GRAVEL	ISSN 1678-5975	Dezembro - 2016	V. 14 – nº 1	1-10	Porto Alegre

Quartz OSL dating of Pre-and Post-Little Ice Age beach ridges in Ravenna coastal plain northwest Adriatic Sea (Emilia-Romagna, Italy)

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Received 22 august 2016; accepted 01 december 2016.

RESUMO

A técnica de datação por luminescência opticamente estimulada (LOE) foi aplicada em grãos de quartzo coletados em cristas de praias na planície costeira de Ravenna/Itália. Essas datações fornecem o primeiro quadro cronológico para propor a evolução da área costeira de Ravenna durante o Holoceno tardio. Nove amostras de sedimentos arenosos foram coletadas a uma profundidade de 0,4 m das cristas de praias, presentes em duas barreiras arenosas da planície costeira de Ravenna, uma barreira interior e uma outra exterior, no sentido do mar. A barreira interior apresenta idades de 687 ± 204 a 399 ± 66 anos, enquanto a barreira exterior apresenta idades inferiores a 165 ± 57 anos. Estes resultados permitem complementar os trabalhos anteriores realizados sobre a evolução da planície costeira de Ravenna e demonstrar a influência da Pequena Idade do Gelo (LIA) na modelação da morfologia da zona costeira durante o Holoceno tardio. Assim, através destes dados é possível propor a divisão da planície costeira de Ravenna em barreiras arenosas de idades Pré-LIA e Pós-LIA.

ABSTRACT

The optically stimulated luminescence (OSL) dating technique was applied to quartz grains from beach ridges in the Ravenna coastal plain. This provides the first chronological framework to constrain the evolution of the Ravenna coastal area during the late Holocene. Nine sand samples were taken at 0.4 m depth from beach ridges present in two sand barriers of the Ravenna coastal plain, an inland and a seaward sand barrier. The inland sand barrier shows ages from 687 ± 204 to 399 ± 66 years while the seaward sand barrier present ages younger than 165 ± 57 years. These results allow complement the previous works carried out about Ravenna coastal plain evolution and show the influence of the Little Ice Age (LIA) to shape the morphology of the coastal zone during the late Holocene. Through these data, it is possible to propose the division of the coastal plain of Ravenna in Pre-LIA and Post-LIA sandy barriers.

Key words: barrier-lagoon; coastal evolution; geomorphology.

INTRODUCTION

In the last years, the optically stimulated luminescence (OSL) dating method has been an important tool to determine burial ages of sedimentary deposits and contributing to the coastal evolution system studies (Alappat *et al.*, 2015; Argyilan *et al.*, 2005; Clemmensen *et al.*, 2012; Murray-Wallace *et al.*, 2002; Rémillard *et al.*, 2015; Sawakuchi *et al.*, 2011 and 2012; Zular *et al.*, 2015). For the coastal systems characterized by barrier-lagoon depositional system, the OSL dating method have been applied successfully, especially quartz-rich sands from beach ridges or dunes are present in the local morphology (Rémillard *et al.*, 2015). Considering the barrier-lagoon coastal system where beach ridges and dunes are present, the OSL dating of the quartz grains from beach ridges sands allows to improve the knowledge about the response of the coastal system do sea level and climate changes (Guedes *et al.*, 2011; Zular *et al.*, 2013, and 2015; Dillenburg *et al.*, 2017).

During the Quaternary, glacial and interglacial periods modullated by insolation cycles controlled sea level changes and the buildup or erosion of coastal depositional systems. In a shorter timescale, abrupt millenial to secular climate events provoked severe shifts in sediment input to coastal and marine depositional systems and induced important changes in coastal settings. In the secular timescale, the Little Ice Age (LIA) had an important influence to shape the late Holocene coastal zones in subtropical settings around the world (Dillenburg *et al.*, 2000; Schwab *et al.*, 2000; Scarelli, 2016). According with many authors (Carbognin and Tosi, 2002; Fanget *et al.*, 2013; Marabini and Veggiani, 1992; Scarelli *et al.*, 2016; Simeoni and Cobau, 2009), the LIA had an important influence to determine the modern morphology of the Ravenna coastal plain in the northwest Adriatic Sea through changes in the sediment supply equilibrium.

However, the influence of the LIA on the Ravenna coastal plain is poorly constrained so far due the lack of precise chronological data to reconstruct changes in coastal morphology, where all studies were based mainly in qualitative analyzes using photointerpretation or historical charts. Although previous work based on interpretation of aerial pictures and historical charts have been able to define an important framework about the coastal evolution in the Ravenna area during the LIA (Bondesan *et al.*, 1995; Rizzini, 1974; Scarponi *et al.*, 2013; Stefani and Vincenzi, 2005; Veggi and Roncuzzi, 1973; Veggiani, 1973), geochronological data are required to reconstruct the response of the Ravenna coastal system to secular climate changes.

The aim of this work is the comparison between morphological changes in the Ravenna coastal plain and late Holocene climate changes using quartz OSL dating applied to beach ridge sands. This is necessary to define a coastal evolution model for the Ravenna area during the late Holocene and shed light about the response of diverse coastal settings to climate changes projected for the next decades.

The specific aims of this study are: i) the OSL dating of beach ridges in the area where their morphology is preserved to clarify the influence of late Holocene climate changes on the Ravenna Coastal Plain and to increase the chronology resolution and accuracy of its coastal evolution model; ii) test the coastal evolution model proposed by Scarelli *et al.* (2016), which suggests the presence of inland and modern sand barriers separated by a lagoon environment developed during the LIA.

STUDY AREA

The Ravenna coastal plain (Fig. 1) is characterized by low elevation relief, with dune crest between 1.5 to 3 m above medium sea level (MSL) (Regione Emilia-Romagna, 2010), fine and medium sand grain size (Armaroli and Ciavola, 2011), and a microtidal regime, with a neap mean range of 30 – 40 cm and a spring neap mean range of 80 – 90 cm. According Armaroli *et al.* (2012), the beaches have a slow gradient of 0.03° and mean backshore/foreshore width of 70 m, representing very dissipative beaches with surf scaling parameters $-\xi 0 < 0.3$.

The waves have low height, with 91% of the waves measured by the Ravenna port tide gauge having less than 1.95 m height. Dominant waves come from the east and storms are caused by the “Bora wind” from the ENE and the “Scirocco wind” from the SE. The transport of coastal sediments is dominated by prevalent waves from NE generated in the open sea, which are responsible for a main littoral drift from south to north (Gambolati *et al.*, 1998). However, in the north part of the study area, the littoral drift shifts from northward to southward, creating a “zero point” that coincides with the Ravenna port (Gambolati *et al.*, 1998; Preti *et al.*, 2009).

During the late Holocene, the LIA from AD 1450 to AD 1850 (Barlow, 2001; Brázdil *et al.*, 2005; Grove, 2001; Jones and Briffa, 2001; Svensmark, 2000) was responsible for changes in sediment deposition (Brázdil *et al.*, 2005), conditioning the morphology of the Ravenna coast through an increase in the sediment load of Apennines rivers, which driven high progradation rates (101 m/yr) of their deltas (Grove, 2001). Climate changes at the beginning of the 19th century (Fig. 2) triggered delta erosion, shifiting the coastal dynamics from river-dominated deltas to wave-dominated deltas sensus Galloway (1975) (Corregiari *et al.*, 2005). These changes in coastal dynamics combined with the diminution of the sediment supply induced coastal erosion in the Ravenna region (Regione Emilia-Romagna, 2012).

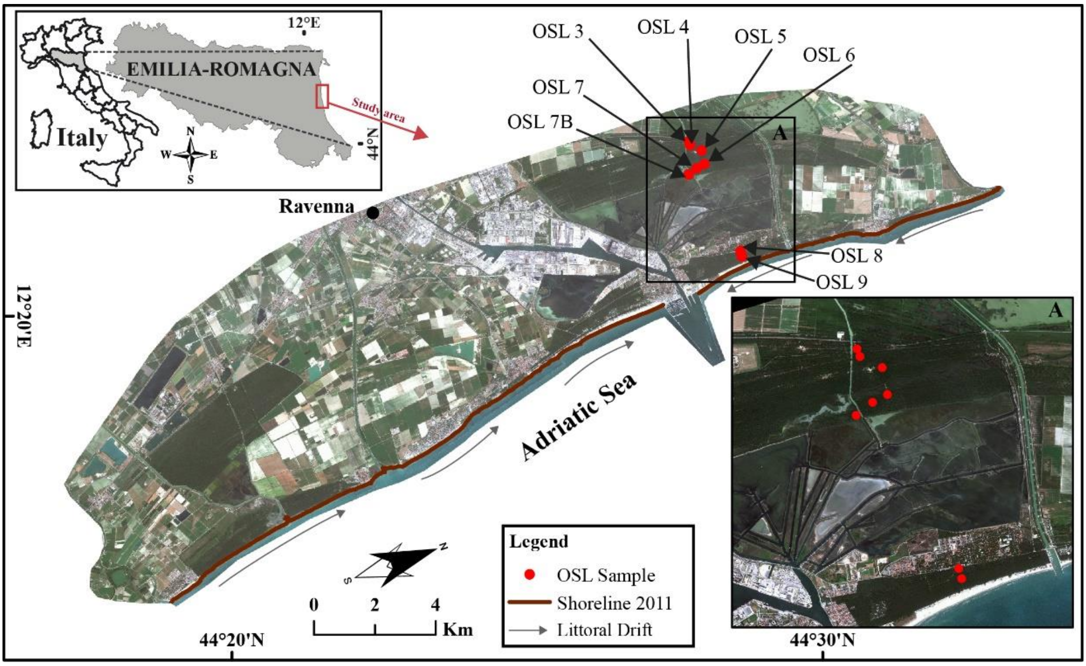

Figure 1. Study area and location of OSL samples. The inset picutre (A) shows the OSL samples location in detail across beach ridges.

The Ravenna coastal plain represents the border of an epicontinental basin developed over a passive continental margin (Ridente and Trincardi, 2005). The north part of the Adriatic Sea extends about 300 km and has a low gradient (0.02° slope) continental shelf (Maselli *et al.*, 2010), with shallow water depth (<50 m) (Bever *et al.*, 2009). The present morphology of the Ravenna coast is the result of a balance between natural coastal dynamics and anthropic changes in the last few centuries, where man-made changes like lagoon and swamp reclamations for agricultural exploitation were fundamental to drive the coastal evolution in this area (Stefani and Vincenzi, 2005).

MATERIAL AND METHODS

Nine sediment samples for OSL dating were collected in the Ravenna Coastal Plain (Fig. 1A). Seven samples were retrieved in beach ridges from the inland sand barrier and two samples were collected in the seaward sand barrier. A trench was performed in each beach ridge and the sand samples were collected at 0.40 m depth using opaque PVC tubes further rolled up in aluminum foil and black plastic bags to protect the samples from light (Fig. 3). The OSL dating procedures were carried out in the Luminescence and Gamma Spectrometry Laboratory (LEGaL) at the Institute of Geosciences of the University of São Paulo.

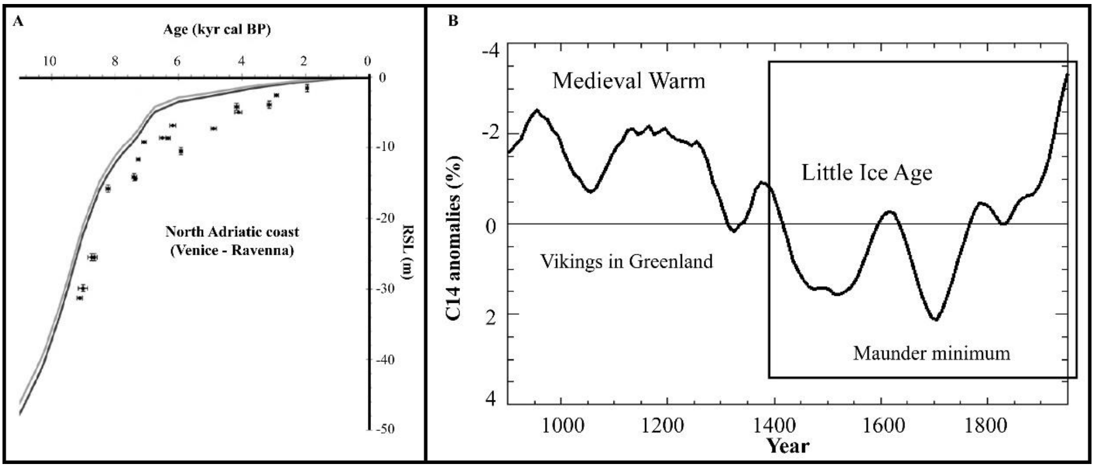

Figure 2. Holocene sea level curve for the North Adriatic Sea (modified from Lambeck *et al.*, 2011). c) Changes in solar activity as indicated by [14]C anomalies and the resulted climate changes (modified from Svensmark, 2000).

Figure 3. Example of choice of ridges (paleo beach ridges) and trench used in sampling of sediments for OSL dating.

The sand samples are dominated by quartz and the estimation of equivalent doses for OSL dating was carried out in quartz aliquots using the Single-Aliquot Regenerative-Dose protocol (SAR) according to Murray and Wintle (2000) and Wintle and Murray (2006). The samples for luminescence measurements were prepared under subdued red light conditions following standard procedures described in (Aitken, 1998). The 180-250 µm grain size fractions were obtained by wet sieving, followed by chemical treatment with H_2O_2 27% and HCl 3.75%, in order to respectively remove organic matter and carbonates. Afterwards, etching with HF 48–51% for 40 min was performed to remove feldspars and outer rinds of quartz grains damaged by alpha particles. Heavy minerals and remaining feldspar grains were removed through a gravity settling in lithium metatungstate solution at densities of 2.75 and 2.62 g/cm3, respectively. OSL measurements were conducted on two Risø TL/OSL DA-20 readers systems equipped with 90Sr/90Y source for beta irradiation (dose rates of 0.075 and 0.109 Gy/s) and blue LEDs (470 nm) for stimulation. The OSL was detected in the UV band using Hoya U-340 filters (290–370 nm). The equivalent dose was determined by linear or exponential fitting of the dose–response data. Only aliquots with recycling ratio between 0.85 and 1.15, recuperation less than 5% and absence of significant infrared signal were used for equivalent dose calculations. A dose recovery test was performed with 5 aliquots of sample OSL 06 using a given dose of 1.05 Gy and pre-heat temperature of 200ºC. The best calculated-to-given dose ratio (1.04 ± 0.20) was achieved by the weighted mean of equivalent doses. Thus, the equivalent dose of each sample corresponded to the weighted mean of at least 20 quartz aliquots.

A high-purity germanium detector (55% of relative efficiency) encased in an ultralow background shield was utilized for estimation of ^{40}K, ^{238}U and ^{232}Th concentrations and determination of radiation dose rates from sediments. The samples were measured after 28 days sealed in plastic containers for radon requilibration. Beta and gamma dose rates were calculated using conversion factors outlined by Guérin *et al.* (2011). Evaluation of cosmic rays dose rate was appraised as a function of latitude, longitude, altitude and depth below surface of the sampling point as described by Prescott and Stephan (1982). Water content for each sample was obtained as a result of differences between the total weight and dry weight after drying the sample in an oven (48 h at 60°C). Error treatment for age calculations follows Aitken (1998).

RESULTS

The equivalent doses, dose rates and OSL ages are shown in Table 1. The dose response curves for all aliquots follow a linear trend (Fig. 4A). The equivalent doses distributions of all dated samples presented relatively low over dispersion (0-35%), suggesting well bleached sediments without post-depositional mixing (Fig. 4B). The OSL ages range from 109 ± 55 to 687 ± 204 years (Table 1) with errors from 8 to 11%, including the period corresponding to the LIA.

Table 1. OSL ages for beach ridges of the Ravenna coastal area. Samples from OSL 03 to OSL 07B were collected in the inland sand barrier while samples OSL 08 and OSL 09 were collected in the seaward sand barrier.

Sample	Longitude	Latitude	Aliquots	^{238}U (ppm)	^{232}Th (ppm)	K (%)	*Cosmic dose rate* (Gy/ka)	*Recycling Ratio* (mean)	Rate Dose (Gy/ka)	Dose (Gy) (Wt Mean)*	*Overdispersion* (%)	Age (years) (Wt Mean)*
OSL 03	12.224563	44.508134	9	5.39 ± 0.19	7.58 ± 0.30	1.52 ± 0.07	0.184 ± 0.015	0.97 ± 0.07	3.44 ± 0.28	2.1 ± 0.7	12.1	610 ± 209
OSL 04	12.226249	44.508203	16	1.71 ± 0.07	7.74 ± 0.30	0.90 ± 0.04	0.183 ± 0.015	1.01 ± 0.07	2.04 ± 0.16	1.4 ± 0.4	8.3	687 ± 204
OSL 05	12.229767	44.510914	6	1.54 ± 0.06	7.50 ± 0.29	0.87 ± 0.04	0.184 ± 0.015	1.03 ± 0.02	1.96 ± 0.16	1.2 ± 0.3	4.3	611± 161
OSL 06	12.235422	44.510491	13	1.05 ± 0.05	4.56 ± 0.20	1.09 ± 0.05	0.186 ± 0.016	1.03 ±0.04	1.76 ± 0.14	1.1 ± 0.2	10.6	624 ± 124
OSL 07	12.236060	44.508021	11	1.23 ± 0.06	4.75 ± 0.22	1.01 ± 0.04	0.183 ± 0.015	1.02 ± 0.05	1.83 ± 0.15	1.0 ± 0.1	8.8	545 ± 71
OSL 07B	12.237661	44.505141	16	1.00 ± 0.05	3.98 ± 0.18	1.04 ± 0.05	0.184 ± 0.015	1.03 ± 0.03	1.75 ± 0.15	0.7 ± 0.1	16.3	399 ± 66
OSL 08	12.274284	44.513050	7	0.93 ± 0.04	3.62 ± 0.17	1.15 ± 0.05	0.186 ± 0.016	0.97 ± 0.05	1.83 ± 0.15	0.2 ± 0.1	5.3	109 ± 55
OSL 09	12.278084	44.512995	11	0.84 ± 0.04	2.80 ± 0.15	1.22 ± 0.05	0.184 ± 0.015	0.99 ± 0.07	1.82 ± 0.16	0.3 ± 0.1	7.8	165 ± 57

Some samples present relatively low natural doses and moderate luminescence sensitivity, which hindered the application a first regeneration dose below the natural dose. Thus, the natural signal was between the signals of the zero dose and the first regeneration dose. However, the linear dose response curves ensured reliable estimation for the natural dose, supporting the discussion assertions about the chronology of beach ridges development in the Ravenna coastal system.

DISCUSSION

The OSL ages obtained for studied beach ridges corroborate the hypothesis that the Ravenna coastal plain developed a sand barrier before the LIA and the actual sand barrier was developed after the LIA as proposed by Scarelli *et al.* (2016).

The beach ridges of the inland barrier (OSL 3 to OSL 7B, Fig. 1) show ages between 687-610 years (OSL 03 and 04) and 399 years ago (OSL 7B) (Table 1). These ages indicate that the beach ridges in the inland sand barrier were shaped during the Medieval Climate Anomaly (MCA) before the LIA, which began at AD 1450. The beach ridges near the shoreline in the seaward sand barrier (OSL 08 and 09) have OSL ages younger than 165 ± 57 years (Table 1), which correspond to a Post LIA sand barrier developed after AD 1850. The Figure 5 shows the OSL ages obtained for the nine sediment samples retrieved from beach ridges in the Ravenna coastal area and their correspondence with the Pre-LIA (MCA), LIA and Post-LIA periods.

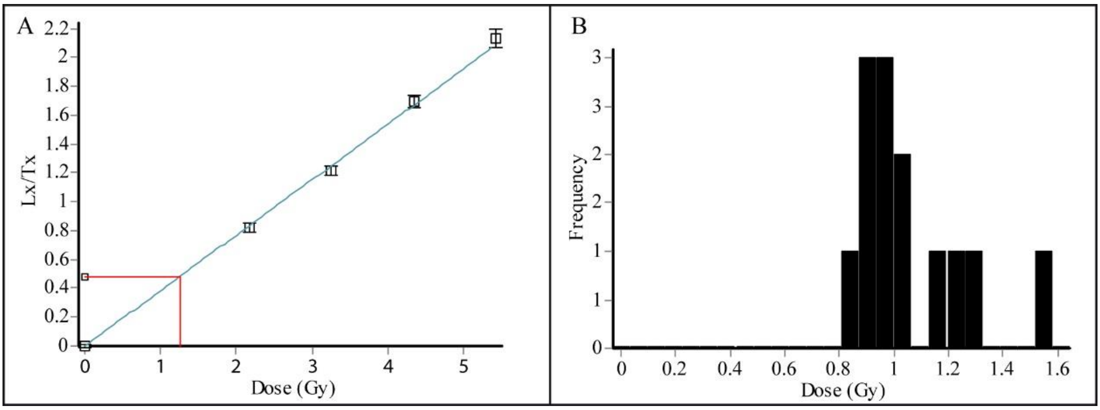

Figure 4. A) Dose response curve for a quartz aliquot of sample OSL 06. B) Equivalent doses distribution for quartz aliquots of sample OSL 06.

The presence of the samples 07 and 07B in the area that correspond with the LIA period (Fig. 5) may be explained due the fact at the beginning of the LIA period about 1450, the Ravenna coastal plain system dynamic passed from a Wave Dominated to a River Dominated coast (Galloway, 1975). The sedimentary deposition in the coast of the inland barrier still occurred, although the most part of the Ravenna coast were reworked by the rivers actions. In the middle of the XIX centuries with a climatic improvement and LIA end's, the coastal system returned to a Wave Dominated dynamic and was when began the actual barrier formation, as well show the ages obtained for samples OSL 08 and 09 (Fig. 5).

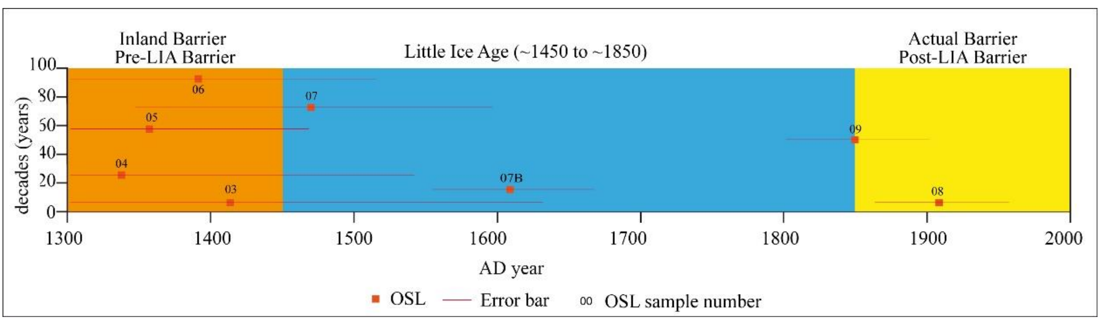

Figure 5. OSL ages representing the formation of beach ridges and their correspondence with climate events of the late Holocene.

The results obtained will be complement the Ravenna coastal evolution model (Fig. 6), which was build integrating the surface and subsurface data but without a chronologic data. In addition, the OSL dating allow to validate the proposal by Scarelli *et al.* (2016), which considered the two sand barriers existent in the Ravenna coastal plain as an inland Pre-LIA barrier and younger Post-LIA barrier (Fig. 6). Despite the relatively high age uncertainties, the OSL ages strongly suggest the shift from a beach ridges system (wave-dominated coast) to a lagoon system during the LIA due increasing influence of fluvial processes in the coastal system.

Despite the relatively high age errors, this work gives an important and unprecedented chronological information about the behavior of the Ravenna coastal plain zone during the late Holocene. For a more precise chronology for changes in the coastal system and calculation of progradation rates of both sand barriers, it is necessary to increase the number of samples collected in each sand barrier and improve luminescence measurements in order to reduce age uncertainties. This would provide a more detailed characterization about shifts in the coastal system under climate and anthropogenic changes in the Ravenna coastal area during the late Holocene.

CONCLUSION

This study obtained the first OSL ages to constrain the evolution of the Ravenna coastal plain during the late Holocene. This chronological dataset provides essential information to reconstruct the local secular coastal evolution. The OSL ages corroborate the hypothesis that the morphological evolution of the Ravenna coastal plain comprised the development of two sand barriers separated by a LIA lagoon system. This work is not only a complement of the previous works about the sand barriers in the Ravenna zone, but it also demonstrates the suitability of quartz from Ravenna sands for OSL dating in the secular timescale. This brings new possibilities to constrain the role of climate and anthropogenic changes for morphological shifts in the Ravenna coastal zone during the last centuries. The results of this study may aid the territorial management, driving the decision-makers mainly in their long period actions inside the Integrated Coastal Zone Management.

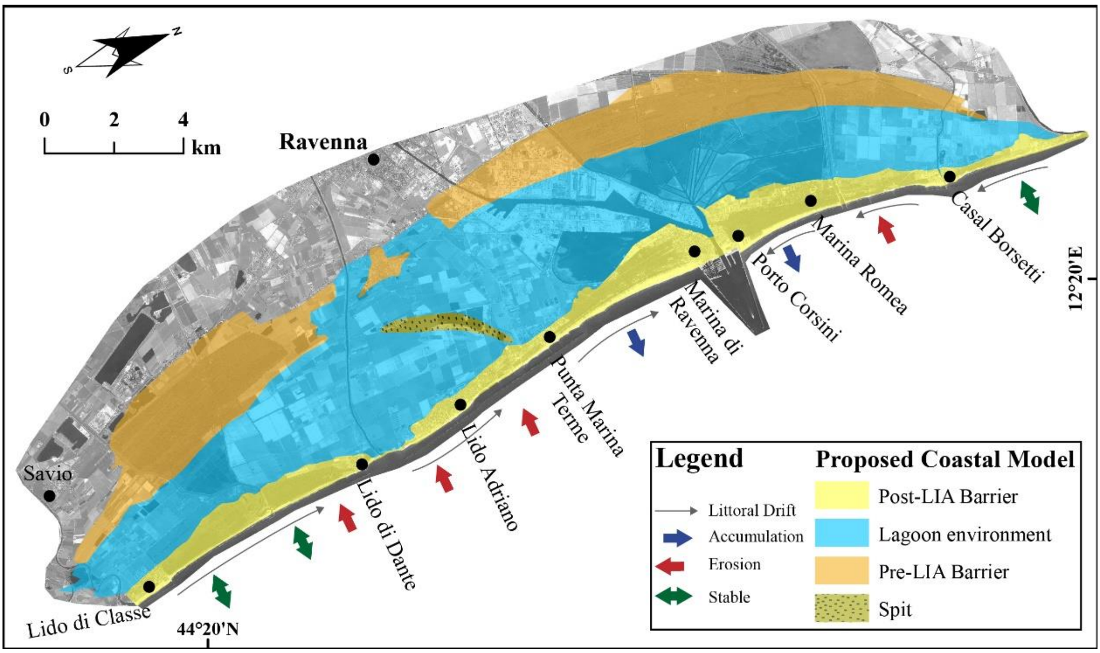

Figure 6. Ravenna coastal plain evolution model proposed by Scarelli *et al.* (2016).

ACKNOWLEDGEMENTS

This research was founded by Fondazione Flaminia (Ravenna, Italy) via the RIGED-Ra project. The work was performed inside the Joint Laboratory of Coastal Evolution and Coastal Management between UFRGS and UNIBO.

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