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FACIES ANALYSIS OF FOUR SUPERIMPOSED TRANSGRESSIVE-REGRESSIVE SEQUENCES FORMED DURING THE TWO LAST INTERGLACIAL-GLACIAL CYCLES (CENTRAL TUSCANY, ITALY)

Abstract - G. Sarti, D. Bertoni, M. Capitani, A. Ciampalini, L. Ciulli, A. C. Feroni, S. Andreucci, G. Zanchetta, I. Zembo, *Facies analysis of four superimposed Transgressive-Regressive sequences formed during the two last interglacial-glacial cycles (central Tuscany, Italy).*

In this paper we present the results of a detailed facies analysis carried out on a set of 115 late Quaternary-Holocene stratigraphic sections from the northern Tyrrhenian coast (central Tuscany, Italy). The stratigraphic leitmotif is the cyclic alternation of coastal-marine and continental deposits grouped in four transgressive/regressive sequences (T-R1-4). The marine-coastal deposits constitute the transgressive base of each T-R sequence; to the top they are replaced by continental deposits that characterize the top of each T-R sequence. Three OSL dates provide the chronological constraints of the T-Rs. Marine deposits related to the last interglacial period (Marine Isotope Stage 5) constitute T-R1, which represents the base of T-R2. T-R2 consists of coastal dune deposits related to the last MIS 5 phase (MIS 5a). T-R3 consists of coastal dunes and marine deposits related to MIS 3. T-R4 (Holocene age) is occasionally preserved within the transgressive tract. The present-day altitude of MIS 5e (T-R1) sea-level markers suggests the occurrence of uplifting tectonic movements within the study area. Conversely, the evidence of the stratigraphic overlap of MIS 3 coastal dune deposits above the MIS 5 beachface sediments implies the activation of subsidence processes that are necessary to compensate the post-MIS 5 eustatic fall rate. As a consequence, the uplift processes responsible of the present-day outcrop elevations of MIS 5 sea-level markers occurred after MIS 3, pointing out a far more complex local tectonic history. This approach, based on facies analysis of the whole sedimentary succession, emphasizes the need of a consistent number of dates in order to better constrain the framework of the spatial-temporal evolution. In the study area, this would enable to improve and/or validate the temporal evolution of the local tectonics. As the context seems to be more complex than the one derived from the sole use of MIS 5e sea-level markers, we encourage the application of this methodological approach to different study areas.

Key words - last interglacial-glacial cycle, facies analysis, aeolian-coastal dune, T-R sequences, sea-level change, tectonic movement, sea-level marker, Tyrrhenian coast, Italy

Riassunto - G. Sarti, D. Bertoni, M. Capitani, A. Ciampalini, L. Ciulli, A. C. Feroni, S. Andreucci, G. Zanchetta, I. Zembo, *Analisi di facies di quattro sequenze trasgressivo-regressive (T-R) sovrapposte, formate durante gli ultimi due cicli interglaciale-glaciale (Toscana centrale, Italia).*

In questo studio sono presentati i risultati di un'analisi di facies dettagliata realizzata su un totale di 115 sezioni stratigrafiche datate tardo Quaternario-Olocene della costa del Mar Tirreno settentrionale (Toscana centrale, Italia). Il leitmotif stratigrafico è rappresentato dall'alternanza ciclica di depositi marino-costieri e continentali raggruppati in quattro sequenze trasgressivo-regressive (T-R1-4). I depositi marino-costieri costituiscono la base trasgressiva-discordante di ciascuna sequenza T-R e sono invariabilmente sostituiti verso l'alto da depositi continentali che caratterizzano, invece, la parte superiore di ogni sequenza T-R. Tre datazioni OSL forniscono i vincoli temporali delle sequenze T-R. I depositi marini relativi all'ultimo periodo interglaciale (Marine Isotope Stage 5, MIS 5) costituiscono la sequenza T-R1, che quindi rappresenta la base della sequenza T-R2. La sequenza T-R2 è costituita da depositi di dune costiere relativi all'ultima fase del MIS 5 (MIS 5a). La sequenza T-R3 consiste di depositi marini e di dune costiere relativi al MIS 3. La sequenza T-R4 (Olocene) è occasionalmente conservata all'interno del sistema trasgressivo. L'attuale quota degli indicatori del livello del mare del MIS 5e (T-R1) è indicativa di un sollevamento tettonico all'interno dell'area di studio. Tuttavia, l'evidenza dell'*overlap* stratigrafico di depositi di dune costiere del MIS 3 al di sopra dei sedimenti di spiaggia del MIS 5 implica necessariamente l'attivazione di processi di subsidenza indispensabili per compensare l'entità dell'abbassamento eustatico post-MIS 5. Ne consegue che i processi di *uplift* responsabili delle attuali quote di affioramento degli indicatori di livello del mare del MIS 5 sono avvenuti posteriormente al MIS 3 designando una storia di tettonica locale ben più complessa. L'applicazione di quest'approccio, basato sull'analisi di facies dell'intera successione sedimentaria, enfatizza la necessità di un congruo numero di datazioni che ne costringano meglio il *framework* di evoluzione spazio-temporale. Ciò permetterà di migliorare e/o validare nell'area di studio il quadro dell'evoluzione nel tempo della tettonica locale. Poiché tale quadro risulta essere molto più articolato e complesso rispetto a quello che deriva dall'esclusivo utilizzo degli indicatori di livello del mare del MIS 5e è auspicabile l'estensione ad altre aree di studio di quest'approccio metodologico.

Parole chiave - ultimo ciclo interglaciale-glaciale, analisi di facies, dune costiere ed eoliche, sequenze T-R, variazioni del livello del mare, movimenti tettonici, indicatori del livello del mare, costa tirrenica, Italia

1. Introduction

The study of past sea levels adds significantly to our understanding of the nature of sea-level variability

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and provides a firmer foundation on which to base projections of future sea-level changes and plan mitigation strategies (Woodroffe & Murray-Wallace, 2012). Sea-level changes along the world's coasts are the sum of eustatic, glacio-hydro-isostatic, and tectonic signals (Lambeck & Chappell, 2001; Potter & Lambeck, 2004; Antonioli *et al.*, 2009; Anzidei *et al.*, 2014, Jara-Muñoz & Melnick, 2015). The glacio-hydro-isostatic part exhibits a well-defined pattern and is readily predictable, whereas the tectonic component has a less regular and more localized pattern that is generally of shorter wave length, and is also less predictable. Together, these components result in a complex spatial and temporal pattern of relative sea-level change around coastlines, the observations of which provide information regarding Earth rheology, rates of vertical tectonic movements, and the global ice-ocean balance during glacial-interglacial cycles (Lambeck *et al.*, 2004).

For the Italian peninsula, the glacio-hydro-isostatic component of post-glacial sea-level rise has been modelled and compared with field data at several coastal sites (Antonioli *et al.*, 2004; Lambeck *et al.*, 2004; Antonioli *et al.*, 2007; Spada & Stocchi, 2007; Antonioli *et al.*, 2009; Lambeck *et al.*, 2010). Over the last few years, several coastal displacement rates have been inferred from the present elevation of sea-level markers covering the entire Italian coast (Ferranti *et al.*, 2006; Antonioli *et al.*, 2009; Lambeck *et al.*, 2011; Antonioli *et al.*, 2017). However, the markers used for the displacement-rate models are irregularly distributed along Italian coasts. In particular, the sea-level indicators used to calculate vertical tectonic motions along the Tuscany coast are strictly concentrated along the northern and southern part; therefore, detailed studies about late Quaternary sea-level markers along the coast between Leghorn and Piombino are lacking.

To infer vertical movements, most studies (e.g., Bard *et al.*, 2002; Lambeck *et al.*, 2004; Ferranti *et al.*, 2006; Antonioli *et al.*, 2009; Lambeck *et al.*, 2011; Rovere *et al.*, 2016) utilize MIS 5 sea-level markers because they are relatively common. Therefore, the inferred vertical movements (uplift or subsidence) are the net sum of all the movements that have occurred during the last 125 kyr. However, between the two last interglacials (MIS 5 and MIS l), other easy recognizable, low rank transgressive events (i.e., MIS 5c and a, MIS 3, MIS 1) are documented in stratigraphic successions above the MIS 5e both in outcrops and the subsurface (Sarti *et al.*, 2005; Aguzzi *et al.*, 2007; Amorosi *et al.*, 2008; Andreucci *et al.*, 2010; Carboni *et al.*, 2010; Milli *et al.*, 2013; Sarti *et al.*, 2015). Due to the lack of accurate sea-level markers, in just few cases these data are utilized to infer or refine tectonic movements (e.g., Milli, 1997). Based on the analysis of 115 stratigraphic sections that outcrop along the coast between Leghorn and Piombino (central Tuscany, Italy), this research shows how the elaboration of detailed space-time facies correlation sketches can strongly improve the tectonic framework histories as deduced through a dataset based only on sea-level indicators. Additional dates are crucial also to further constrain the tectonic movements.

2. Geological setting and background

The coast between Leghorn and Piombino (central Tuscany, Italy) falls in the transition zone between the northern Tyrrhenian Sea and the Apennine chain (Fig. 1). Since the Tortonian, extensional tectonic processes have occurred at the back of the eastward-migrating Apennine chain as a consequence of the progressive opening of the Tyrrhenian Sea (Patacca *et al.*, 1990; Carmignani *et al.*, 1994). Several extensional sedimentary basins, mainly linked to major normal NNW–SSE faults, formed and were filled by Upper Miocene-Quaternary continental and marine deposits (Cantini *et al.*, 2001). The normal and transtensive faults also worked to delimit subsiding areas and structural highs (Mariani & Prato, 1992; Lazzarotto, 1993; Ciampalini *et al.*, 2011). The upper part of the Neogene succession is characterized by a cyclical alternation of Upper Pleistocene-Holocene shallow-marine and continental deposits (few tens of meters thick). This stratigraphic framework is similar to several other Italian and Mediterranean coastal areas (El-Asmar, 1994; Federici & Mazzanti, 1995; Zazo *et al.*, 2003; Nielsen *et al.*, 2004; Galili *et al.*, 2007; Pappalardo *et al.*, 2013; Pascucci *et al.*, 2014). The late Quaternary stratigraphy of this sector drew research interest since the mid-19th century. Due to the excellent preservation of a few outcrops, several studies were carried out over the last three decades, mainly focusing on the Upper Pleistocene successions of the Leghorn and Piombino surroundings (e.g., Barsotti *et al.*, 1974; Cortemiglia *et al.*, 1983; Federici & Mazzanti, 1995; Sarti *et al.*, 2005; Borretto *et al.*, 2017). Two coastal-marine units (known as *panchina*) separated by continental deposits were detected (Dall'Antonia *et al.*, 2004; Ciampalini *et al.*, 2006; Zanchetta *et al.*, 2006; Bossio *et al.*, 2008) around the Leghorn terrace (Fig. 1). The lower unit consists of a few meters thick of shallow marine litharenitic sediments, which locally yields the "*Senegalian fauna*" of Gignoux (1913); it is related to the last interglacial marine highstand of MIS 5e (Barsotti *et al.*, 1974; Mauz, 1999; Zanchetta *et al.*, 2004). The upper unit is made of a well-stratified aeolian litharenitic layer and is correlated to MIS 3 (Zanchetta *et al.*, 2004; Ciampalini *et al.*, 2006). Southwards, the late Quaternary successions are very similar (Blanc, 1953; Ottmann, 1954; Cortemiglia *et al.*, 1983). Similar to what is observed

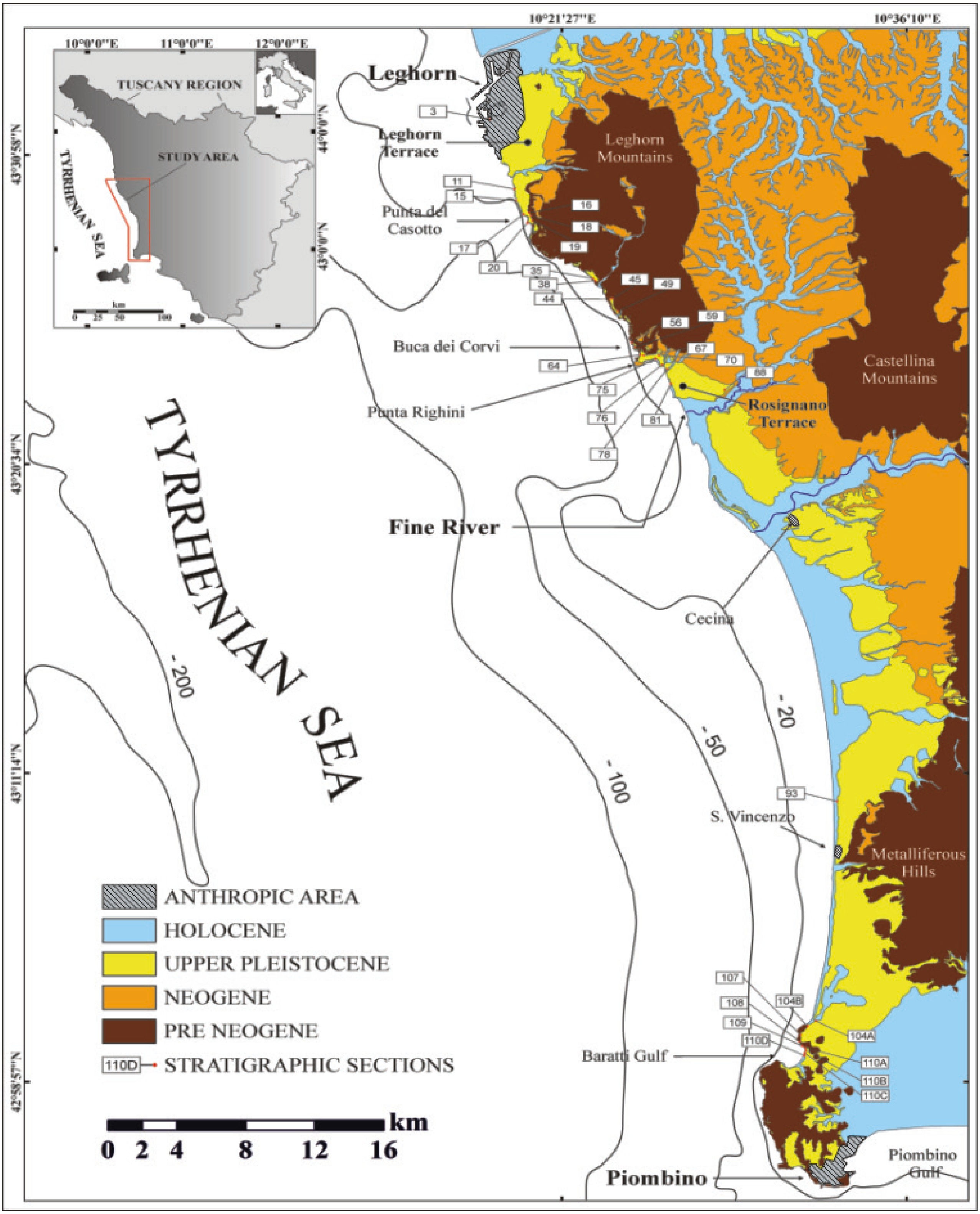

Fig. 1 - Location map of the study area and schematic geological setting. Numbers indicate the location of the most complete stratigraphic logs measured. See also Table 1 for their geographic coordinates and elevation above sea level.

around the Leghorn terrace, the sequences consist of the repeated stacking of transgressive litharenitic layers separated by reddish continental deposits, which in turn are capped by unconformity surfaces. Specifically, the Buca dei Corvi succession (Fig. 1) has a subaerial unconformity with a marine thin shell-bed that was deposited in a foreshore depositional environment. This layer yielded the "*Senegalian fauna*" and is correlated to the marine highstand that occurred during MIS 5e (Hearty & Dai Pra, 1987; Mauz, 1999). The two overlying litharenitic layers were deposited in a coastal-aeolian setting and related to MIS 5c and the Holocene, respectively (Hearty & Dai Pra, 1987; Mauz, 1999). Two new dates (Boretto *et al.*, 2017) constrain the continental low stand deposits outcropping below the Holocene succession to the last Glacial phase, according to the presence of a non-marine oligotypical mollusc assemblage characteristic of cold and dry climate conditions.

Unlike the Leghorn terrace and Buca dei Corvi successions, four transgressive episodes have been identified along the Baratti cliff section. Each episode is represented by an upper shoreface/foreshore deposit (Sarti *et al.*, 2005). Similar to what is observed to the north, the transgressive layers are sandwiched between reddish silty and sandy weathered colluvial deposits. The occurrence of the "*Senegalian fauna*" from the marine layers along the Baratti cliff section has never been reported. Based on some dates recorded along the Baratti cliff section, the oldest three marine layers have been correlated to MIS 5c, MIS 5a and MIS 3 respectively, while the uppermost age was between MIS 2 and MIS 1 (Hearty & Dai Pra, 1987; Mauz, 1999).

3. Materials and methods

3.1. Geological mapping and facies analysis

This study was based on detailed facies analysis along with geological mapping carried out within a regional mapping project sponsored by the Tuscany Region (C.A.R.G.). The field survey was carried out using 1:10000 topographic maps. As a whole, 115 sites were examined within the study area. The geographic coordinates of the studied outcrops are shown in Tab. 1. The detailed stratigraphic analyses, performed in all the sites, were based on lithological-sedimentological observations, which took into account sediment colour, grain size, texture, fossil contents, degree of alteration, petrographic characteristics, sedimentary structures, physical characters of surfaces, and faunal content. Due to the widespread presence of unconformity surfaces, transgressive-regressive sequences *sensu* Embry (1993, 1995) were employed to reconstruct the vertically stacked patterns of the analysed successions.

3.2. OSL datings

Three OSL dates (Tab. 2) were performed at the Nordic Laboratory for Luminescence Dating, Risø DTU (Denmark) to refine the chronological framework. The analysed samples (1 kg each) were collected from three different stratigraphic levels of aeolian sandstones (sites 38, 88, 93; Fig. 1). Sampling was carried out in daylight, packaged with black opaque plastic and promptly sealed. In laboratory under red light, the core of each sample was chemically treated with acids (HCl and H_2O_2) to obtain siliciclastic grains. The grains were successively sieved and separated by density using a heavy liquid solution (2.68 gm l^{-1}). To separate and remove feldspar impurities from quartz grains, the low density fraction was etched wi th hydrofluoric acid (HF) for 40 minutes. Checks by IR-stimulated luminescence analyses were conducted to verify the absence of residual feldspar contamination.

4. Facies description

Four main sedimentary facies have been identified across the study area: they were utilized to infer stratigraphic correlations. The facies descriptions, which include sedimentological, paleontological features and depositional environmental interpretation, are summarized below as follows:

4.1. BM Facies: coarse-grained Beach Marine deposits

This facies invariably marks the base of the succession and consists of well-rounded and sorted pebble to cobble clast-supported conglomerate, resting on a pre-Quaternary substratum. The base of BM facies, just above the substratum, is characterized by the presence of scattered clasts up to 20 cm in size frequently holed by *lithofaga* bands (Fig. 2h). The clast composition reflects the local lithology of the substratum. Coarse sands, sometimes bearing broken remains of marine molluscs, constitute the matrix. This facies, 1-2 m thick, shows a fining-upward trend (Fig. 2g). Sedimentary structures such as imbrication and plane bedding have been observed. Locally, faintly low-angle planar-cross stratification is present. This facies is interpreted as a marine transgressive event that accumulated a pebble foreshore to upper shoreface deposit.

4.2. SM Facies: sandy Shallow Marine deposits

This facies, which is 1-2 m thick, shows a transitional relationship with the underlying marine conglomerate. It consists of a coarse-grained, well-cemented litharenite showing low-angle plane bedding (Fig. 2e) up to trough cross-bedding (Fig. 2f). Small scattered pebbles are ob-

Table 1 - Geographic coordinates and elevations of the studied outcrops. The sections shown in Fig. 1 and Fig. 5 are marked in bold.

Site no.	Locality name	East (Longitude)	North (Latitude)	Section base elevation (m a.s.l.)
1	Pian di Rota	608,306	4,825,712	15
2	Terrazza Mascagni	604,815	4,821,080	0
3	**Accademia Navale**	**605,923**	**4,819,436**	**0**
4	Ardenza	606,472	4,818,469	0
5	Monte Tignoso	607,429	4,818,965	10
6	Casa Centi	607,573	4,818,695	14
7	Rio Le Brescie	608,724	4,818,024	17
8	Villa Pascoli	607,457	4,818,163	16
9	Villa Serena RSA	607,371	4,818,002	25
10	Banditella	606,857	4,817,801	8
11	**Viale di Antignano**	**606,686**	**4,817,653**	**5**
12	Via Caduti	606,986	4,817,291	14
13	Le Pianacce	607,508	4,817,287	16
14	Stazione Antignano	607,497	4,816,706	22
15	**Spiaggia pendola**	**607,005**	**4,816,500**	**5**
16	**Villa Bellavista**	**607,513**	**4,816,365**	**25**
17	**Scoglio della Nave**	**607,280**	**4,815,991**	**12**
18	**Galleria Variante**	**607,534**	**4,816,234**	**18**
19	**Case Firenze**	**607,599**	**4,815,992**	**17**
20	**Punta Casotto**	**607,483**	**4,815,601**	**12**
21	Maroccone	607,694	4,814,972	10
22	Torre del Boccale	607,611	4,814,708	14
23	Cala del Leone	609,531	4,813,239	15
24	Fosso Madonnina	610,909	4,812,606	25
25	Quercianella	611,010	4,812,395	21
26	S.S. n°1 Aurelia	611,057	4,812,410	25
27	Fosso Stazione	611,135	4,812,414	30
28	Quercianella Stz.	611,087	4,812,313	20
29	Il Convento	611,182	4,812,220	25
30	Quercianella	611,073	4,812,099	13
31	Casa Lami	611,253	4,812,136	26
32	Casa Lami	611,131	4,812,017	14
33	Sentiero del bosco	611,327	4,812,059	26
34	Sentiero del bosco	611,405	4,812,037	35
35	**La Chioma**	**611,371**	**4,811,969**	**22**
36	La Chioma	611,312	4,811,793	9
37	La Chioma	611,442	4,811,844	20
38	**La Chioma**	**611,537**	**4,811,768**	**16**
39	Colonia Rifredi	611,474	4,811,456	14
40	I Morticini	611,925	4,811,119	20
41	I Morticini	611,969	4,811,146	26
42	I Morticini	611,996	4,811,101	26
43	Botro della vipera	612,126	4,810,754	16
44	**Botro della vipera**	**612,170**	**4,810,795**	**21**
45	**Botro della vipera**	**612,233**	**4,810,847**	**26**
46	Villa Menicanti	612,315	4,810,598	23
47	Villa Menicanti	612,370	4,810,496	23
48	Campolecciano	612,357	4,810,185	21
49	**Campolecciano**	**612,502**	**4,810,134**	**32**
50	Villa D'Acour	612,402	4,810,023	20
51	Case Fortullino	612,727	4,809,476	3
52	Il Fortullino	612,990	4,809,493	22
53	Botro dell'Arancio	613,263	4,809,179	15
54	S. Lucia	613,432	4,808,841	15
55	Le Forbici	613,458	4,807,977	26
56	**Botro della Fontina**	**613,563**	**4,807,745**	**30**
57	Botro della Fontina	613,534	4,807,747	19

Site no.	Locality name	East (Longitude)	North (Latitude)	Section base elevation (m a.s.l.)
58	Botro della Fontina	613,511	4,807,713	15
59	**Buca dei Corvi**	**613,640**	**4,807,570**	**10**
60	Buca dei Corvi	613,639	4,807,621	33
61	Torre del Sorriso	613,649	4,807,502	32
62	Buca dei Corvi	613,662	4,807,438	28
63	Baia del Sorriso	613,735	4,807,315	24
64	**Fosso del Quercetano**	**613,926**	**4,807,334**	**20**
65	Baia Quercetano	614,011	4,806,940	12
66	Baia Quercetano	613,988	4,806,909	11
67	**Via Zug**	**614,112**	**4,806,914**	**20**
68	Castello Pasquini	614,304	4,806,795	30
69	Castiglioncello	614,305	4,806,759	20
70	**Fosso Piastraia**	**614,838**	**4,806,970**	**28**
71	Botro Grande	614,038	4,806,392	18
72	Villa Celestina	614,384	4,806,503	5
73	Pineta Marradi	614,615	4,806,519	5
74	Porticciolo	614,761	4,806,613	9
75	**Porticciolo**	**614,859**	**4,806,600**	**5**
76	**Villa Casamarina**	**615,275**	**4,806,268**	**2**
77	Baia di Caletta	615,445	4,806,131	0
78	**Baia della Crepatura**	**615,426**	**4,805,967**	**0**
79	Crocetta	615,544	4,805,979	3
80	Fosso dei Mille	616,308	4,805,392	10
81	**Lo Scoglietto**	**615,700**	**4,805,048**	**0**
82	Botro Secco	616,541	4,805,274	12
83	Botro Secco	616,980	4,805,550	20
84	I Canottieri	615,744	4,804,898	0
85	Punta del Lillatro	615,906	4,804,204	0
86	Le Fontanelle	619,313	4,804,889	15
87	Il Poderino	619,176	4,805,360	30
88	**Podere Catalano**	**619,381**	**4,805,208**	**25**
89	La Fornace	619,621	4,805,152	20
90	Podere Renaione	625,311	4,784,821	4
91	Podere La Bassa	625,782	4,779,897	5
92	Fosso della Carestia	625,823	4,779,230	4
93	**Podere Pianetti**	**625,856**	**4,778,688**	**8**
94	Le Porcarecce	627,538	4,778,370	35
95	Azienda Paradiso	625,690	4,777,751	6
96	Fosso Casa rossa	627,029	4,777,522	33
97	Botro ai fichi	626,137	4,775,783	25
98	Villa Biserno	625,472	4,769,004	8
99	Botro ai Marmi	625,116	4,769,019	3
100	La Principessa	624,968	4,767,422	5
101	Podere di Rimigliano	625,754	4,767,456	5
102	Poggio Formiche	624,969	4,763,774	5
103	Canale allacciante	626,035	4,763,120	5
104A	**Podere Torre Nuova**	**623,647**	**4,763,611**	**3**
104B	**Podere Torre Nuova**	**623,707**	**4,763,602**	**5**
105	Gli Scoglietti	623,516	4,763,610	0
106	Villa Barone	623,121	4,763,208	1
107	**Villa Barone**	**623,146**	**4,763,128**	**0**
108	**Lo Scivolo**	**623,264**	**4,762,342**	**0**
109	**Poggio La Fornace**	**623,349**	**4,762,282**	**1**
110A	**Baratti**	**623,565**	**4,762,116**	**0,5**
110B	**Baratti**	**623,616**	**4,762,044**	**0,5**
110C	**Baratti**	**623,624**	**4,762,013**	**1**
110D	**Baratti**	**623,608**	**4,761,884**	**0,5**

served at the base of the SM facies. Mollusc fragments, echinoids, red algae and foraminifera are common alongside this facies. The overall characteristics of SM facies suggest an upper shoreface marine environment.

4.3. A Facies: sandy Aeolian deposits

A facies consists of yellow well-cemented fine-grained litharenite that is up to 3 m thick. These deposits are characterized by both trough and low to high-angle planar and cross stratification. Distinctive aeolian sedimentary structures such as pin stripe lamination, convex-upward stratification (Fig. 2c) and contorted bedding (Fig. 2d) are frequently observed. Occasionally, fragments of echinoids and strongly abraded molluscs (land snails) are scattered within the deposits.

4.4. PC Facies: Pedogenized Continental deposits

This facies exhibits different characteristics depending on its stratigraphic position. The PC facies commonly consists of massive reddish silt to sandy structureless deposits that are up to 1.5 m thick, containing rhizoconcretions and, sometimes, continental molluscs (Fig. 2a). These deposits are frequently considerably pedogenized and organized in composite sequences of decarbonated soils (Fig. 2b). Manganese nodules, slickenside structures and diffuse mottle are common. Locally, a lenticular, massive concentration of angular to sub angular fine-grained pebbles was observed at the base. As a whole, these deposits show a lenticular arrangement and sometimes are absent in the stratigraphic succession. The characteristics of PC facies suggest a wide set of continental environments, ranging from alluvial deposits subjected to prolonged phases of subaerial exposure with the development of a soil and a colluvial at slopes.

5. Results

According to the geological and geomorphological features, two main sectors can be individuated across the study area (Fig. 1). The northernmost extends between the Leghorn terrace and the Fine River and is characterized by beach deposits bearing "*Senegalian fauna*". The southernmost sector extends between the Fine River and the Piombino promontory and is characterized by beach deposits with no evidence of "*Senegalian fauna*".

5.1. The coast between the Leghorn terrace and the Fine River

In this area a total of 89 stratigraphic sections have been analysed (Tab. 1). The late Quaternary deposits crop out patchily along the southern margin of the polycyclic Leghorn terrace. Four distinct facies compose the Upper Pleistocene sequence (Fig. 3). The base of the succession consists of BM facies, lying on an angular unconformity above the substratum. BM facies crops out along the inner margin of the terrace at an altitude of approximately 16 m above present day sea-level (a.s.l.), whereas the altitude of BM facies drops down to 7 m below present day sea-level (b.s.l.) northwards, towards the Leghorn harbour dry-dock (Barsotti *et al.*, 1974). Data from two boreholes (www.regione.toscana.it) drilled in the Rosignano plain reveal the presence of fossiliferous conglomerate deposits to a depth of 2 and 5 m b.s.l. respectively, which are tentatively correlated with the conglomeratic BM facies that crops out above the Leghorn terrace. BM facies grades upwards into the SM facies. The former overlaps the substratum up the inner margin of the terrace at approximately 20 m a.s.l. and drops towards the dry dock down to 4 m b.s.l. The SM facies is characterized by the presence of the "*Senegalian fauna*". Many mollusc fragments, echinoids, red algae and foraminifera are also common. An unconformity divides SM facies and the overlying continental PC facies. This is made of a reddish massive sandy-silt deposit containing many small rhizoconcretions. A non-marine mollusc fauna made of a snail association was recognized within the PC facies (Malatesta, 1942) and is related to a phase of climatic deterioration probably connected to MIS 5d (Zanchetta *et al.*, 2004). Upwards, a yellowish litharenite level (A facies) rests unconformably above the continental deposits. The A facies crops out mainly along the inner margin of the terrace at an altitude of approximately 21 m a.s.l. The uppermost portion of the sequence consists of a massive, deeply weathered, reddish sandy-silt continental succession (PC facies). In this stratigraphic position, the PC facies corresponds to the "*Sabbie di Ardenza*" Formation (Lazzarotto *et al.*, 1990), which has been correlated to MIS 4 or the beginning of MIS 3 based on the Middle Palaeolithic remains (Zanchetta *et al.*, 2006). Southwards, the Upper Pleistocene facies is well exposed at the La Chioma (Fig. 1, sites 35 to 38) and Buca dei Corvi (Fig. 1, site 59) sections (Fig. 3). Above the pre-Quaternary substratum, the La Chioma section starts with the BM facies, which crops out at an altitude of 16 m a.s.l. Upwards, the conglomerates are truncated by an unconformity upon which rests the PC facies. These reddish continental and intensely weathered deposits comprise an angular clast-supported breccia, which is representative of slope subaerial degradation processes (Lazzarotto *et al.*, 1990). PC facies is sharply overlain by an aeolian deposit (A facies). A new date recorded in this study with the OSL technique indicates an age of 53 ± 4 kyr for this deposit. The Buca dei Corvi section exhibits one of the more complete successions in the

Table 2 - Age of the transgressive-regressive sequences. See Figure 3 for the dating techniques utilized (ND, no data; NP, T-R not present).

Locality name **Locality no.**	**La Chioma** **(38)**	**Buca dei Corvi** **(59)**	**Pod. Catalano** **(88)**	**Pod. Pianetti** **(93)**	**Baratti** **(110)**
T-R_4	*N.D.*	9.7 ± 2.4 11.4 ± 0.2 13.1 ± 0.9	*N.P.*	N.P.	7 ± 1 15 ± 1
T-R_3	53 ± 4	*N.D.*	*N.P.*	56 ± 4	19 ± 2 47 ± 6 42 ± 11
T-R_2	*N.D.*	93 ± 34	68 ± 2	N.P.	43 ± 25 68 ± 8 77 ± 10
T-R_1	*N.D.*	> 108	*N.P.*	*N.P.*	> 100

FACIES	**DESCRIPTION**	**INTERPRETATION**
PC	Pedogenizzed silty/sandy structureless deposits containing rizhoconcretions and continental mollusks	Pedogenizzed continental deposits
A	Yellow well-cemented fine litharenite characterized by contorted bedding and convex upward stratification	Sandy aeolian deposits
SM	Coarse-grained litharenite showing low-angle planar cross-stratification up to cross-bedded stratification	Sandy shallow marine deposits
BM	Well-rounded and sorted cobble to pebble clast supported, organized in a fining upward trend	Coarse-grained beach marine deposits

FIGURES

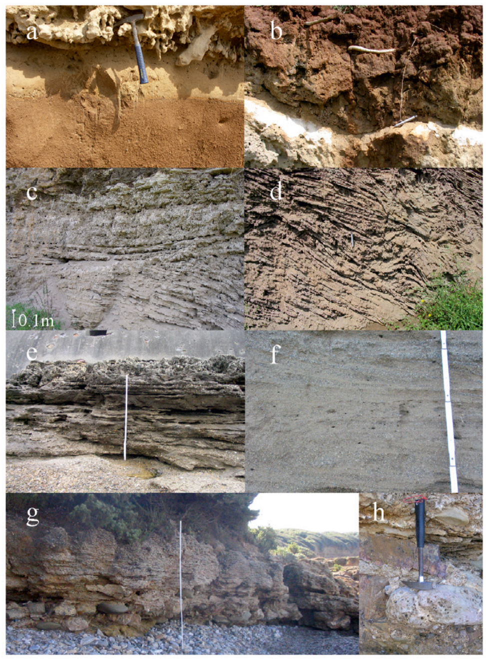

Fig. 2 - Simplified scheme of the major facies associations identified along the study area.

whole study area (Fig. 3). From the bottom to the top, the stratigraphic succession is composed of SM facies bearing the "*Senegalian fauna*" along with fragments of red algae, echinoids, bryozoans, and benthic foraminifera. Two marine bioclasts levels and some scattered well-rounded clasts are also observed within this facies. A thermoluminescence date indicates an age over 108 kyr for this deposit (Mauz, 1999). The base of the marine deposit is located at 10 m a.s.l. The top of the SM facies is truncated by an unconformity upon which rests a structureless reddish silty-clay deposit (PC facies). Upwards, two sedimentary aeolian units, likely separated by an unconformity, have been recognized. The lowest is composed of a cemented fine to medium sand showing well-developed planar and trough cross stratification alongside pin stripe lamination and contorted bedding layers. Scattered foraminifera and fragments of echinoids are also observed. A thermoluminescence date indicates an age of 94 ± 34 kyr for this unit (Mauz, 1999). The uppermost aeolian deposit consists of an alternation of well-cemented medium to coarse sand and reddish silty sand truncated at the top by a pedogenetic alteration profile containing many rhizoconcretions. The upper part of the sections is made of a succession of continental units (PC facies) that consist of: *i*) a faintly stratified clast-supported breccia supplied by the surrounding substrate; *ii*) a massive yellowish sandy silt with scattered angular clasts, which bears terrestrial molluscs and rhizoconcretions (loess unit of Ottmann, 1954); two new dates (Fig. 3) indicate that this unit developed during the Last glacial phase (Borretto *et al.*, 2017); *iii*) fine to medium brown bioturbated sand with rhizoconcretions and some isolated broken gastropods. The development of a reddish paleosol, bearing an oligotipycal terrestrial mollusc assemblage (Sarti *et al.*, 2005; Zanchetta *et al.*, 2006; Borretto *et al.*, 2017) is indicative of semi-arid, cold climatic conditions (Esu *et al.*, 1989), and is correlated, in Italy, with glacial phases (Malatesta, 1959; Conato *et al.*, 1980; Di Vito *et al.*, 1998). Therefore, this unit can be correlated to MIS 2 considering the amino-acid racemization data of Hearty & Dai Pra (1987). The PC unit is truncated at the top by parallel and low angle cross stratified deposits interpreted by Ottmann (1954) as reworked loess and consisting of reddish silty sand and medium to coarse sands with oriented pebbles at the base organized in a fining-upwards trend and dated to 9.7 ± 2.4 kyr (Mauz, 1999). This unit is here interpreted as aeolian coastal deposits. At the top is overlain by a present soil.

In the Rosignano Terrace (Fig. 1), the outcrops become extremely patchy, and complete sections such as Buca dei Corvi are missing. From Punta Righini to the Fine River (Fig. 1), the elevation of the beach deposits bearing "*Senegalian fauna*" falls from 16 m a.s.l. to 4 m b.s.l. Along the coastal cliff of the Rosignano Terrace, Upper Pleistocene deposits commonly rest in transgression above pre-Quaternary formations. The base of the succession consists of the BM facies, which lies on an angular unconformity above the substratum. Upwards, a yellowish litharenite level characterized by trough and contorted bedding and convex upward stratification (A facies) has been recognized. An unconformity divides BM facies and the overlying aeolian facies. The former overlaps the substratum along the inner margin of the terrace, up to an altitude of 26 m a.s.l. near Podere Catalano (Fig. 1, site 88), where an OSL date (this study) indicates an age of 68 ± 5

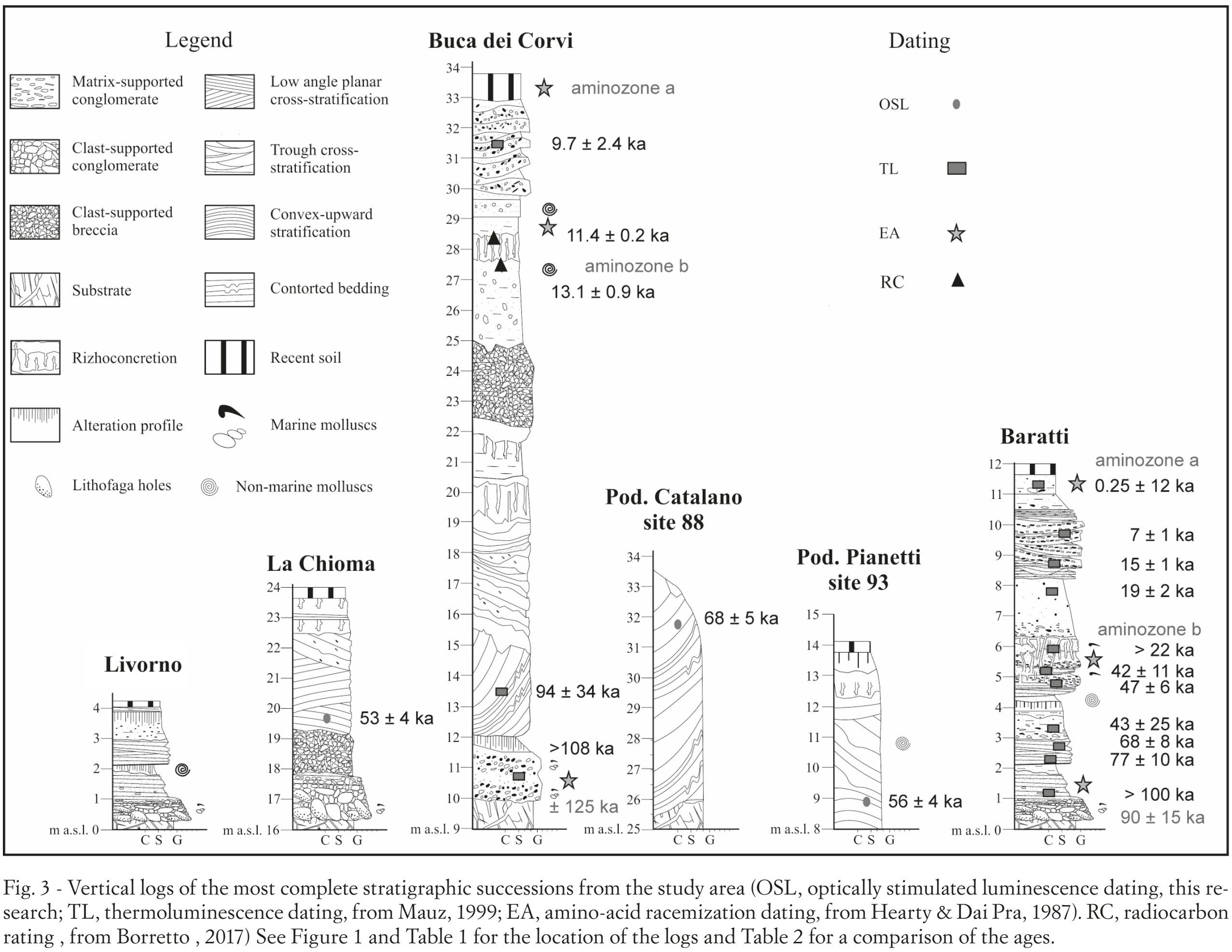

Fig. 3 - Vertical logs of the most complete stratigraphic successions from the study area (OSL, optically stimulated luminescence dating, this research; TL, thermoluminescence dating, from Mauz, 1999; EA, amino-acid racemization dating, from Hearty & Dai Pra, 1987). RC, radiocarbon rating , from Borretto , 2017) See Figure 1 and Table 1 for the location of the logs and Table 2 for a comparison of the ages.

kyr. A deeply weathered reddish sandy-silt continental succession (PC facies) bearing rhizoconcretions characterizes the top of the sequence.

5.2. The coast between the Fine River and the Piombino promontory

A total of 26 stratigraphic sections have been analysed in this part of the study area. Several successions, which are Upper Pleistocene-Holocene in age, crop out discontinuously in this coastal sector. Among these, the most complete and representative section is located along the present day sea-cliff of the Baratti Gulf (Figs. 1 and 3). Here, the succession is very similar to that observed along the coast between Leghorn and the Fine River and consists of an alternation of marine-coastal and reddish continental deposits separated by unconformities. The Baratti cliff succession starts upon a subaerial unconformity that marks the top of the pre-Quaternary substratum at 1 a.s.l. (Fig. 3). The base of the section consists of a fining-upward clast-supported conglomerate that exhibits imbricated boulders bearing a *lithofaga* band (BM facies). Although evidence of "*Senegalian fauna*" is lacking, scattered broken marine molluscs are frequently observed. BM facies grades upward into SM facies, which is characterized by faintly low-angle cross stratification and mollusc fragments, red algae, echinoids, and foraminifera. A thermoluminescence date indicates an age over 100 kyr for this deposit (Mauz, 1999). As a whole, BM and SM facies record the deepening and fining upward transition from a gravelly beach foreshore to upper shoreface depositional environment. Considering the gradual transition and the depositional environments, BM and SM facies can be considered as a facies association. Above an irregular unconformity that caps SM facies, a lenticular and massive weathered reddish silty-sandy layer containing scattered reworked bioclasts (PC facies) has been observed. Upwards, a new transgressive marine deposit (SM facies) made of an alternation of coarse-grained sands and small pebble laminae and planar and cross bedding is recorded. Two thermoluminescence dates indicate that the deposition of the SM facies occurred between 77 ± 10 and 68 ± 8 kyr (Mauz, 1999). The marine deposits are again capped by PC facies, which consists of a massive silty sand deposit with, locally, a basal concentration of angular to sub angular pebbles. PC facies was dated by Mauz (1999) to 43 ± 25 kyr. At the top, the succession is covered by a very thin, lenticular level made of a moderately sorted massive sandy-silt layer rich in small rhizoconcretions and subangular quartz grains and bearing an oligotypical non-marine mollusc assemblage. From a palaeoclimatic point of view, this assemblage indicates arid, cold climatic conditions and has been referred to the MIS 4 (Sarti *et al.*, 2005). An unconformity divides PC facies from the overlying SM facies, for which luminescence results set the beginning of deposition to 42 ± 11 and 47 ± 6 kyr and the upper part of the deposit to over 22 kyr (Mauz, 1999). SM facies is characterized in this stratigraphic position by both inchoate weathering and root traces. This was caused by the strong pedogenesis experienced by the overlying reddish massive silt (PC facies). The deposition age of PC facies dates to 19 ± 2 kyr (Mauz, 1999). After this phase of subaerial exposition, a further event of marine transgression occurred. The SM facies, which shows a planar and cross bedding alternation of cemented fine sands, is organized in thin layers and massive silty-sands from the base to the top and records a new transgressive event. Upwards, the silty sands alternate with cemented, well-sorted pebbles. Marine mollusc fragments, foraminifera, echinoid spines and bryozoans are frequently observed within this facies. According to Mauz (1999), the deposition of this facies occurred between 15 ± 1 and 7 ± 1 kyr. Reddish massive silty sands (PC facies) bearing Etruscan artefacts and iron wastes constitute the uppermost portion of the Baratti cliff section. The Upper Pleistocene succession of Baratti plunged approximately 4° S-SW. For this reason, the two basal marine transgressive deposits do not crop out northwards, whereas the third one passes laterally to a prevalent backshore environment (A facies). This aeolian facies rests at altitudes ranging between 5 to 15 m a.s.l. directly on the substratum, bearing an oligotypical non-marine mollusc assemblage, i.e., *Rumina decollata, Pomatias elegans, Monaca* sp. and *Cepaea* sp., which can be considered similar on present day Italian coastal dunes (Giusti & Castagnolo, 1982; Esu & Girotti, 1991). An OSL date recorded by this study on these deposits provides an age of 56 ± 4 kyr.

5.3. Stratigraphic correlations

Transgressive surfaces represent sedimentary key-markers that are very easy to identify, especially in coastal marine depositional settings (Fig. 4). In this regard, T-R sequences constitute a very pragmatic tool to reconstruct vertically stacked patterns in a succession (Lopez-Blanco *et al.*, 2000; Aguzzi *et al.*, 2007; Amorosi *et al.*, 2008; Chorrocano *et al.*, 2012). In the study area, four stratigraphically overlapping T-R sequences, spanning in age from MIS 5 to MIS 1, have been identified. The youngest sequence (T-R_4), which is Holocene in age, occasionally preserves the transgressive tract exclusively. By contrast, the Holocene sequence is well preserved in the southern and northern parts of the study area, in the subsurface of the Pisa and Piombino plains (Amorosi *et al.*, 2004; Rossi *et al.*, 2011; Sarti *et al.*, 2012; Rossi *et al.*, 2017). The transgressive tract of T-R_1 is exclusively formed

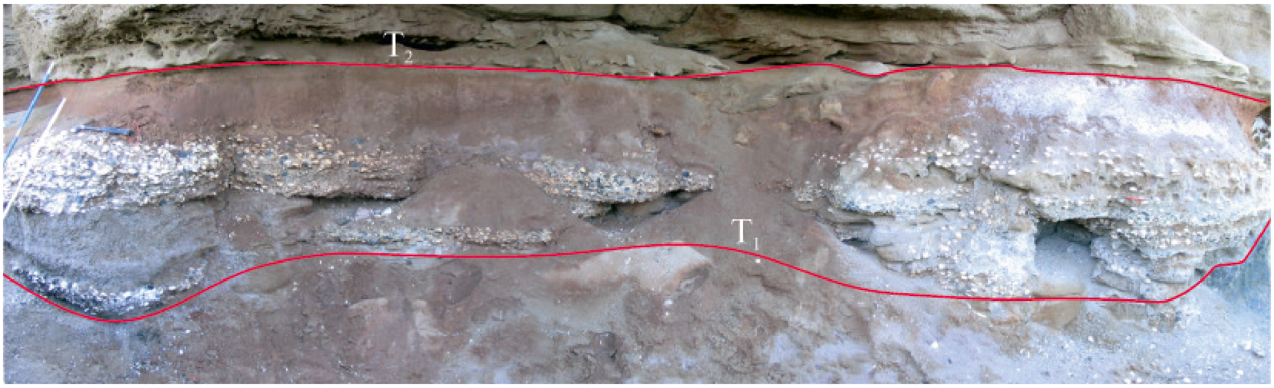

Fig. 4. Examples of transgressive surfaces from the Buca dei Corvi section (location in Figure 1 and Table 1; log description in Figure 3). T_1 constitute the base of the T-R_1 sequence related to MIS 5. T_2 is the base of the T-R_2 sequence formed during MIS 5a. Note in both cases the abrupt lithological changes. Reddish pedogenized deposits (PC facies, see Figure 2) are overlaid by a mollusc shell debris layer (T_1). Aeolian deposits in a sharp contact above PC facies.

by shallow marine deposits. The transgressive deposits belonging to T-R_2, T-R_3 and T-R_4 mainly formed in an aeolian coastal dune setting. The base of T-R_1 is well characterized in terms of depositional facies (foreshore-upper shoreface), fossiliferous content ("*Senegalian fauna*"), and chronological dating (Hearty & Dai Pra, 1987; Mauz, 1999; see Table 2) and was deposited during the last interglacial (MIS 5e).

As a whole, the T-R_1 sequence crops out patchily, though not always complete, for approximately 20 km between Leghorn and Rosignano and along the Baratti cliff (Fig. 5) at heights between 0 and 25 m a.s.l. The shallow marine deposits related to MIS 5e, which unconformably overlie a pre-Neogene substratum, record a fining- and deepening-upwards trend abruptly truncated by an unconformity (see the Buca dei Corvi section, Fig. 3). The upper part of the T-R_1 sequence is composed of continental reddish and intensely pedogenized deposits showing distinctive depositional features as a function of the local supply area. These deposits are strongly discontinuous and testify prolonged phases of subaerial exposure. Southwards, T-R_1 crops out widely along the Baratti cliff section; the absence of "*Senegalian fauna*" within the marine deposits could leave some uncertainties on regards to matching this older transgressive-regressive sequence to MIS 5e. However, this age interpretation is supported by: *i*) the overall stratigraphic architectural framework derived by the study area; *ii*) the ambiguous meaning of "*Senegalian fauna*" as a chronostratigraphic marker, which is facies-controlled (Hillaire-Marcel *et al.*, 1986; Zazo *et al.*, 1999; Asioli *et al.*, 2005; Torres *et al.*, 2010; Mauz *et al.*, 2012; Torres *et al.*, 2013); and *iii*) the very little difference in ages as reported by Mauz (1999) between the oldest Baratti and Buca dei Corvi marine deposits (Fig. 5, Table 2). The top of the marine deposits is truncated by an unconformity upon which a continental pedogenized unit is developed, similar to what observed in the Buca dei Corvi area.

The T-R_2 sequence is well exposed at Buca dei Corvi and, southwards, at Baratti, whereas it only crops out to the north along the western outer margin of the Leghorn terrace (Fig. 1). The transgressive surface of T-R_2 merges into the unconformity that caps the T-R_1 sequence. Aeolian deposits cropping out between 10 and 25 m a.s.l. characterize the transgressive tract of T-R_2 along the area between Leghorn and Rosignano. A lateral transition to shallow marine deposits (at approximately 1 m a.s.l.) is observed along the northern edge of the Leghorn Terrace (Fig. 5, site 3) and the Baratti cliff (Fig. 5, site 110). The ages recorded at Buca dei Corvi and Baratti match these deposits to MIS 5a (Hearty & Dai Pra, 1987; Mauz, 1999; see Table 2). Note that continental mollusc fauna, indicative of cold and arid climatic conditions and related to MIS 4, occur in the upper part of the T-R_2 sequence along the Baratti cliff (Sarti *et al.*, 2005). This implies that the T-R_2 sequence developed between MIS 5a and MIS 4. In the study area, T-R_2 is truncated by a non-depositional/erosive surface that merges with the transgressive surface of the overlying T-R_3 sequence. The transgressive portion of the T-R_3 sequence is prevalently composed of aeolian deposits that formed during MIS 3 (Mauz, 1999). Shallow marine deposits are only preserved along the Baratti cliff. Similar to what is observed in the T-R_2 sequence, we interpret the Baratti marine deposits as a lateral facies variation in the coastal aeolian deposits that crop out to the north (Table 2). These deposits are often encased in morphological traps such as small valleys or canyons and formed within a pre-Quaternary substratum. This may be the reason for their poor lateral continuity. The upper regressive portion, expressed through a depositional environment change related to a sea-level fall, records

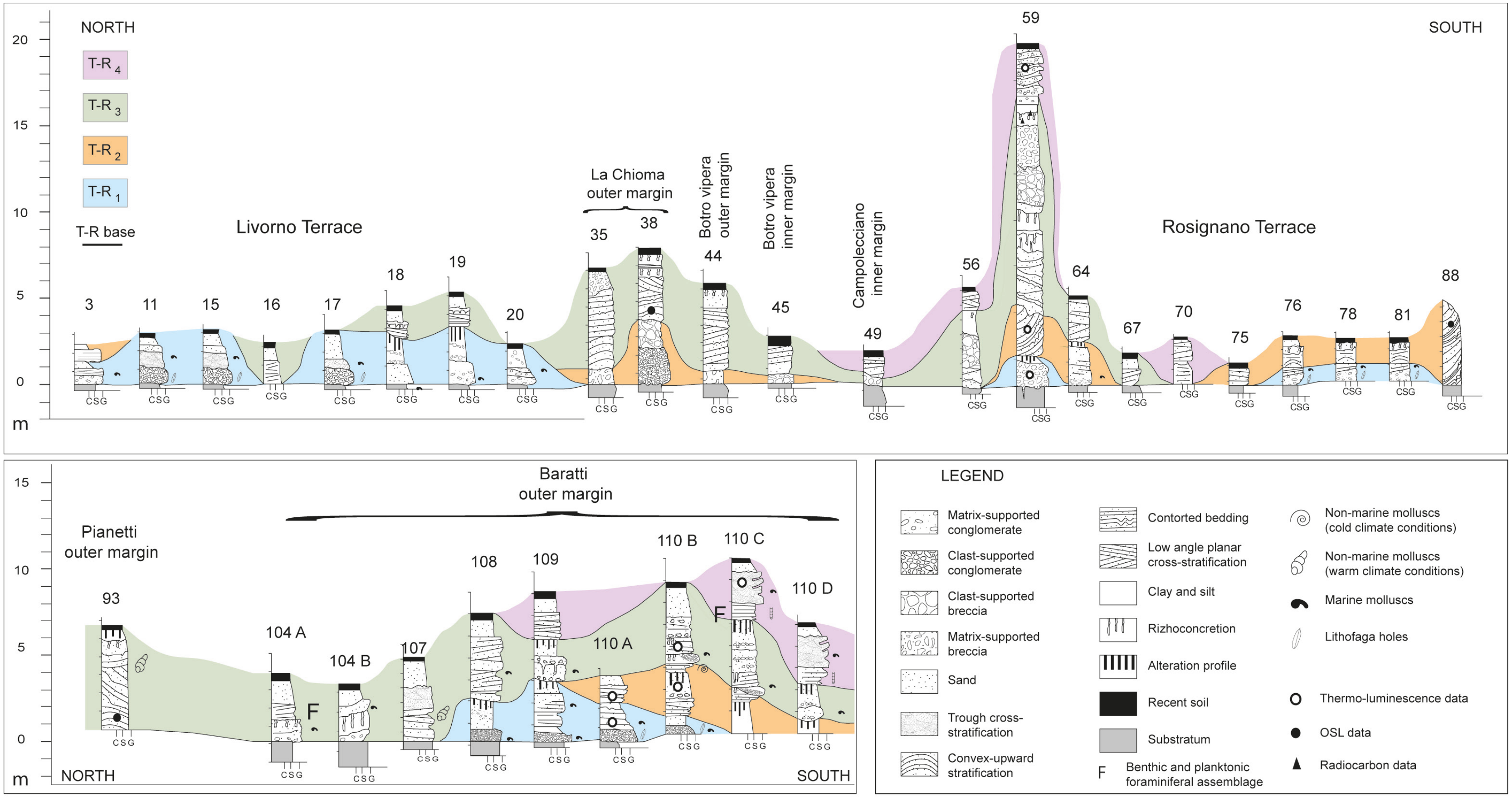

Fig. 5 - Stratigraphic correlation panel linking 32 vertical sections roughly N-S oriented along the study area. Facies architecture is inferred by the transgressive tract of each T-R sequence. See Figure 1 and Table 1 for the location and elevation of the sections. Note the exaggeration of the vertical scale. Horizontal distance between adjacent sections not to scale (for correct horizontal scale, see Figure 1). The elevation of each section is equalized to zero in order to make the stratigraphic correlations more readable and clearer (see Table 1 for the exact elevations).

the deposition of sediments within a continental environment, which is characterized by the occurrence of a wide variety of physical processes as a function of the local morpho-sedimentary setting. In this regard, depositional and erosional processes might have concurrently occurred in adjacent areas. At the same time, pedogenesis, instead of deposition or erosion, might have affected the contiguous area. It is worth noting the presence of a terrestrial mollusc fauna association indicative of warm climatic conditions in the upper portion of the T-R_3 sequence. The T-R_3 sequence can be well tracked from Leghorn to Baratti (Fig. 5).

The transgressive deposits in the T-R_4 sequence only crop out above the continental deposits of the T-R_3 sequence along Buca dei Corvi and Baratti. They were formed in a coastal aeolian and marine setting, respectively. The top of the transgressive portion is sharply truncated by a subaerial surface and reddish soil containing Etruscan artefacts. The age of this new transgressive event ranges from Upper Pleistocene to Holocene (Table 2). However, we are inclined to consider the oldest age recorded at Baratti as incorrect (15 kyr falls during the last strong sea-level lowering related to MIS 2) despite the stratigraphic continuity observed within the beachface deposits. Therefore, the younger transgressive-regressive sequence outcropping at Baratti is considered Holocene in age (MIS 1). This implies a northward lateral facies transition from beachface (Baratti) to aeolian coastal deposits (Buca dei Corvi).

6. Discussion

In terms of sequence stratigraphy, the studied succession records two fourth-order sequences that formed during the last two interglacial cycles (MIS 5e-MIS 1). The older interglacial sequence exclusively preserves the transgressive tract and corresponds to T-R_1. A forced regressive systems tract (FRST) and transgressive systems tract (TST) form the last glacial-interglacial cycle. Within the FRST, two fifth-order sequences corresponding to T-$R_{2\text{-}3}$ have been detected.

The cyclic arrangement of late Quaternary deposits identified in the study area is common to several Mediterranean areas, independent of their geo-tectonic setting. Examples are documented in Sardinia, Italy (Andreucci *et al.*, 2010; Carboni *et al.*, 2014), Liguria, Italy (Pappalardo *et al.*, 2013), southern Spain (Bardají *et al.*, 2009), and Israel (Mauz *et al.*, 2013). A similar cyclic depositional arrangement has also been identified beneath the subsurface of several Mediterranean coastal plains such as those of the Arno (Amorosi *et al.*, 2009; Amorosi *et al.*, 2013; Rossi *et al.*, 2017), Tiber (Milli *et al.*, 2013), Po (Amorosi *et al.*, 2008), Rhone (Boyer *et al.*, 2005) and Nile (Mauz *et al.*, 2012) rivers and has been interpreted as due to the interaction between glacio-eustatic changes and local tectonics. In the outcropping sequences, the identification of sea-level markers plays a decisive role in deciphering and estimating the tendency of a zone to experience vertical (uplift/subsidence) movements. In the study area, sea-level markers are exclusively concentrated within the oldest T-R sequence that formed during MIS 5e. This is in accordance with most studies (e.g., Bard *et al.*, 2002; Lambeck *et al.*, 2004; Ferranti *et al.*, 2006; Antonioli *et al.*, 2009; Lambeck *et al.*, 2011; Rovere *et al.,* 2016), which utilize MIS 5 sea-level markers because they are the most common and are relatively easy to link with sea-level curves to infer vertical movements. Nevertheless, evidence of climatic/tectonic signatures on the youngest T-R sequences can also be inferred, although not quantitatively, from facies analysis.

In the study area, the aeolian deposits that widely characterize the T-$R_{2\text{-}4}$ sequences were formed within a depositional coastal setting (see T-R_2 sequence) according to the characteristics of the present-day wave-dominated coastal systems of the Mediterranean. This indicates that they must be genetically connected to the depositional trajectory of their respective coastline (e.g., Anthony, 2009; Tamura, 2012). As coastal dunes indicate a close proximity to the coastline, the stratigraphic position and the present-day elevation of the outcropping coastal dune deposits may be additional "sea-level markers", though not as much precise, to evaluate the consistency of the interpretations (in terms of climatic/tectonic signature) when compared with the available sea-level curve.

From north to south, the marine deposits belonging to T-R_1 (MIS 5e) crop out from 4 m b.s.l. (outer margin of the Leghorn terrace) to 20 m a.s.l. (inner margin of the Leghorn terrace, Fig. 5). South of Leghorn, the altitude decreases down to 10 m a.s.l. (Buca dei Corvi, site 59) and to 0 m a.s.l. in Baratti (Fig. 5). A sea-level marker (*lithofaga* band) has been identified for these deposits. Because the sea level was higher during the MIS 5e than during the present (≈7 m a.s.l., Ferranti *et al.*, 2006), a differential tectonic movement between Leghorn and Piombino should necessarily be expected. In particular, the uplift tendency that affected the Leghorn Terrace as documented by Nisi *et al.* (2003) and Ferranti *et al.* (2006) should have reached a maximum value in the southern part of the inner-margin (Fig. 5, site 18).

The transgressive tract of T-R_2 (MIS 5a) crops out (Figs. 1, 5) along the outer margin of the Leghorn Terrace (2 m a.s.l., site 11) and along the Baratti cliff (2 m a.s.l., site 109-111) and consists of shallow marine deposits. This implies a tectonic deformation of the T-R_1 deposits before the deposition of the subsequent units. It is absent within most of the coastal sector between the Leghorn Terrace and Rosignano, with the exception of the aeolian deposits that outcrop at Buca dei Corvi (site 59) at an higher elevation (12 m a.s.l.). This might be due either to erosion or non-deposition processes. Based on the available data, the two hypotheses are both reliable, even if the arising tectonic implications are very different from one another. Even though coastal dunes are not sea-level markers, the facies analysis criteria and stratigraphic correlation suggest that the deposition of the Buca dei Corvi sand dune did not occur too far from the coeval shoreline (about some tens or hundreds of meters). Therefore, we hypothesize that the T-R_2 discontinuous distribution between the Leghorn and Rosignano terraces, along with the higher elevation of the Buca dei Corvi deposits, is the result of post-depositional erosional processes.

The comparison with available sea-level curves suggests two different scenarios for MIS 5a. Considering Siddall *et al.* (2003), the sea level was 20 m lower than present day, whereas Dorale *et al.* (2010) indicated a sea level approximately 1 m higher than now. If we consider Siddall's curve, the stratigraphic superimposition of MIS 5a deposits above MIS 5e observed at Leghorn and Baratti (Figs. 3, 5) along with the aeolian deposits at Buca dei Corvi bears significant tectonic implications. In particular, the study area should have been affected by severe subsiding processes between the MIS 5a and 5e transgressive sequences. In accordance with the Dorale *et al.* (2010) curve, the study area could be considered tectonically stable. In both cases, the present-day outcrops suggest an overall post-MIS 5a uplift tendency, mostly in the area of Buca dei Corvi.

The MIS 3 transgressive coastal-marine event (T-R_3) crops out in a stratigraphic succession above the MIS 5/4 deposits to an altitude between 2 and 25 m a.s.l. (Fig. 5). This event is composed of a broadly continuous coastal aeolian deposits containing marine and warm molluscs, and of shallow marine deposits at Baratti. On the whole, the MIS 3 transgressive tract records a depositional environment close to the coastline. The available sea-level curves indicate that the sea level lowered from ca. -22 to -85 m a.s.l. during MIS 3 (Bard *et al.*, 1990; Bard *et al.*, 1996; Chappell *et al.*, 1996; Lambeck *et al.*, 2002; Waelbroeck *et al.*, 2002; Cutler *et al.*, 2003; Antonioli *et al.*, 2004; Rabineau *et al.*, 2006; Caputo, 2007; Siddall *et al.*, 2007). The overlap of the T-R_3 transgressive sequence on the Tyrrhenian ones should stress a post-Tyrrhenian tectonic environment, where the subsidence rate was slightly greater than the MIS 5a and 3 highstand-eustatic fluctuations. Despite the lack of sea-level markers, facies analysis data suggest that these values conflict by an order of magnitude with the present day distribution of the outcrops, implying the occurrence of an uplift tectonic event post-MIS 3. The effect of tectonics on the Upper Pleistocene evolution of Tuscany is also highlighted by previous studies (e.g., Censini *et al.*, 1991; Cantini *et al.*, 2001; Brogi *et al.*, 2005; Benvenuti *et al.*, 2008) and by the fact that the late Quaternary succession in Baratti is wholly tilted to the S-SW. These considerations contrast with the late Quaternary tectonic evolution proposed for the study area by Nisi *et al.* (2003) and Ferranti *et al.* (2006), who suggest a post-Tyrrhenian deformation history exclusively related to slow uplifting or stable conditions.

To explain the present day position of the aeolian deposits related to MIS 4 and late MIS 3, an alternative hypothesis has been proposed for other coastal areas by several authors (Bateman, 2004; Andreucci *et al.*, 2010; Pappalardo *et al.*, 2013). According to this hypothesis, the aeolian dunes were fed by deflation of the sandy shelf area that was exposed during the sea level lowstand (i.e., glacial phases). Therefore, sand dunes should have been detached from their coeval coastline. This depositional model could explain the different elevations of the aeolian deposits if compared with the relative sea-level curve. Therefore, no tectonic processes could be needed, but at the same time cannot be excluded. This interpretation describes a windy climate characterized by strong and persistent winds able to move large amounts of sand inland (Andreucci *et al.*, 2010). In the study area, these transport-depositional processes conflict with the occurrence of coeval shoreface-foreshore deposits (Baratti section, Fig. 3). Therefore, the T-R_3 aeolian deposits should be considered as close to, and not detached from, their coeval palaeo-coastal line.

The T-R_4 transgressive tract (MIS1) patchily crops out. Shallow marine deposits are only preserved at the Baratti cliff at 8-10 m a.s.l. The uncertainty on the T-R_4 dating consistency prevents speculation regarding the comparison of different sectors in the study area, even if the foreshore's contribution to the fourth transgressive sequence of Baratti suggests slight uplift tectonics in the Holocene for this part of the study area.

The application of facies analysis criteria to the whole MIS 5-MIS 1 stratigraphic succession indicates that subsidence was the major local tectonic factor across the study area up to MIS 3. On the other hand, the present-day outcrop altitude distribution suggests tectonic inversion since MIS 2. Further studies are needed to strengthen this interpretation. A revision of published data available for the Mediterranean area deriving both from outcrops and subsurface to examine the implications inherent in the stratigraphic superimposition of late Pleistocene-Holocene deposits above the MIS 5e sediments should greatly contribute to an in-depth understanding of the tectonic history.

7. Conclusions

The main results of this study can be summarized as follows:
i) the detailed facies analysis suggests the identification of four superimposed transgressive-regressive sequences (T-R_{1-4}) that are late Pleistocene-Holocene in age (MIS 5-MIS 1);
ii) each T-R consists of transgressive marine-coastal aeolian deposits that alternate with continental regressive units and palaeosols;
iii) the areal distribution of sea-level markers belonging to T-R_1 (MIS 5) and their comparison with the sea-level curves suggest that the area between Leghorn and Piombino is subject to uplift processes;
iv) extending the facies analysis approach to the three T-R_{2-3} sequences, which are in a stratigraphic succession above T-R_1 (MIS 5e), indicates that subsidence was the main local tectonic factor up to MIS 3, regardless of eustatic sea-level changes;
v) in accordance with this approach, the local tectonic history of the study area has been split into a late Pleistocene phase characterized by subsidence followed by a late Pleistocene-Holocene (post-MIS 3) phase mainly dominated by uplift processes, suggesting a significantly more complex local tectonic history;
vi) the application of this approach to other outcrop or subsurface successions may validate or improve the local tectonic evolution resulting from the sole use of sea-level marker data.

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