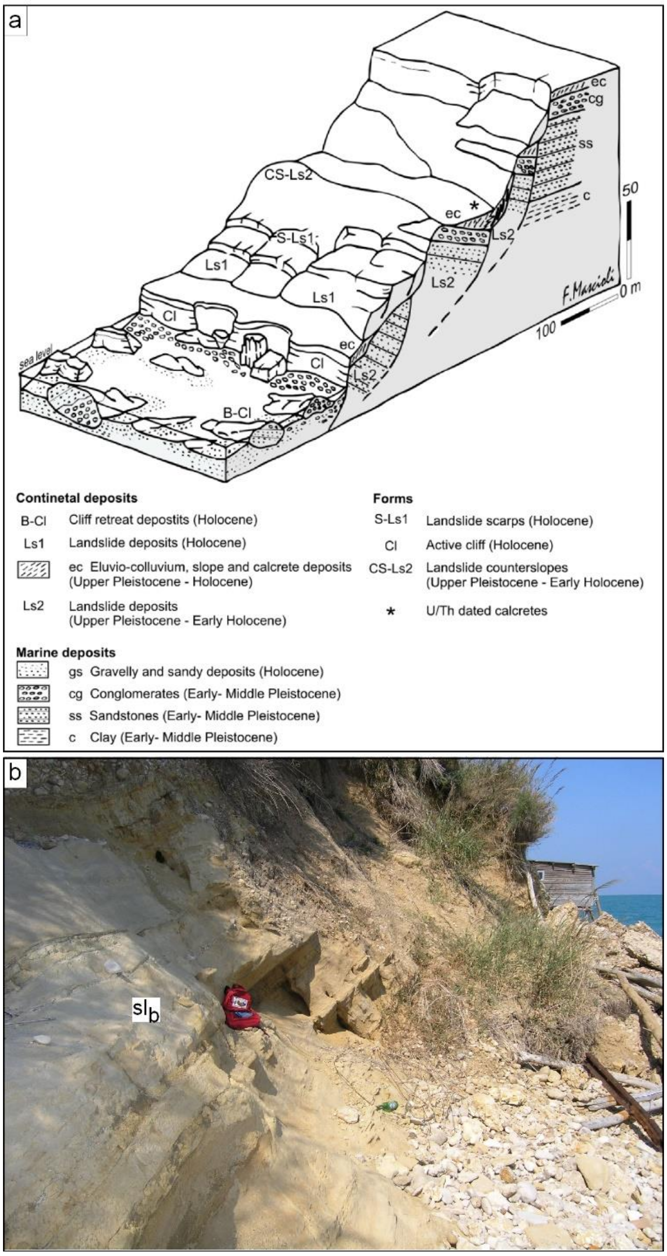

Fig. 9: Coastal slopes. **a**) Block diagram summarizing coastal slope geomorphological and stratigraphical features. **b**) Punta del Guardiano coastal slope, sandstone (sl_b) landslide blocks at sea level, outcropping with counterslope attitudes (dipping up to 35° SW) and covered by recent gravel beach deposits.

5.1.4 Cliffs on slope continental deposits

Cliffs on slope continental deposits extend approximately over 3% of the coastal area, mainly located at Torre Mucchia, Punta Aderci and Punta della Mucchiola areas (Table 1, Fig. 4). Cliffs are up to >10 m high and developed on Late Pleistocene to Holocene slope - colluvial deposits (sl_a, Fig. 10a). They consist of brown sands alternating with poorly to moderately cemented ochre layers, including up to 10 cm-thick gravel layers of rounded calcareous granules and pebbles of 1-20 mm in size as well as silt levels (Fig. 10b). These deposits lie on an erosive surface over the marine conglomerate (cg), with a maximum thickness of approximately 4 m and clinostratification parallel to the slopes (Fig. 10c). Some of these cliffs, as the case of Punta della Mucchiola, are also developed on ancient landslide deposits. In the Punta Aderci area, huts with ceramic remains as well as an historical ossuary are present within the deposits (Usai et al., 2003), which are now cut back by the recession of the cliffs.

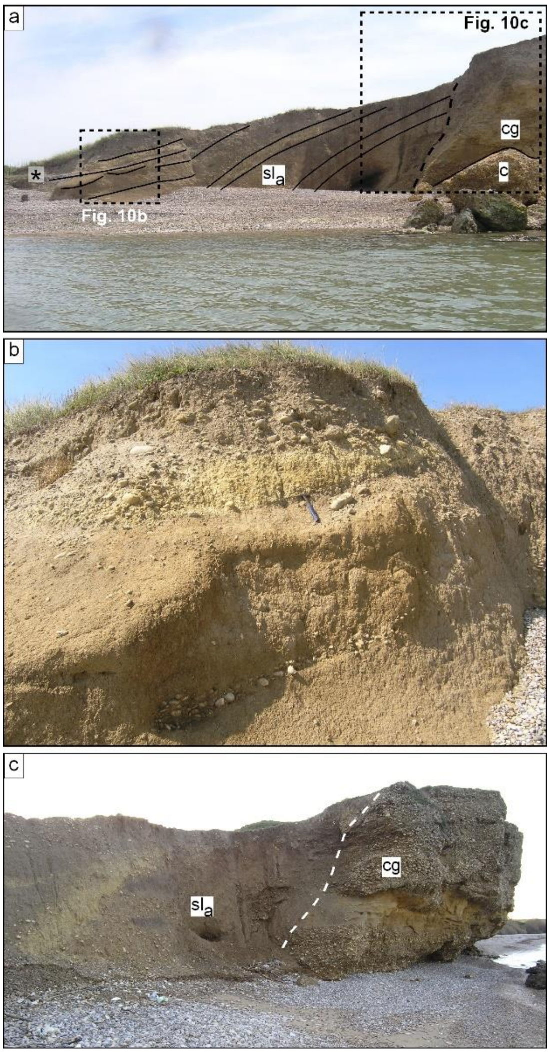

Fig. 10: Cliffs on continental deposits. **a**) Punta Aderci cliff on finely laminated sandy colluvial and slope deposits (sl_a) with clino-stratification and overlying an erosive surface (dashed line) on a marine conglomerate (cg); * marks the location of archaeological findings dated to historical times (Usai et al., 2003). **b**) Close up of the sand and silt deposits with granules and pebbles thin layers. **c**) Slope and colluvial deposits (sl_a) lying on an erosive surface over the marine conglomerate (cg).

5.2 Structural setting and jointing

The structural setting of the bedrock unit in the coastal area is defined by horizontal or gently (<5°) NE-dipping strata connected to the Pleistocene regional uplift. Two tectonic discontinuities systems affect the bedrock unit with NE-SW to NNE-SSW and NW-SE to WNW-ESE directions (Fig. 4). The NE-SW to NNE-SSW system does not affect the Quaternary continental deposits. The NW-SE to WNW-ESE discontinuities are mostly sealed by Holocene colluvial and slope deposits along the coast, but in the inner hilly area they affect the late Middle - Late Pleistocene fluvial deposits and secondary valley development (Fig. 4). The first system pre-dates the Early Pleistocene, and the second occurred during the late Middle-Late Pleistocene and may be connected to the uplifting and gentle tilting of the clay-sand-sandstone-conglomerate sequence.

Large joints pervasively affect the rock masses all along the cliffs and coastal slopes. The main orientations are N-S, NE-SW and NW-SE, both parallel and perpendicular to the coastline, with vertical or seaward dipping (Table 2, Fig. 4). The spacing ranges from a few decimetres to 3-5 m, with larger values occurring in the conglomerate bedrock and smaller ones mostly occurring on sandstones. The persistence is usually several metres and, locally, joints affect the whole cliff (Fig. 11a, b). The joint apertures range from <1 cm up to 3 cm. The latter are enlarged by tensile stresses along the free faces of the cliffs and strongly control the development of rockfalls and large roto-translational landslides.

5.3 Cliffs and coastal slopes landforms

The main landforms are generated by coastal processes, as notches, beach systems, and shore platforms, and gravity-induced slope processes, as several different types of landslides (Table 1, Fig. 4).

Notches are present and well developed (up to some metres deep) at the feet of sandstone and conglomerate cliffs, whereas discontinuous, small (depths of a few decimetres) notches are incised on poorly cemented layers on sandstone cliffs, and their deepening is limited by hanging rockfalls.

On conglomerate cliffs, notches develop deeply in poorly cemented clayey sandstone interbedded layers outcropping at the cliff bases. Due to the hardness of overhead conglomerates, they develop up to 7 m in depth and 4 m in height, i.e. at Punta Ferruccio (Fig. 7a,b,c). On cliffs on sandstone discontinuous notches are also present, even though the deepening is limited to few decimetres by hanging rockfalls. Locally, i.e. Punta dell'Acquabella, where the base of sandstone cliffs is made of conglomerate lenses, notches several metres deep and just 1 m high are incised (Fig. 6b,c). Where a horizontal shore platform is present (Fig. 7d,e), the notches are usually small and discontinuous and mainly occur on weak sandstone lenses within the conglomerates. The incision of notches is continuously active where a continuous wave erosion is present (Fig. 6b,c) or active only during heavy sea storms if notches are partially protected by a narrow beach (Fig. 7b). Pebbly-sandy pocket beaches (Fig. 7b) with widths ranging from metres to tens of metres are scattered at the cliff bases between the main promontories. They reduce the coastal erosion on the cliffs, sometimes preventing it and defining inactive cliffs. Several sectors exhibit sandy beaches, generally up to some hundreds of metres wide and locally connected to dune systems that permanently prevent coastal erosion, thus outlining relict palaeocliffs.

The submerged parts of cliffs are mostly characterized by sandy seabed with slopes ranging from 0.7% to 2.0%. A gravelly seabed represents the continuation of small pocket beaches below sea level, and are mostly fed by the erosion of cliffs and surrounding headlands. However, 70 to 100 m-wide sub-horizontal-type shore platforms occur at the bases of Punta Aderci, Punta della Penna, and Punta dell'Acquabella cliffs (Fig. 7d,e). The shore platforms are cut on well-cemented conglomerates (Punta Aderci) or on sandstones (Punta della Penna and Punta dell'Acquabella). Several rocks rising up to 1.5 m above sea level, comprising well-cemented conglomerate, are present at the outer margin of platforms (Table 1, Fig. 7e).

Gravity-induced slope landforms consist of landslides, rockfalls and topples. Large ancient rotational slides are widespread along the coast (Fig. 4) and outline large undulated coastal slopes. They are bounded by continuous and marked top scarps, up to 20-40 m high, and internally characterized by several secondary scarps separating distinct landside terraces, with marked lateral continuity, related to multiple sliding surfaces. These scarps are due to displacements within the clay-sandstone-conglomerate sequence, involving coastal slopes where the top clay layers lay several tens of metres above sea level (Fig. 9). These landslides are mostly ancient and inactive (except for the Vasto landslide, Calamita et al., 2012), being overlain by recent colluvial and calcrete deposits. However, the lower parts of the coastal slopes feature small cliffs up to 10 m high (slope-over-wall profile) and are affected by local reactivations or new roto-translational sliding and lateral spreadings, often damaging roads, facilities and houses.

Rockfalls affect the cliffs due to coastal erosion, notch deepening and the opening of joints under tensile stress (Fig. 11a, b, d). They occur both on sandstone (i.e. Torre Mucchia, Punta Lunga, and Punta dell'Acquabella, Fig. 12a, b, c) and conglomerate cliffs (i.e. Punta Ferruccio, Punta Aderci and Punta della Penna, Fig. 12d, e). Rockfall deposits comprise heterometric boulders, up to 5 m on conglomerate and 3 m on sandstone. Topples occur when vertical and large spaced joints parallel to the cliff are present (Fig. 12f). Translational slides mainly affect coastal cliffs on soft sediments and the toes of coastal slopes on ancient landslide deposits (Fig. 11c). Slides and falls also occur along cliffs on continental deposits and are again induced by notch incisions (Fig. 12g, h). Resulting deposits are quickly dismantled by waves and covered by beach deposits (Fig. 12i). The main cliff segments are separated by the main rivers reaching the coast perpendicularly, with fluvial plains up to 3 km in width. Occasionally, the cliffs are intersected by dry valleys descending from the side of the mesa and plateau relief, and in many cases the dry valleys have been truncated due to active cliff erosion and left hanging.

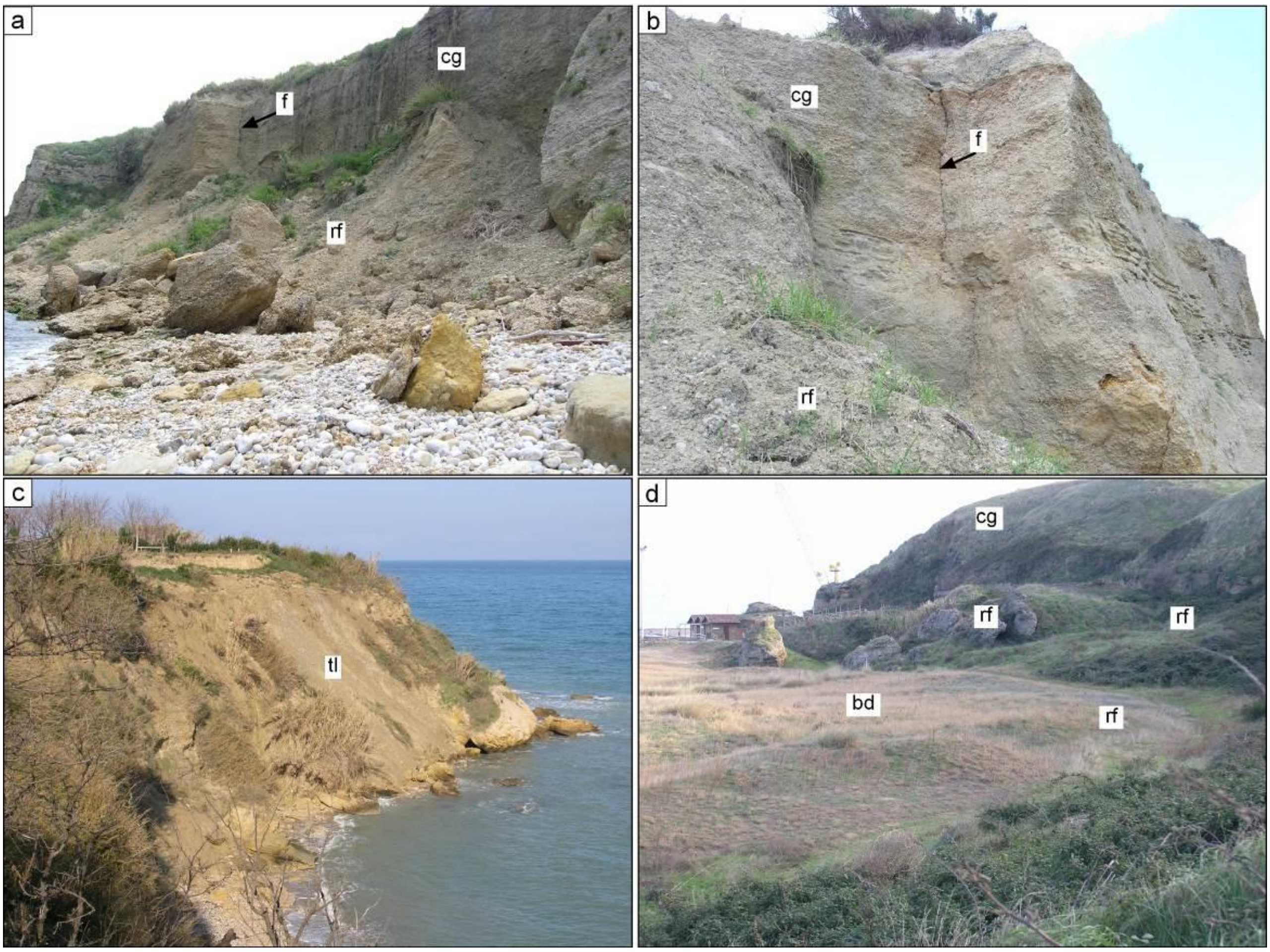

Fig. 11: Gravitational slope landforms. **a**) Punta Ferruccio, rockfall deposits (rf) made of conglomerate blocks at the conglomerate cliff (cg) foot; the cliff is defined by large parallel joints, which cut large conglomerate blocks off. **b**) Punta Ferruccio, tension cracks and fractures (f) on conglomerate (cg) that cut conglomerate blocks off, inducing rockfalls (rf). **c**) Punta Lunga, translational slide (tl); **d**) Punta della Penna, rockfall deposits (rf) consisting of conglomerate blocks partly covered by beach and dune deposits (bd) along a conglomerate cliff (cg).

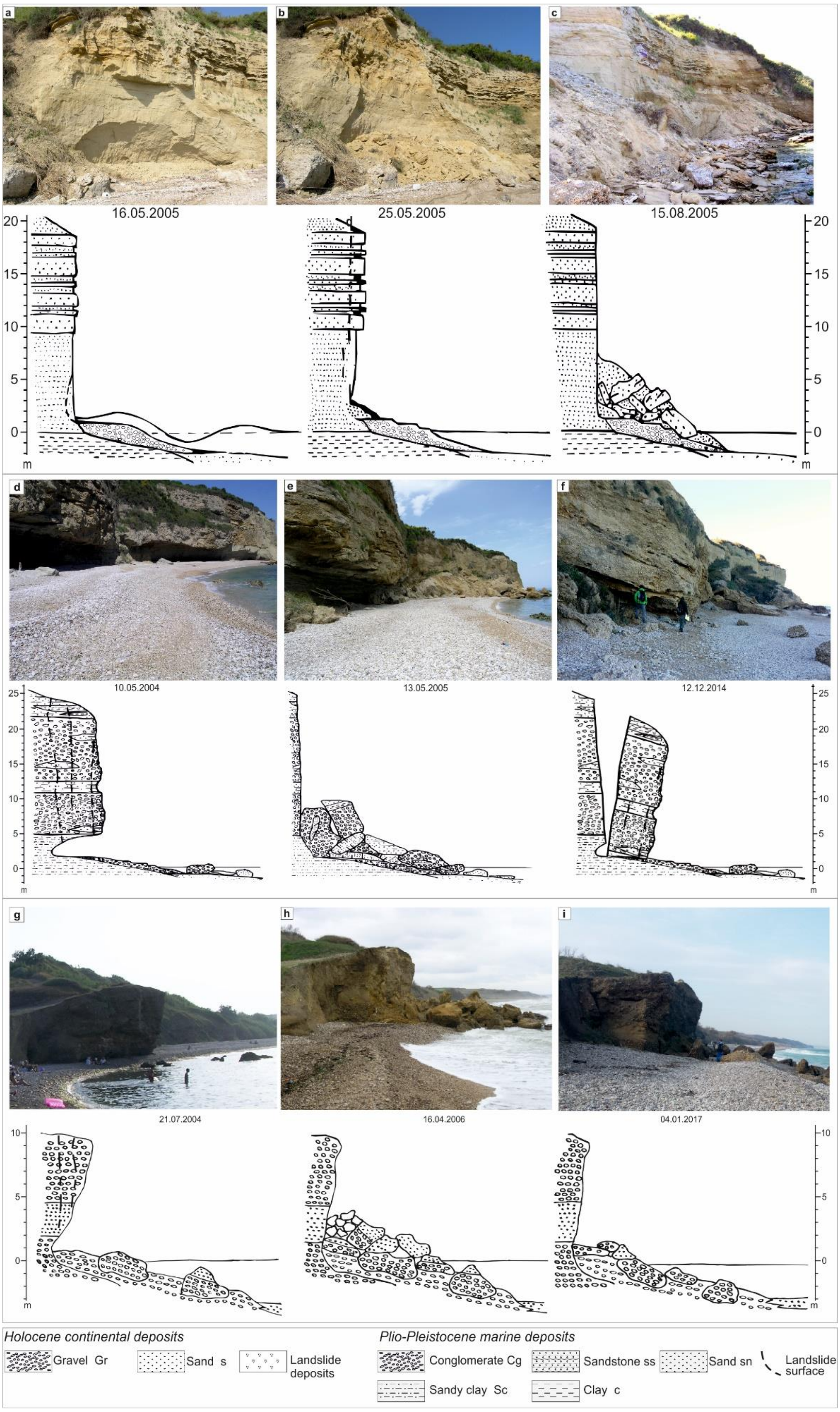

Fig. 12: Landslides and retreat processes observed through multi-temporal surveys, outlining two different evolutions related to rockfall and lithological features. Cliff on soft rocks at Torre Mucchia: **a**) wave erosion; **b**) first rockfall phase affecting the whole cliff; **c**) second rockfall phase. Cliff on hard rocks at Punta Ferruccio: **d**) wave erosion and notch development; **e**) fall failure; **f**) toppling. Landslides and retreat processes observed through multi-temporal surveys, outlining the evolution of a cliff on soft continental deposits at Punta Aderci: **g**) wave erosion and jointing; **h**) rockfall of well cemented conglomerate boulders; **i**) slope deposit removal by wave action.

5.4 Cliff retreat

The overall values over a 60-year time span range from 9 m to 57 m, corresponding to rates variable from 0.15 m/yr to ~1 m/yr (Fig. 13). The step-like trend of the graph outlines the episodic and localized nature of cliff recession over a short time span. The highest values (~1 m/yr) occur on the main promontories (Punta Turchino and Punta del Guardiano) developed on coastal slopes over large ancient landslides, where the cliff bases are easily incised by marine erosion. High values of retreat rates also involve cliffs developed on conglomerates (Punta Ferruccio and Punta della Penna) and sandstone (Torre Mucchia and Punta Lunga) with notches (0.85-0.65 m/yr), as well as cliffs on continental deposits (0.9 m/yr, Punta Aderci 2).

Moderate retreat values occur on cliffs on hard sandstone and conglomerates (0.48 m/yr, Punta Acquabella), whereas the lowest value (0.15 m/yr; Punta Aderci 1) occurs on hard conglomerate cliffs with poor evidence of coastal erosion at their bases (no notch, large shore platform). Moderate to low values have affected the Punta Mucchiola area (~0.25 m/yr). The coastal slopes and embayments between the main promontories are largely armoured to prevent coastal erosion along the path of an ancient 1800s railway, which was later abandoned and moved some kilometres inland in the late 1900s (due to instabilities connected to coastal erosion, which is cutting the coastal barriers off).

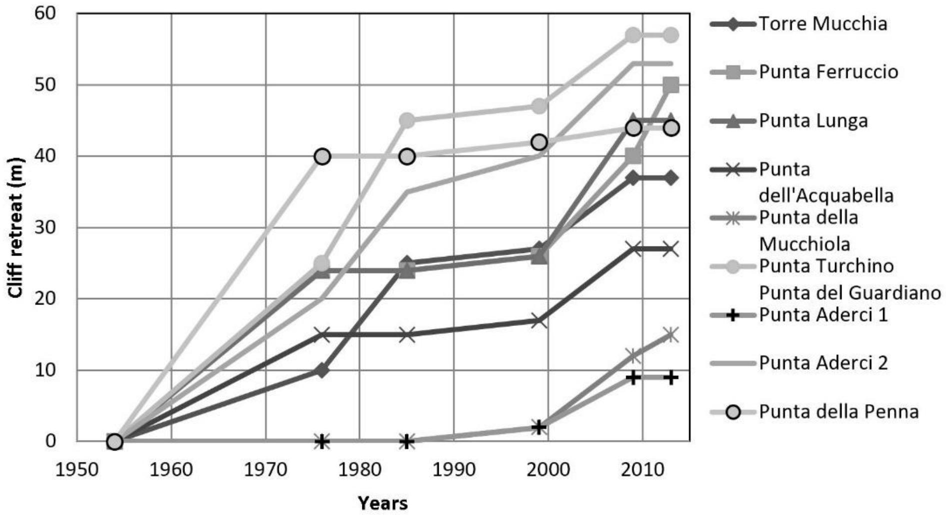

Fig. 13: Cliff retreat measured for the eight sites analysed in this work (Table 1) over a 60-year time span range (1954-2013).

6. Discussion

The overall analysis defined a gently indented coast with cliffs over 25 m high and coastal slopes over 100 m high. They are the eastern margin of a mesa-plateau landscape, made-up of clastic marine Early-Middle Pleistocene sedimentary bedrock. Rock types range from poorly consolidated clay and sand, to well consolidated, moderately cemented sandstones and conglomerate. The bedrock is covered by scattered Late Pleistocene – Holocene continental slope and colluvial deposits as well as by large landslides. Locally, cliffs and slopes are rimmed by sand-gravel beaches, pocket beaches or by up to 500 m-wide coastal plains.

The investigated area is composed of several cliff/coastal slope segments separated by the alluvial plains of major and minor rivers. The quantitative analysis of the overall plan morphology through the indentation index outlines a close to steady-state coast with some local prominent indentations (Mastronuzzi et al., 1992; Maracchione et al., 2001).

6.1 Late Pleistocene-Holocene continental succession of the rock coasts

The bedrock units are covered by a complex Late Pleistocene-Holocene continental succession constrained by new chronological data (Fig. 14). The deposits of large landslides are the most ancient along the coast and are only pre-dated by the terraced Middle-Late Pleistocene fluvial deposits of the main valley crossing the coast (D'Alessandro et al., 2008; ISPRA, 2012a,b,c; Piacentini et al., 2015). The landslide deposits are covered by patches of slope deposits and eluvium-colluvium deposits encrusted by calcretes (dated back to the middle of the Late Pleistocene, 31 ± 4 ky and 52 ± 8 ky BP, Table 2, Fig. 14). This back-dates the underlying large landslides at least to the lower part of the Late Pleistocene (during a sea-level fall and lowstand) or to the late Middle Pleistocene (as also suggested by Della Seta et al., 2013), whereas they have been partially reactivated in recent times (e.g. Vasto landslide, Buccolini et al., 1994).

The toes of inactive cliffs and palaeocliffs are covered by colluvial clay-sand deposits and landslide deposits that have been dated back to the Late Pleistocene (42 ± 4 ky BP, Table 2, Fig. 14) and to the Early Holocene (Table 2, Fig. 14), respectively, pointing to an early Late Pleistocene development of the inactive cliffs (possibly during the Tyrrenian sea-level highstand). Further constraints are imposed by travertines approximately dated to 9 ± 7 ky BP (Table 2). They encrust the inactive cliffs and blocks at their base (Fig. 14), whose formation can be therefore supposed during the early Holocene. Beach and dune systems that protect inactive and palaeocliffs are related to two main depositional phases known in the Adriatic area: the first occurred approximately 2,500 years ago, as documented in the Apulia region in the southern Adriatic area

(Mastronuzzi and Sansò, 2002), and the second is dated to the Late Middle Age, as documented in the study area (Miccadei et al., 2011b; Fig. 14). Some local beach-dune systems, covering palaeo- and inactive cliffs, are very recent (<70 yrs) and anthropogenically generated by the realization of harbours (e.g. Punta Penna, Miccadei et al., 2011b).

Colluvial deposits blanket small valleys along the coast, cover the slopes surrounding the cliffs and the coastal slopes and locally are subject to local erosion by the present cliffs. Occasionally, they contain remains of huts with ceramic remains dated to historical times, which in Punta Aderci were attributed to Bronze Age, XI-VIII century BC (Usai et al., 2003), whereas an ossuary could be possibly attributed to the Black Plague that occurred in 1,350 AC or to a typhus epidemic in 1,817 AC. This outlines the very recent (centennial and decadal) and continuous development of the active cliffs cutting back the valleys.

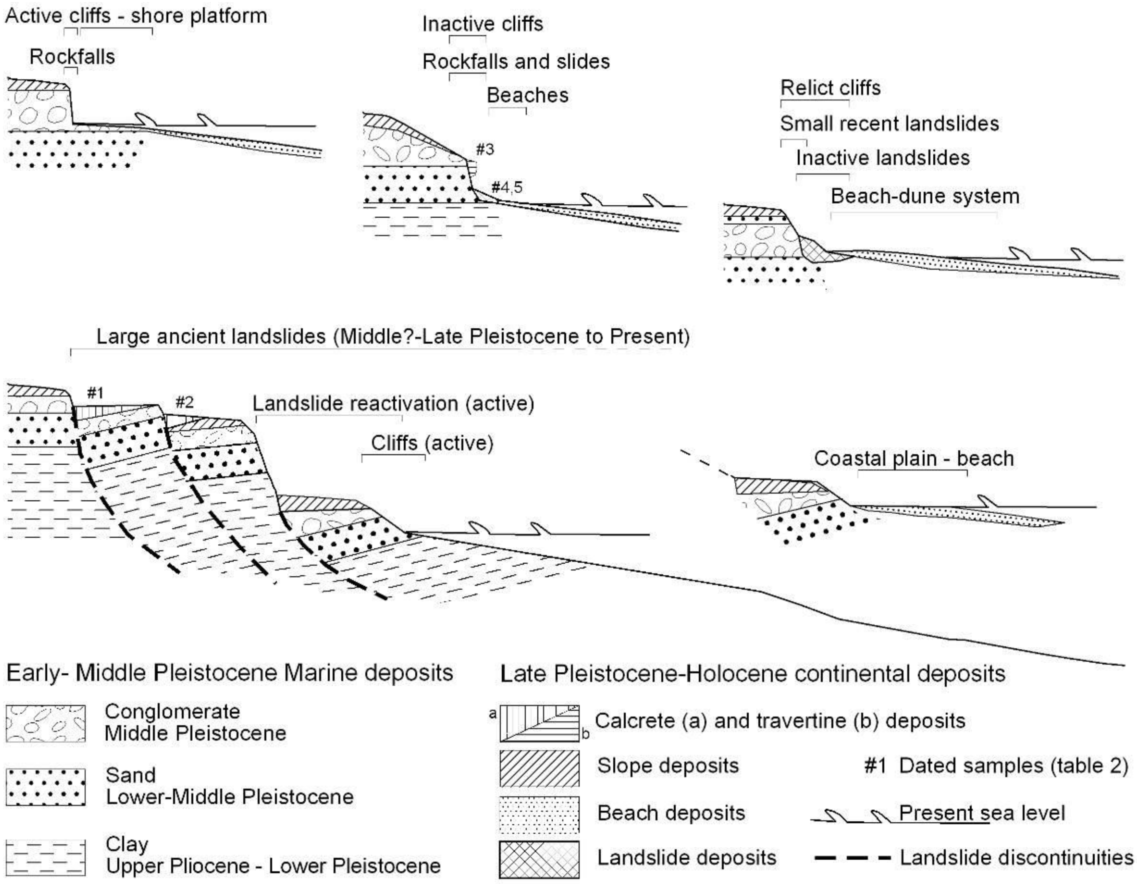

Fig. 14: Schemes of the Late Pleistocene – Holocene continental deposits along the coastal area and the active, inactive and relict-palaeocliffs and coastal slopes. These deposits lie above the Early-Middle Pleistocene clay-sand-sandstone-conglomerate marine to transitional regressive bedrock sequence.

6.2 Types of rock coast

A large variability of landforms has been documented, and eight different types of coast have been recognized that outline a very heterogeneous coastal system. As shown in the scheme of Fig. 15, the different types are the result of different combinations of (1) lithological features (cliffs on conglomerates, cliffs on sandstone, and cliffs on slope deposits) and (2) state of activity (active and inactive cliffs, and palaeocliffs). The coastal slopes fall within a distinct category. The areal and cartographic distribution of these types are summarized in Fig. 16 and Table 3.

6.2.1 Active cliffs

The heights of active cliffs range from 5 m to more than 25 m, and the morphological profiles vary from vertical to sub-vertical. Notches can be present at the cliff bases. They developed during the Holocene after the last sea-level rise and, due to the rapid evolution, eroded historical continental deposits of Middle Ages, XI-VIII centuries BC 1300s, 1800s (Punta Aderci). Active cliffs are affected by coastal processes and are the result of rapid cliff erosion cycles, including wave-cut processes with toe erosion and notch formation, cliff instability, mass movements, formation of talus and beach deposits, erosion of talus and beach deposits, and resumptions of toe erosion (Fig. 17; for a comparison, see also Colantoni et al., 2004; Dornbusch et al., 2008; Brooks and Spencer, 2010; Sunamura, 2015). Talus and beach deposits play, in this case, a contradictory role, protecting the cliffs from a constant wave's erosion and increasing the wave-induced abrasion process during storm events. This is strongly controlled by lithological variations along the cliff profiles and at the cliff toes (i.e. elevation of the bedrock c/sgc, interface) and local structural features, and produces a great variability in cliff morphology and different retreat rates (from 0.15 m/yr to ~1 m/yr). Therefore, five types with different geomorphological behaviours have been distinguished. Where a shore platform is present, these types can be grouped into cliffs with type-B shore platforms (Sunamura, 1992), which is unusual for soft rocks but is locally due to the occurrence of moderately cemented conglomerates, and into lithologically controlled morphostructures that range from moderately to rapidly retreating (Finkl, 2004). The large variability is related to the alongshore and vertical differences in lithology and structural setting.

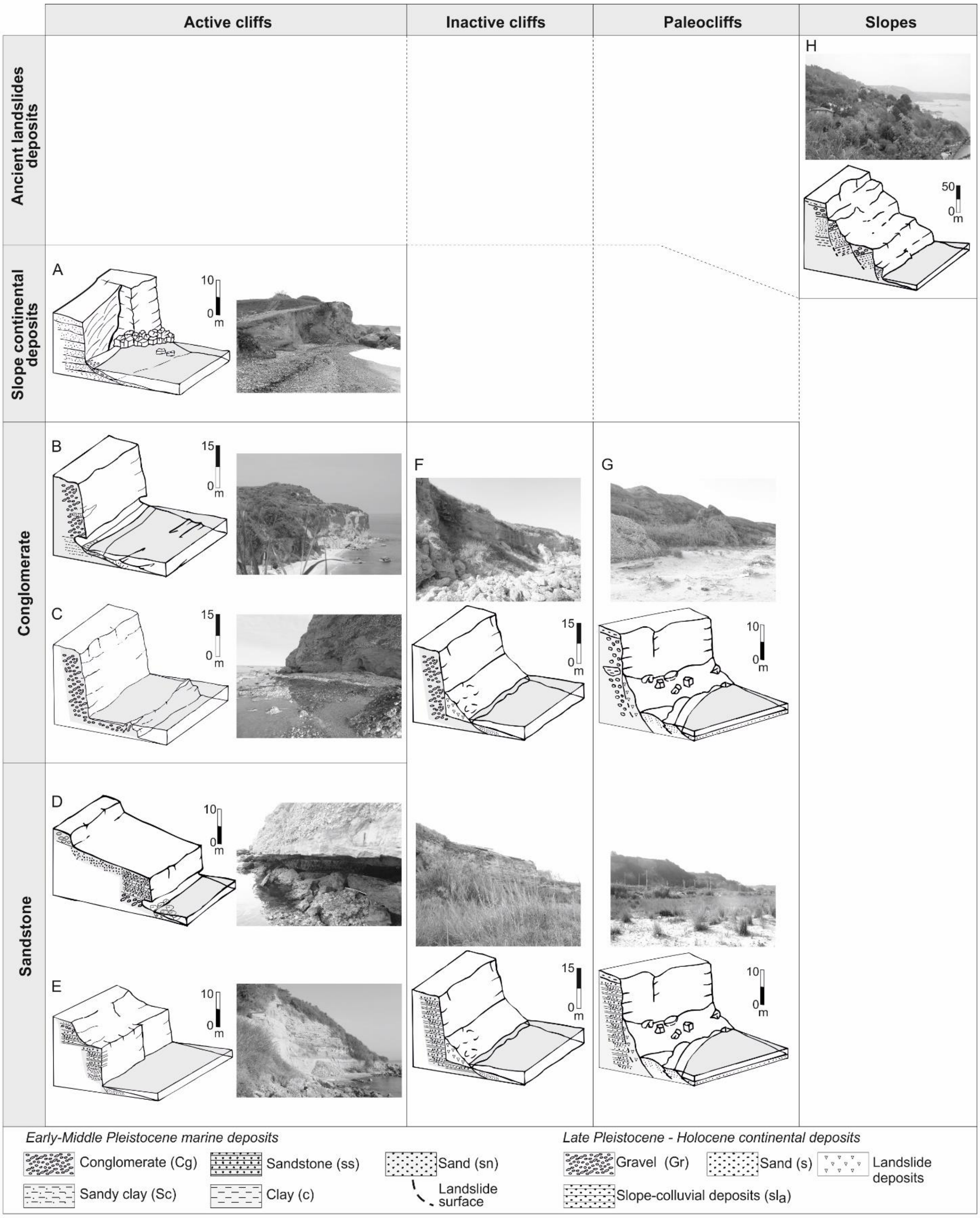

Fig. 15: Cliff types defined in the studied coastal area. **A**: active cliff on slope continental deposits; **B**: active cliff on conglomerate, with notch; **C**: active cliff on conglomerate, with horizontal shore platform; **D**: active cliff on sandstone, with notch; **E**: active cliff on sandstone; **F**: inactive cliff; **G**: palaeocliff; **H**: coastal slope.

Type	Length (m)	%
A - Active cliff on continental deposits	325	0,5
B - Active cliff on conglomerate with notch	245	0,4
C - Active cliff on conglomerate with shore platform	545	0,8
D - Active cliff on sandstone with notch	260	0,4
E - Active cliff on sandstone	1100	1,7
F - Inactive cliff on sandstone and conglomerate	9100	13,8
G -Palaeocliff on sandstone and conglomerate	10500	15,9
H - Coastal slope on clay-sand-sandstone-conglomerate	28150	42,8
Low coast	15600	23,7

Table 3 Distribution of cliff types and coastal slopes in the study area.

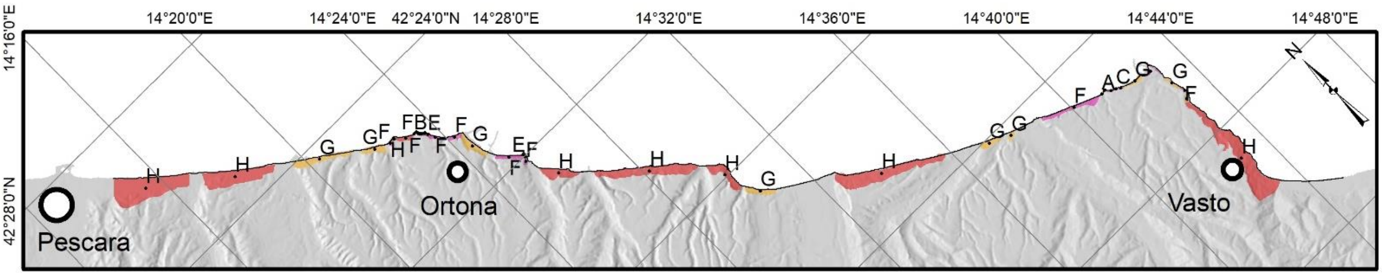

Fig. 16: Planimetric distribution of cliff types and coastal slopes in the studied coastal area. Lettering refers to Fig. 15 and Table 3.

	ACTIVE CLIFF - A	ACTIVE CLIFF - B	ACTIVE CLIFF - C	ACTIVE CLIFF - D	ACTIVE CLIFF - E	INACTIVE CLIFF - F	PALAEOCLIFF G	COASTAL SLOPE - H
H_c	5<H<10	>25 m	>25m	>25m	>25 m	15<H<25	15<H<50	>100m
L	Slope continental sandy deposits	Conglomerate	Conglomerate	Sandstone	Sandstone	Conglomerate Sandstone	Conglomerate Sandstone	Landslide deposits
L_f	Sand	Conglomerate Silty sands	Conglomerate	Sandstone Conglomerate	Sandstone	Slope-Rockfall deposits	Slope, landslide, beach, dune deposits	Landslide deposits
L_e	Sand	Conglomerate	Conglomerate	Sandstone	Sandstone	Conglomerate Sandstone	Conglomerate Sandstone	Sandstone Conglomerate
J	--	Joints enlarged by tensile stress	Joints enlarged by tensile stress	Joints enlarged by tensile stress	--	--	--	Joints control on landslide development
SP	--	--	Horizontal	Horizontal	--	--	--	--
N	--	On silty sand	(small on conglomerate)	On conglomerate	--	--	--	--
P	Marine erosion (inducing landsliding)	Marine erosion (inducing landsliding)	Marine erosion (inducing landsliding)	Marine erosion (inducing landsliding)	Marine erosion (inducing landsliding)	Gravitational processes	Gravitational processes	Gravitational processes, local marine processes
R	~0.5.-1.0 m/yr	~0.85 m/yr	~0.15 m/yr	~0.5 m/yr	~0.65 m/yr	--	--	--

Table 4 Lithological, tectonic and geomorphological features of the types of rock coasts defined in this study (see Fig. 15, 16, Table 3). H_c: cliff height; L: main lithology; Lf: lithotypes at the cliff foot and shore platform; Le: lithotypes at the cliff upper edge; J: jointing; SP: shore platform, according to Sunamura's classification (1992); N: notch; P: main geomorphological processes; R: retreat rate.

Active cliffs on slope continental deposits (A) are usually 5-10 m high (Fig. 16, Tables 3, 4). They are developed on very soft rocks, are bordered by small sand-gravel beaches or by a gently sloping sand-gravel seabed and show no notches at their bases. These cliffs are affected by intense wave erosion with connected small rockfalls comprising soft rock blocks (progressively removed by wave action in a ~15-year time span, with the rejuvenation of coastal erosive processes at the cliff, Fig. 12g,h,i). Cliff retreat ranges from moderate to high (with a rough estimation of 0.5-1.0 m/yr, as documented in the Punta Aderci area, Fig. 12g,h,i).

Active cliffs on conglomerate with notches (B) are >25 m high (Fig. 16, Tables 3,4). Their feet are often on soft sandy-clay lithotypes overlaid by medium-hard jointed conglomerate rock (bedrock c/scg interface below present sea level) and notches are deeply developed in the sandy-clay deposits (following the notch morphology recognized by Sunamura, 1992, and summarized by Trenhaile, 2015, and Antonioli et al., 2015). Cliff height, notch depth, rock strength and tensile stress (progressively enlarging the cliff-parallel tectonic joints) are the main factors controlling cliff evolution. The notches may be incised up to 7-10 m before a cliff becomes unstable, which induces large topple and fall failures (also according to Kogure et al., 2006; Trenhaile, 2015). The duration of the notch incision/cliff failure process has been documented to be approximately years or tens of years (Fig. 12d, e, f), resulting in retreat rates of up to >0.85 m/yr (Fig. 13).

Active cliffs on conglomerate with horizontal shore platforms (C) are up to >25 m high (Fig. 16, Tables 3, 4) and are developed in jointed moderately cemented conglomerate with sand-sandstone lenses (bedrock c/scg interface below present sea level). They are fronted by shore platforms cut on conglomerate (type-B shore platform, Sunamura, 1992), the outer margins of which are characterized by small rocks. Small notches can be occasionally present at the bases of cliffs and are mostly cut into weak sand-sandstone lenses. The marine erosion on the platform strongly prevails on the cliff dynamics, as confirmed by cliff retreat rates as low as ~0.15 m/yr (Fig. 13).

Active cliffs on sandstone with notches (D) are up to >25 m high (Fig. 16, Tables 3, 4) and are developed on moderately consolidated to cemented jointed sandstone (bedrock c/scg interface close to present sea level). The dimensions and shapes of the notches are variable according to the hardness of the sandstone layers (Trenhaile, 2015) and may be up to >3 m deep. Notch deepening induces rockfalls and topples. Cliff height, notch depth, rock strength and jointing control cliff evolution that is manifested by recession connected to episodic and localized landslides (Fig. 12a, b, c) and results in moderate retreat rates of <0.5 m/yr (Fig. 13).

Active cliffs on sandstone without notches (E) are <25 m high (Fig. 16, Tables 3, 4) and are developed on poorly consolidated horizontal sandstone layers (bedrock c/scg interface close to present sea level). They are affected by intense wave erosion, which induces frequent rockfalls rather than notch incision due to the occurrence of soft sandstones. Poorly consolidated rockfall deposits are rapidly weathered and removed by wave action, rejuvenating the process and inducing overall retreat rates up to 0.85-0.65 m/yr (Fig. 13).

6.2.2 Inactive cliffs

Inactive cliffs (F) are characterized by vertical scarps ranging from 15 m to more than 25 m high with concave convex slopes in the lower part (Fig. 16, Tables 3, 4). They are on conglomerate or sandstone with clay layers and lenses. The bases of the cliffs are covered by slope and rockfall deposits, which restrain the effects of present-day coastal erosion (Sunamura, 1992). In some cases, cliff inactivity is related to anthropic protective barriers armouring the cliff bases (see also Griggs and Trenhaile, 1994). Gravity-induced slope processes, which primarily induce translational sliding and occasional small rockfalls, and the incision of small dry valleys, are the only active processes, the distributions of which are related to lithological features and strengths and triggered by meteorological events. The cliffs are covered by landslides (as old as up to 10 ky), slope and colluvial deposits (dated back to 42.8 ±1.5 ky at Punta Penna) and are occasionally encrusted by travertines (U/Th dating 9.0±7.0 ky at Punta Ferruccio), suggesting that these cliffs were first formed during the early Late Pleistocene (possibly during the Tyrrhenian sea-level highstand), after which they experienced slow evolution and retreat due to subaerial processes (e.g. weathering and landslides, Fig. 17). Cliffs on sandstone are evolving more rapidly, with small landslides and rockfalls affecting the upper cliff edges.

6.2.3 Palaeocliffs

Palaeocliffs (G) are 15 m to > 50 m high, mostly with concave convex profiles, and they comprise sandstone or conglomerate with clay layers and lenses (Fig. 16, Tables 3, 4). The cliff bases are covered by densely vegetated landslide-slope deposits. These deposits are covered by beach-dune deposits up to several tens or some hundreds of metres wide. Palaeocliffs are the result of the change in coastal processes from erosive to depositional, with the formation of beach-dune systems and coastal plains at the bases of the cliffs (Miccadei et al., 2011b). The latter prevent wave erosion under any condition at the cliff base, in their present geomorphological setting.

Most likely paleocliffs formed during the Holocene or early Late Pleistocene, similarly to inactive cliffs. The state of paleocliff was established at least during the Middle Holocene, since beaches were developed at their bases in historical times (i.e. 2,500 years ago Mastronuzzi and Sansò, 2002) and in the Late Middle Age (Miccadei et al., 2011b). Locally, as the case of the northern Punta Penna area, cliffs activity have been prevented by the formation of a beach and a dune system in very recent times (Fig. 17), caused by variations of the alongshore drift due to harbours built in the 1950s (Miccadei et al., 2011b). Even though the palaeocliffs are mostly stabilized by a cover of recent deposits, slope processes can be occasionally activated due to minor rockfalls and slides that affect the cliffs' edges and are triggered by meteorological events (Fig. 17).

6.2.4 Coastal slopes

Coastal slopes (H) are several km-long slopes up to more than 100 m high (Fig. 16, Tables 3, 4) that have step-like or slope-over-wall morphology. They are developed on clay-sand-sandstone-conglomerate bedrock (bedrock c/scg interface well above present sea level) covered by large roto-translational landslides made of large blocks of sandstone and conglomerate that are tilted counterslope, with large landslide terraces. The bases of the slopes are subject to intense coastal erosion, forming cliffs that are almost vertical, 5-10 m high, or they are fronted by a coastal plain.

The main landslides are mostly inactive and are consistent with similar morphologies documented along the Adriatic coast (Crescenti et al., 1986; Aringoli et al., 2002, 2013; Fiorillo, 2003; Colantoni et al. 2004; Iadanza et al., 2009; Calamita et al., 2012 and references therein). New data on Quaternary eluvium-colluvium and calcretes overlaying landslide deposits and filling landslide counterslopes and ponds provide a chronological constraint (31 ± 4 ky and 52 ± 8 ky) and date the oldest gravitational processes to at least the early Late Pleistocene. The large landslides were demonstrated to be possibly induced as single roto-translational mechanisms by the combined roles of regional uplift, local jointing and glacioeustasy-induced sea-level fluctuations (Lambeck and Purcell, 2005; Lambeck et al., 2011; Antonioli, 2012; Della Seta et al., 2013) and local effects of coastal erosion (Fig. 17).

Inherited Pleistocene landsliding affects the recent geomorphological dynamics. Historical and recent landslides widely involve the lower part of coastal slope. Occasionally, the upper part of the slopes is involved, with the sliding surfaces displacing Pleistocene landslide deposits and also reactivating older surfaces. Reactivations are mostly induced by a combination of meteorological conditions, such as heavy rainfall, rapid snowmelt and marine erosion at the slope base (Buccolini et al., 1994; Calamita et al., 2012; Fiorillo, 2003). Small cliffs are occasionally formed at the base of the slopes, inducing a slope-over-wall profile, and recede due to coastal erosion and small landslides.

6.3 Distribution of landforms, geomorphological processes and evolution of the rock coast

Finally, this study defined the distribution of landforms, geomorphological processes and cliff retreat responsible for the present coastal setting and evolution, thus contributing to an outline of the general distribution of hazards on these rock coasts (Fig. 14, Fig. 16). In the overall coastal segment, cliffs and slopes are dominated by gravitational (79%), coastal (3%), and spatially and temporally overlapping coastal and gravitational (18%) landforms.

Two types of overall recession mechanism and evolution affect the coastal system. The cliffs have followed the recession model suggested by Sunamura (1983, 1992, 2015): i) coastal erosion induced by wave action has defined retreating cliffs, which is favoured by low lithological strength; ii) erosion at the cliff toes has induced notch incisions and different types of slope instabilities (from rockfalls to slides), which are also controlled by bedrock lithology strength and jointing (the largest landslides affect cliffs on sandstone and conglomerates where deep notches are incised); iii) talus debris and landslide deposits have been deposited at the bases of the cliffs, which are then protected from further erosion; iv) where these deposits are removed by coastal processes, the cycle is rejuvenated, and cliff erosion proceeds, defining active cliffs (high to very high expected hazards); v) where the coastal processes are not able to remove the talus/landslide deposits, the cliffs become inactive, and further erosional processes and retreat are connected to subaerial processes (weathering-landsliding) induced by meteorological events; vi) where a large coastal plain (including beach and dune systems) is formed fronting a cliff, it becomes a palaeocliff. Historical and repeated field observations have confirmed the episodic and localized nature of cliff recession, which occurs over decadal timescales as a discrete step-like process, but there are also variable overall rates on the order of 10^{-2} to 10^{-1}m/y (i.e. from 0.15 to ~1 m/yr) due to the along-shore variability of rocks exposed to wave erosion, which confirm the observed rates on this cliff types (Davies et al., 1972; Griggs and Savoy, 1985; Sunamura, 1994; Colantoni et al., 2004; Quinn et al., 2009).

The coastal slopes are the result of a long-lasting evolution beginning in the (end of) Middle-Late Pleistocene with the formation of large rotational and translational landslides. The bases of the coastal slopes are in many cases rejuvenated by coastal erosion, with the cutting of small cliffs, the formation of new landslides and the local reactivation of ancient landslides (occasionally large parts of the ancient landslides are reactivated). When beach systems and coastal plains are developed fronting the coastal slopes, this rejuvenation is inhibited.

Because the coastal areas host small to large urban settlements, infrastructure (railways, roads, and harbours), tourist facilities, and sites of cultural and traditional importance, the active processes affecting the coastal cliffs and slopes expose the population to geomorphological hazards connected to subaerial and coastal processes due to local-short term (meteorological events, coastal wave erosion, and seismicity) and regional-long term (tectonic uplift and sea-level fluctuation) changes. Active cliffs are dominated by coastal processes (inducing cliff retreat) and are affected by expected hazard conditions ranging from high to very high, as summarized in Fig. 17. The highest expected hazard are on active cliffs with notch (due to large, sudden rockfalls and topple landslides where deep notches are incised) and on active cliffs on sandstones (due to the lower strength, frequent landsliding and a fast recession rate). The occurrence of shore platform may partly prevent erosional processes and the highest expected hazard.

Inactive cliffs are mainly shaped by gravitational processes induced by meteorological events on the cliff scarp and by coastal marine deposition along the beaches covering the cliffs; the expected hazard conditions range from moderate to high (Fig. 17). The palaeocliffs, which are fronted by large coastal plains, are dominated by gravitational processes and represent moderate to high expected hazards due to local landsliding on the cliff scarp (Fig. 17).

The general hazard conditions of coastal slopes are expected to be highly variable (Fig. 17) and worthy of detailed analysis because they are connected to two different types (in terms of spatial and temporal distribution) of gravity-induced instabilities: 1) large, ancient and long-term instabilities affecting the main coastal slopes at a several-km scale, which were connected to regional processes (uplift-sea level fluctuation) and might be reactivated by particular geomorphological and meteorological conditions; and 2) small, local and short-term instabilities that are related to meteorological events and coastal wave-cut processes at the toes of the coastal slopes.

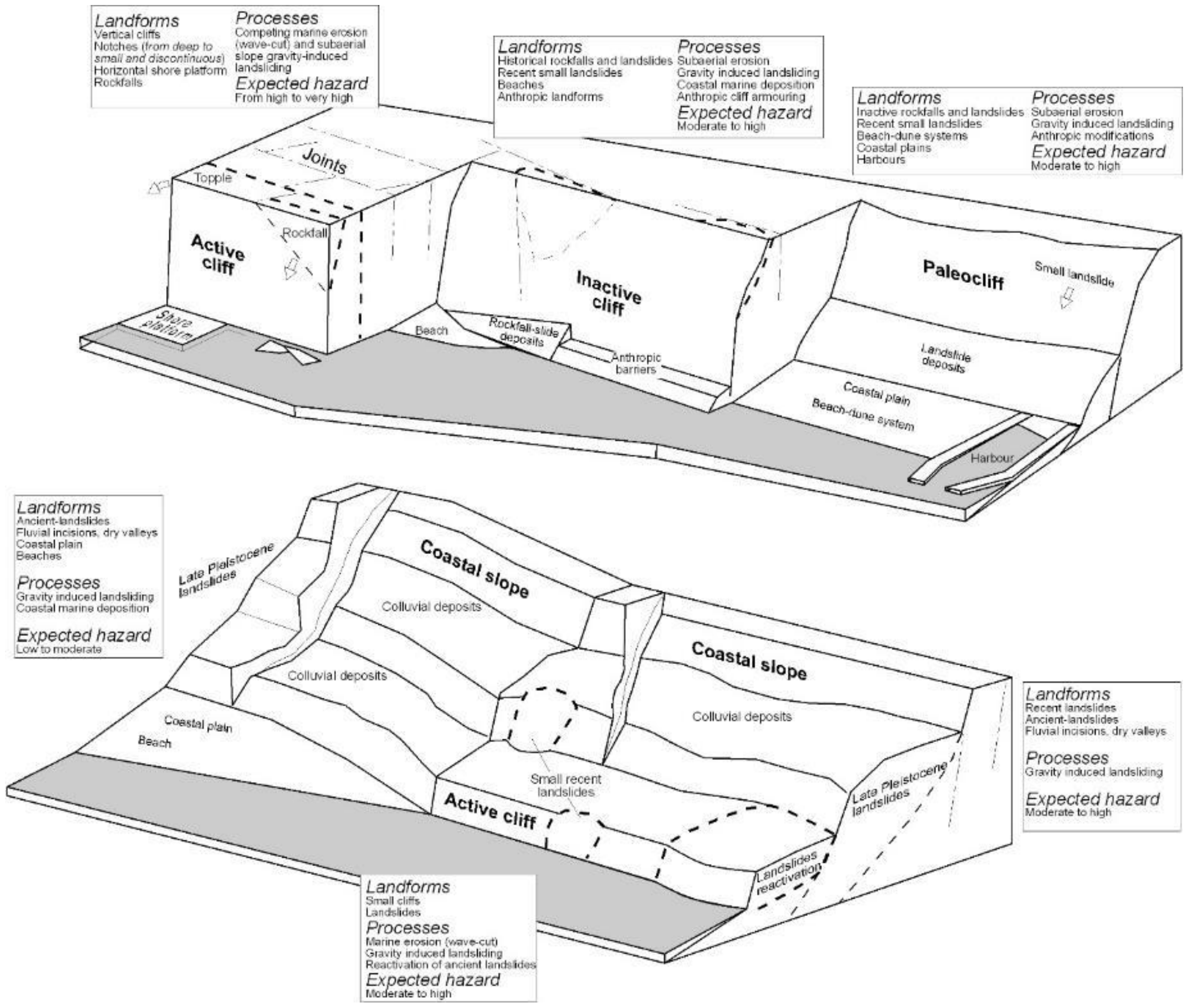

Fig. 17: Distribution of landforms and processes on the rock coast system on soft clastic rocks of the Central Adriatic Italian area.

7. Conclusions

This study focused on the rock coast of the mid-Western Adriatic Sea, developed on soft clastic marine rocks, which is a poorly represented rock coast type in the Mediterranean area. The overall coast, with a focus on eight areas of cliffs and coastal slopes, was investigated by combining detailed geological-geomorphological surveys of the emerged and submerged areas, aerial photo time-series and DEM analysis, paleontological stratigraphical attributions and sediment datings.

The litho-stratigraphical features and chronological constraints of the Late Pleistocene – Holocene continental deposits allowed the long-term evolution of the coastal system and its timing to be outlined in the framework of sea-level changes. Large roto-translational landslides characterize the overall shape of the coastal slopes. They occurred at least in the early Late Pleistocene (post-Tyrrhenian sea-level fall to lowstand), or possibly in the late Middle Pleistocene, and are partially reactivated in recent times by the present morphoclimatic conditions. Palaeocliffs and inactive cliffs are covered by Late Pleistocene and Holocene landslides deposits, which date the cliff formation to the early Late Pleistocene (Tyrrhenian sea-level highstand). In other cases, beaches, dunes and travertine deposits date their formation to the early Holocene. Some palaeo- and inactive cliffs have a very recent decadal history related to the realization of the Ortona and Vasto harbours in the 1950s. Finally, active cliffs are documented to have a recent centennial, decadal and present evolution.

Lithological bedrock features, structural settings and jointing, continental cover deposits, state of activity, and competing coastal and gravity-induced slope processes define eight different types of coastal cliffs/slopes. Their distribution is mainly connected to the structural elevation of the bedrock sequence, with clay/sandstone-conglomerate interface well above present sea level for coastal slopes, close to present sea level for cliffs on sandstone, and below present sea level for cliffs on conglomerate. In addition, it was observed that, besides the elevation of the clay/sandstone-conglomerate interface, the local lithological variability of the bedrock and continental deposits are largely responsible for the distribution, morphology and geomorphological evolution of the coastal types. Active cliffs are subjected to a rapid recession, although episodic and localized over a short time span. Highly variable retreat rates were assessed, from 0.15 m/yr (type A), where shore platforms are present, to ~0.5 (type D) and 0.65 (type E), due to the variable strength of sandstone, and up to ~1 m/yr due to very soft materials (type A) and the development of deep notches inducing cliff collapsing (type B). The erosion cycle consists of wave-cut processes triggering mass movements, erosion of talus and beach deposits and consequent reactivation of toe erosion. On inactive and palaeo-cliffs the resumption of toe erosion is inhibited by the coastal deposits and landslides. The coastal slopes are the result of a long-lasting evolution beginning in the Middle(?)-Late Pleistocene with the formation of large rotational and translational landslides. Their bases are continuously rejuvenated by erosive processes, producing small cliffs, new landslides and local reactivations of ancient landslides.

Finally, the study outlines the importance of combining geological and geomorphological approaches, and integrated detailed analysis of field and laboratory data to characterize morphology, bedrock litho-stratigraphical features, structural features and jointing, superficial continental deposits, and landform distribution. This allows the investigation of the active geomorphological processes and their relationship to the Late Quaternary history, which actually (i) improve the comprehension of the different evolutionary modes, (ii) provides a basis for planning and undertaking studies on geomorphological hazards and for the assessment of effective coastal management, (iii) is meaningful for analyses of coastal areas with similar morphotectonic settings inside and outside the Mediterranean area, and (iv) provides useful data to define coastal evolution in scenarios of future sea-level rise.

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