RELATIVE SEA LEVEL VARIATIONS AT ALEXANDRIA (NILE DELTA, EGYPT) OVER THE LAST MILLENNIA: ARCHAEOLOGICAL IMPLICATIONS FOR THE ANCIENT HARBOUR

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Abstract: *During the 19th century, remains of an ancient harbour were found underwater at a depth of 5 to 6 meters in the eastern port of Alexandria. A research program was undertaken to determine when the harbour of Alexandria submerged underwater. Data were collected through underwater surveys by scuba diving and by campaigns of corings on land. Geomorphological (i.e. notches and pebble beaches), archaeological (harbour structures), and biological (i.e. marine macrofauna, bioconstructions, and biodepositions) sea level indicators were correlated to understand changes in relative sea level during the last 6 millennia. For each proxy, the altitudinal (vertical) and chronological ranges of imprecision were discussed. The results indicate that the rate of the relative sea level rise is ~80 mm per century between the middle of the 6th millennium and the 5th–6th c. AD. An abrupt relative sea level rise (3.5 m + 1.5 m) occurred during the mid 8th c. to the end of 9th c. AD. In the 8th c. AD, a similar phenomenon was observed for Heracleion (25 km east of Alexandria). Thus, a wide movement of sinking affected in a synchronous manner the western coastal margin of the Nile delta. Since this 8th-9th c. AD event, the subsidence has increased around 2 m. The role of abrupt sinking events and subsidence remain determining in the deltaic context to anticipate future coastal adaptations and the risk of submersion.*

Key words: *sea level; Holocene; subsidence; collapse; geoarchaeology; Mediterranean; ancient harbour; ancient city, risk; Alexandria; Nile delta, Egypt*

Introduction

Fluctuations of the sea level are induced by melting ice and eustatic or/and tectonic factors (Flemming 1969; Waelbroek *et al.* 2002; Lambeck *et al.* 2004a; Pirazzoli 2005). Their understanding is essential for determining former sea level changes during ancient times, on the basis of different sea level indicators. Geomorphological (Pirazzoli 1996; Kershaw and Guo 2001), archaeological (Schmiedt 1972; Pirazzoli 1976, Caputo and Pieri 1976; Rovere *et al.* 2011), and biological (Laborel and Laborel-Deguen 1996; Stirling and Andersen 2009; Pirazzoli and Thommeret 1973; Morhange 1994; Morhange *et al.* 2001, Goiran *et al.* 2009) proxies provide sources of information for relative sea level in historic times, especially for low tidal range areas such as the Eastern Mediterranean. Correlating these proxies helps to establish a precise relative sea level curve in Alexandria (Egypt) that can be compared with previous sea level reconstructions in the Eastern Mediterranean, summarised by Brückner *et al.* (2010).

Alexandria was founded in 331 BC by Alexander the Great on the western edge of the Nile delta. The ancient city was established on an outcrop of a sandstone substratum dating to the Pleistocene. Over the last ten years important archaeological vestiges have been discovered underwater near the location of the ancient lighthouse, where the fort of Qaît Bey was built in the 15th century (Empereur 2000). The underwater excavations have revealed a jumble of more than 2500 ancient stone blocks situated between 6 and 8 m below the present sea level. In the eastern bay of Alexandria, late Roman port structures lie underwater at a depth between 5 and 6 m (Mahmoud-Bey 1872; Goddio *et al.* 1998; 2006). This discovery raises fundamental questions: first, how to characterise this sea level change; was it continuous or did it occur by successive steps, second, when did it happen, third, was it a homogeneous phenomenon at the scale of the harbour, and fourth, what were

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its causes? To answer these questions, a research programme on relative variations in sea level was undertaken. A double approach was pursued. First, underwater surveys by aqualung diving were carried out. The objective was to find, on the hard substratum, evidence for previous Holocene sea levels. Second, an onshore coring campaign was led. The aim was not only to determine and date

Fig. 1 Location map

by radiocarbon the different facies of the fossil beach, but also to compare the present biological sea level with the Holocene's sea level curve, defined by the upper limit of the barnacles present on the quays of the eastern harbour of Alexandria. Knowledge on changes in sea level and on paleodepths enabled to characterise the subsidence of the western edge of the Nile Delta. The importance of this event, combined with the sea level rise, should lead to a reflexion concerning a future adaptation of the coast in anticipation of the risk of submersion.

1. Material and methods

1.1 Geomorphological indicators

At about –6.5 m (Goddio 1998), notches from erosion were discovered in the Pleistocene sandstone substratum (Fig. 1). They were interpreted to be of mediolittoral origin (Goddio *et al.* 1998). The mediolittoral stage corresponds to the tidal range (40 cm at the site of Alexandria) and the play of the waves. But two elements must be taken into account: (i) these notches could have been generated in the infralittoral stage by an abrasion related to strong currents that mobilised sandy banks having strong erosive power. The infralittoral stage is permanently submerged and its lower edge corresponds to the depth of light penetration. (ii) Although these notches are considered to be mediolittoral, they correspond to a form of erosion and are thus difficult to date (Evelpidou and Pirazzoli 2014 ; Marriner *et al.* 2014). As a consequence, these notches can reveal an ancient sea level or an ancient sea bottom. Gathered with other indicators, their morphogenesis can be linked to the right hypothesis.

1.2 Bioconstructions

Bioconstructions of *Cladocora* are used as a proxy to measure the lower index on the relative sea level curve. No upper mediolittoral or infralittoral bioconstruction was discovered in the underwater zone as the substratum is very soft and does not allow corals to attach themselves onto it. However, many colonies of *Cladocora caespitose* were discovered in the infralittoral zone. These are cemented fossil reefs from which some samples were taken. *Cladocora* populations constitute bioherms *in situ* and provide bathymetric information, although with a large margin of imprecision (Peirano *et al.* 1994; Laborel 1961, Laborel *et al.* 1978). Bioherms are fossilised remains of corals forming a carbonate rock formation. Thus, *Cladocora* serves as a chronological marker for measuring sea levels (Fig. 2). It enables the establishment of the lower limit of the relative sea level curve. For each dated reef, the sea level is always situated above its present bathymetric position. The validity of the radiocarbon dating was reinforced by X-ray analysis of the *Cladocora* branches' skeletons which are composed of 99 % aragonite. This implies a rapid *post mortem* fossilisation and averts the problems of neogenesis which are likely to disturb the coral system and falsify the radiochronological measurements (Table 1).

1.3 Macrofaunal indicators

The methodology focused on the comparison between ancient fossil macrofaunal assemblages with present assemblages to estimate the ancient water column. This indicator is based on the work of Péres (1961), Péres and Picard (1964), Bellan-Santini *et al.* (1994), Morhange (1994), Bernasconi M.-P. and Stanley D.J. (1994) on the biocenosis populations in present ecosystems in the Mediterranean.

From the top of the infralittoral zone to about a depth of 2.5 m to 3 m, the Fine Sands in Shallow Waters (FSSW) biocenosis develops. Fine Sands in Shallow Waters (FSSW) constitut the 'upper beach'; it relates to large beaches of submerged fine sand (Goiran et al. 2015). The presence of this biocenosis indicates the proximity of a shore with about 3 m of margin of imprecision (Fig. 2). Thus, it is possible to obtain an approximate paleo-depth by comparing the paleo-biocenosis sampled in the cores with present-day biocenosis in the Mediterranean.

1.4 Granulometric indicators

Facies containing rolled pebbles were identified in the cores. These pebbles came from the transport of anthropogenic waste material (pottery sherds, elements of construction). In the eastern bay, the only process that could have transported and shaped these pebbles is the surf zone.

These rolled pebbles tend to be well-preserved and reveal the position of an ancient shoreline (Rokoengen *et al.* 1982; Forbes *et al.* 1991). The pebbles of discoidal shape accumulated higher on the beach than the spherical pebbles. Likewise, the

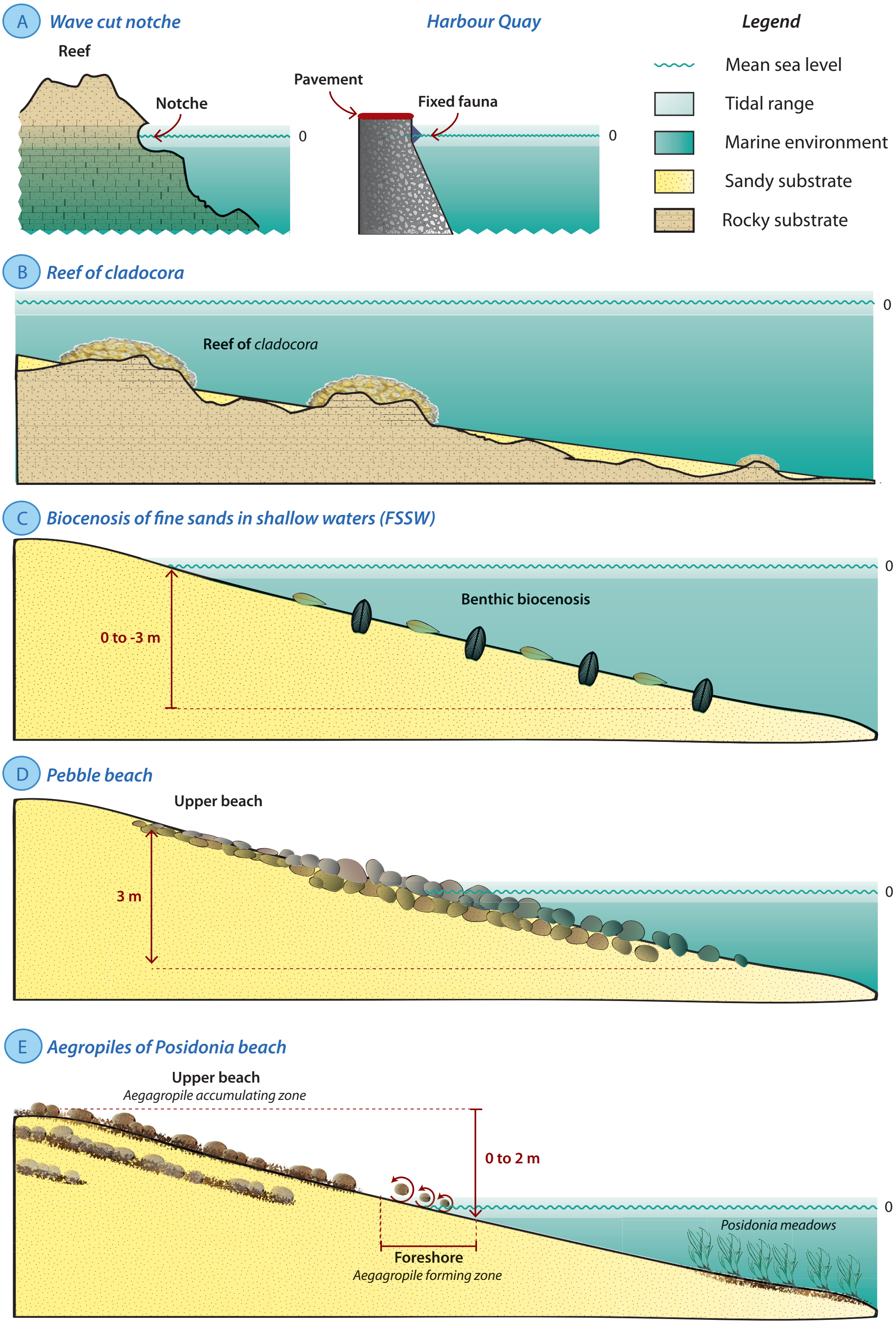

Fig. 2 Methodological presentation of the sea level variation indicators

Ref on the diagram	Samples	RSL indicator	Nature of the sample	Radiocarbon laboratory code	Depth below present biological sea level (barnacles) in cm	Radio-carbon age in years BP	Calibrated age AD/BC (interval after correction with the marine curve) 2013	Calibrated age BP (interval after correction with the marine curve) 2013	Calibrated age AD/BC (interval after correction with the terrestrial curve) 2013	Calibrated age BP (interval after correction with the terrestrial curve) 2013	Archaeo-logical dating
1	IX 28	marine bottom	cladocora	Ly-10617	-750	[5485 ± 50]	cal BC 4028–3779	cal BP 5728–5977			
2	II 25	marine bottom	cladocora	Ly-8870	-730	[5360 ± 55]	cal BC 3919–3652	cal BP 5601–5868			
3	XI 27	marine bottom	marine shell	Poz-1640	-700	[4625 ± 40]	cal BC 3021–2821	cal BP 4770–4970			
4	II 20	marine bottom	cladocora	Ly-10570	-690	[4640 ± 50]	cal BC 3077–2822	cal BP 4771–5026			
5	XI 24	marine bottom	marine shell	Poz-1638	-620	[4430 ± 45]	cal BC 2830–2521	cal BP 4470–4779			
6	II 18	marine bottom	cladocora	Ly-8871	-615	[4195 ± 50]	cal BC 2471–2180	cal BP 4129 - 4420			
7	XI 23	marine bottom	marine shell	Ly-1366 (OxA)	-590	[3890 ± 50]	cal BC 2059- 1745	cal BP 3694–4008			
8	II 17	marine bottom	marine shell	Ly-10569	-560	[2085 ± 45]	cal AD 161–408	cal BP 1543–1789			
9	IV 28	marine bottom	marine shell	Poz-1636	-550	[2305 ± 35]	cal BC 70 - cal AD 132	cal BP 1819–2019			
10	IX 19	marine bottom	marine shell	Ly-15386	-550	[1925 ± 40]	cal AD 375–589	cal BP 1361–1575			
11	I 8	pebble beach	pebble beach	-	-540	-	-	-			Vth-VIth AD
12	XI 21	marine bottom	marine shell	Poz-1637	-540	[3665 ± 40]	cal BC 1735–1505	cal BP 3454–3684			
14	II 16	marine bottom	marine shell	Poz-1643	-510	[2065 ± 40]	cal AD 198–422	cal BP 1528–1752			
Quay	Quay	harbour struture	archaeology	-	-500	-	-	-			Vth- VIth AD
15	XI 18	marine bottom	marine shell	Poz-1658	-490	[2150 ± 35]	cal AD 107–325	cal BP 1626–1843			
16	II 15	marine bottom	marine shell	Ly-10567	-480	[1935 ± 55]	cal AD 331–608	cal BP 1342–1619			
17	V 17–18	aegagropiles	charcoal	Ly-10737	-460	[1330 ± 35]	-	-	cal AD 646–769	cal BP 1182–1305	
19	II 14	marine bottom	marine shell	Ly-1305 (OxA)	-450	[1845 ± 45]	cal AD 446–657	cal BP 1294–1505			
20	II 13	marine bottom	marine shell	Ly-1465(Gro-18284)	-420	[1890 ± 45]	cal AD 409–625	cal BP 1326–1541			
21	II 9	marine bottom	marine shell	Ly-8873	-270	[1720 ± 45]	cal AD 589–774	cal BP 1177 - 1361			
22	II 8 G	pebble beach	pebble beach	-	-200	Relative : between [1635 ± 35 BP] and [1720 ± 45 BP]					
23	II 8 S	macrofauna (SFHN)	marine shell	Ly-1522	-200	[1635 ± 35]	cal AD 672–842	cal BP 1108–1278			
24	II 7	macrofauna (SFHN)	marine shell	Ly-1521	-180	[1530 ± 35]	cal AD 773- 975	cal BP 975–1178			
25	V 9–11	aegagropiles	marine plant	Ly-10736	-170	[1175 ± 30]	cal AD 1167–1295	cal BP 656–784			
Notche 1	-	Sea level	notche	-	-670	Relative : before 2850 BP					
Notche 2	-	Sea level	notche	-	-680	Relative : before 2850 BP					
Cladocora 1	Alex 8	Marine bottom	cladocora	Ly-10564	-1400	[5625 ± 40]	cal BC 4204–3967	cal BP 5916–6153			
Cladocora 2	Alex 16	Marine bottom	cladocora	Ly-10566	-1600	[2140 ± 50]	cal AD 92–360	cal BP 1859–1591			
Cladocora 3	Alex 22	Marine bottom	cladocora	Ly-10565	-900	[5650 ± 75]	cal BC 4277–3944	cal BP 6226–5893			

Table 1 Radiocarbon dates

return current dragged preferentially by gravity the more spherical pebbles onto the upper part of the underwater beach (Carter and Orford 1993; Vella 1999). The pebbles sampled by cores are quasi-spherical and their shape varies between 1 and 8 cm. Therefore, correlating these characteristics with the biocenotic assemblage of the fine sands from the upper levels reveals mediolittoral or upper infralittoral deposits (Goiran 2001). The geographical context of a relatively closed bay, as at Alexandria, limits the altitudinal extension of the pebbles, as pebble beaches are reflective and have a strong slope with a limited surf zone (Sherman *et al.* 1993; Carter and Orford 1993; Anthony 1991).

Consequently, although this is debated, it is possible to establish an uncertainty range (Fig. 2) for the altitudinal extension of these mediolittoral pebble beaches of ±1.5 m (Vella 1999; Vella and Provansal 2000; Goiran *et al.* 2000).

1.5 Biodepositions

Egagropili are balls of fibrous material from the foliage of Posidonia seagrass which are fashioned by the back and forth movement of the waves in the surf zone when the leaves are shed from these plants on the seabed (Boudouresque and Jeudy de Grissac, 1983; Jeudy de Grissac A. and Bouderesque C. F. 1985; Kelletat 1997; Pergent and Pergent-Martini 1988). These *egagropili* often accumulate at the high part of beaches during storm episodes (Schulke 1974). Sometimes these *egagropili* are covered and fossilised by accumulations of sand on the beach. In this case, the *egagropili* are an indicator of the proximity of a shore with an imprecision range of 2 m (Fig. 2) related to the highest storm surges measured at Alexandria (El-Fishawi N.M. and Khafagy A.A. 1991).

1.6 Archaeological indicators

In addition to the natural indicators of sea level changes, anthropological indicators were used, namely archaeological indicators. In the eastern bay, which corresponds to the ancient Magnus Portus described by Strabo (Yoyotte *et al.* 1997), the ancient harbour structures are 6 m underwater. They were discovered by Mahmoud Bey (1872). More recently, a team of divers has established a cartography of these archaeological interface structures, and Yoyotte has dated them to the late Roman period (Goddio *et al.* 1998; de Graauw 2000; Empereur 2000; Mostafa *et al.* 2000). An important aspect of these quays concerns their upper facing which is still in place and perfectly preserved (Goddio 1998; 2006). This observation points to two elements: (i) they became rapidly submerged, otherwise the surf zone (mediolittoral) would have abraded this fragile facing. (ii) Concerning the relative variations in sea level, the preservation of this top course indicates that it was definitely situated below sea level and was not eroded by wave action. These harbour structures thus provide a fundamental chronological and bathymetric marker for the mobility of the shore. The maximal altimetry imprecision for this type of structure is estimated to be + 1 m (Fig. 2).

1.7 Radiocarbon dating and margins of imprecision

Previous indicators only allow to estimate ancient sea levels and consequently the periods of intense relative sea level change. Radiocarbon dating permit to date (Reimer *et al.* 2013) these indicators. To refine the results of the radiocarbon analyses and to be able to compare them with other series of dates of coastal sites in the Mediterranean and the Delta (Goodfriend and Stanley 1996), a project to measure the age of the seawater at Alexandria was carried out in order to take into account the problem of the local reservoir effect. “The reservoir effect” of 400 years of seawater is not ubiquitous (Stuiver and Braziunas 1993). The contents in ^{14}C are modified by local parameters, because of contributions of older or younger carbonates (upwelling, changes in the currents, etc.). The measurement of the reservoir age of the surface waters of the Mediterranean Sea remains incomplete (Siani *et al.* 2001). The Museum National d’Histoire Naturelle in Paris provided a sample of *Muricopsis Truncle* collected at Alexandria in 1928. The sampling date would have been before the atomic age. The “reservoir effect” of the seawater (370 ± 40 years) is very close to the standard 400 years.

1.8 Tidal gauges along the Nile delta coastline: the monthly range and the rate over several years of sea level variation

The maximum tidal range at Alexandria is 30 cm and the minimum range is 4 cm. The average for one year is about 20 cm. These data were obtained for a one-year period (1976) from the tidal gauge

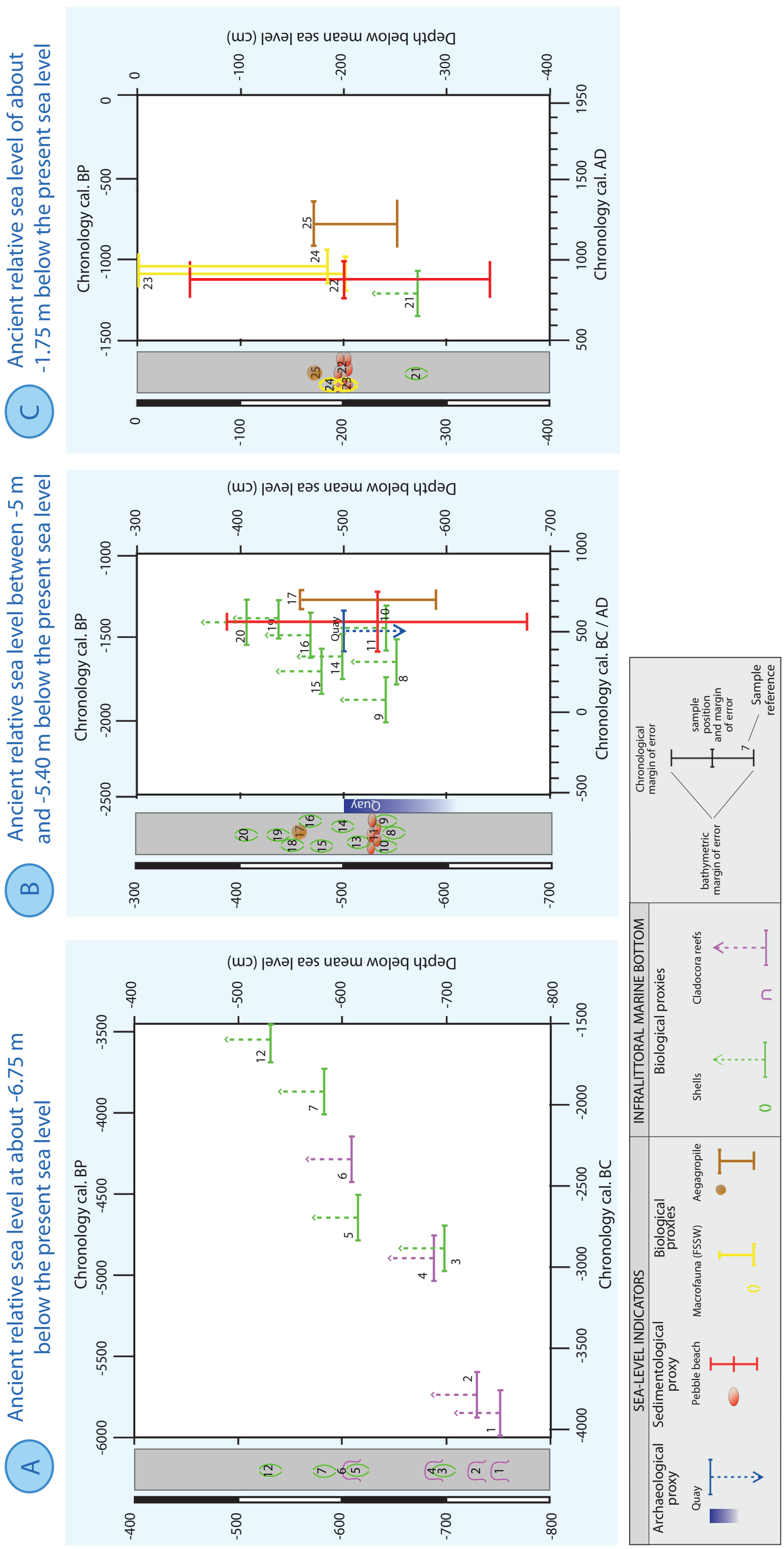

Fig. 3 Results of the sea level variation through time

located in the inner part of the western harbour. For an 11-year period (1956–1966) the mean tidal range was recorded at about 20 cm (El-Din 1997). The monthly range of the sea level during the year is small, seldom exceeding 35 cm, and when averaged for many years (1962 to 1976) is less than 20 cm.

2. Results

The dates for the indicators of the ancient sea levels and the ancient sea beds (marine bottoms) are divided into three groups. The first period lies between the 4th millennium and the 5th century BC and corresponds to indicators situated more than 5.4 m deep. The second corresponds to indicators dating to between the 5th century BC and the 8th century AD, situated between –5.60 m and –4.20 m. The third and last group corresponds to indicators dating from the 8th century AD to the 13th century AD, its depth is above –2.70 m.

2.1 The indicators for sea level dating from the 4th millennium to the 5th century BC, the depth for which is below –5.40 m.

This period is characterised by a total of 10 biological indicators: six of them correspond to *Cladocora* and four to marine shells of the infralittoral zone (Fig. 3a). According to their respective ages, these two types of markers indicate that the sea level was higher and provide the lower limit of the relative sea level curve. Two samples of *Cladocora* (references Alex 8 and Alex 22) were collected from reefs *in situ*. They are situated in the northern part of the eastern harbour (Fig. 1), at –14 m and –9 m respectively below the present sea level and are radiocarbon dated to 4200–3960 cal. BC and 4280–3930 cal. BC. At this time, the sea level was located below –9 m. Because of their great depth, these two samples do not appear in the graph presenting the results. Four other samples of *Cladocora* were found, in the form of broken branches, in the cores (C IX 28, C II 25, C II 20 and C II 18); (figure 1). These samples are located at –7.50 m, –7.30 m, –6.90 m and –6.15 m. They are radiocarbon dated to 4028–3779 cal. BC, 3918–3652 cal. BC, 3075–2821 cal. BC and 2470–2180 cal. BC. They indicate that the sea level lay above –7.50 m at the beginning of the 4th millennium BC and above –6.15 during the first half of the 3rd millennium. The last four samples, from core C XI (XI 27, XI 24, XI 23, XI 21), situated southwest of the *tombolo* (Fig. 1), are marine shells from the infralittoral zone. They lie at –7 m, –6.2 m, –5.90 m and 5.40 m and are radiocarbon dated to 3020–2821 cal. BC, 2829–2519 cal. BC, 2058–1744 cal. BC and 1734–1504 cal. BC. They confirm the general tendency that shows an accretion of the marine bottoms. Thus, at about 1500 BC, the relative sea level was situated above the depth of –5.40 m in relation to the present sea level (Fig. 3a).

2.2 The indicators of sea level dating to between the 4th c. BC and the 8th c. AD whose depth lies between –5.60 m and –4.20 m.

11 points enable tracing of this period, which covers almost all the 1st millennium AD; three of these points are indicators of the sea-level, while the others correspond to marine bottoms (Fig. 3b). A first indicator, sedimentological, was identified as an ancient pebble beach (I-8) positioned at –5.4 m (± 1.5 m). Pottery sherds enabled dating of this ancient sea level to the 5th–6th century AD. In this period, the relative sea level would have been situated between –6.90 m and –3.90 m below the present sea level. A second indicator, archaeological, corresponds to the ancient harbour structures that date to the end of the Roman period, to the 5th–6th century AD (Yoyote, in Goddio 1998). The presence of quays situated at –5 m beneath the present sea level, with a top facing still *in situ* and perfectly preserved, suggests that they became rapidly covered by water, otherwise the surf zone would have abraded this fragile facing. The sea level was thus situated below the top part of the quays, below –5 m. A third indicator, biological, corresponds to *egagropili*. These were found in core CV (V 17–18) (Fig. 1). They were situated at –4.6 m below the present sea level (bpsl) and were dated by radiocarbon to 650–775 cal. AD (Table 1). These *egagropili* indicate the presence of a sea level located below their stratigraphical position (that is, –4.6 m below the present sea level) between the middle of the 7th century and the middle of the 8th century AD. These three indicators reveal the presence of one to three ancient sea levels. The first was situated between –6.90 m and –3.90 m, the second below the top of the breakwater, that is, below –5 m, and the third –4.6 m bpsl. The nine other measurements correspond to shells *in situ* (absence of blunting, bivalves in contact), dated on infralittoral sea beds. These samples, CII 17, CIV 28, CIX 19, CII 16, CXI 18, CII 15, CII 14 and CII 13, provide less precise indica-

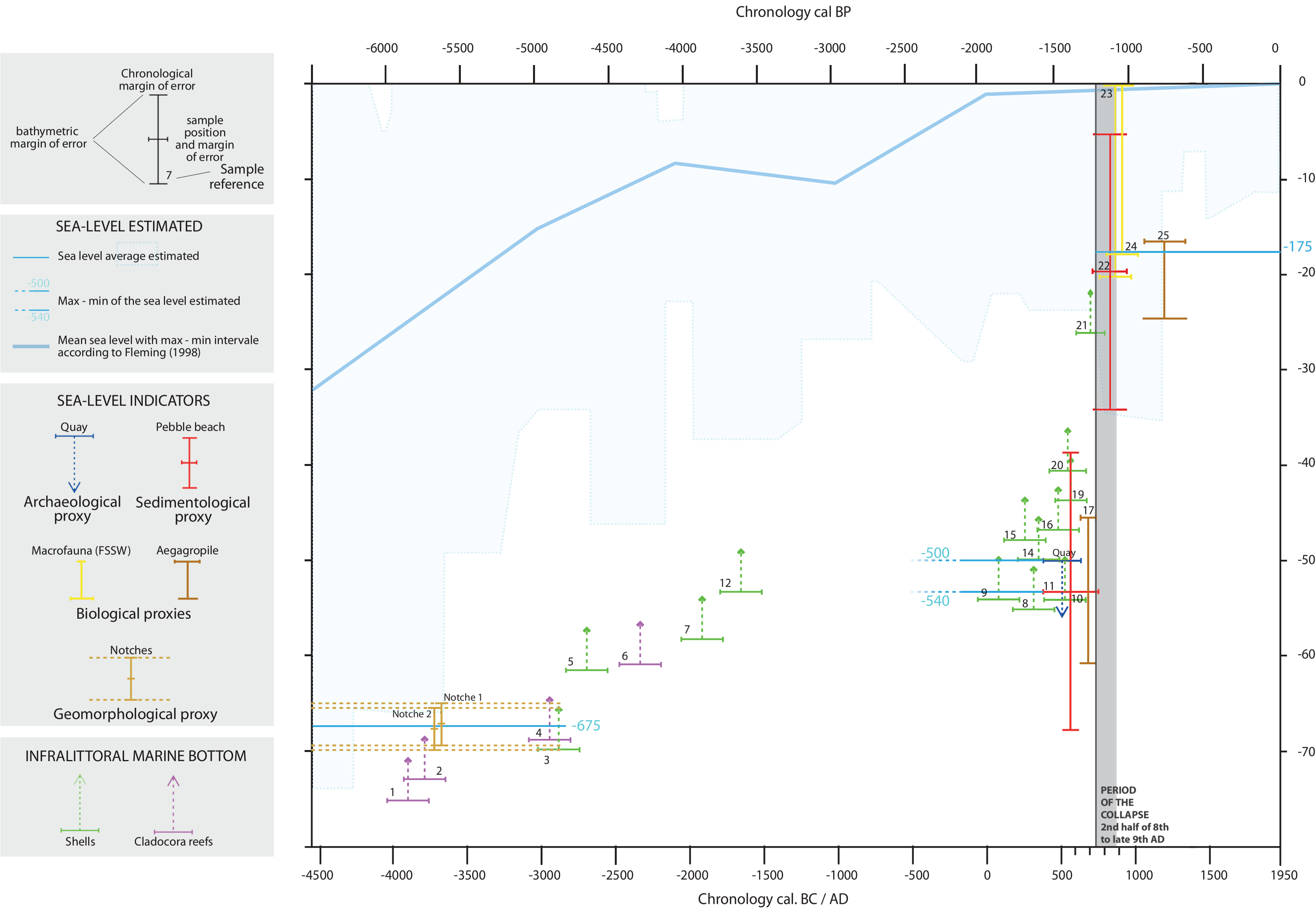

Fig. 4 Age versus depth: relative sea level rise and collapse of the ancient harbours of Alexandria

tions in bathymetric terms as they can only tell us that the sea was present above the depth and the age of the respective samples. They are dated to 161–412 AD cal., –69 cal. BC, 132 cal. AD, 374–589 cal. AD, 198–426 cal. AD, 106–321 cal. AD, 327–609 cal. AD, 449–65 cal. AD and 410–628 cal. AD (Table 1). These shells suggest the presence of a sea level above –5.50 m, dated by radiocarbon between the 2nd and the 5th centuries AD (CII 17) (Fig. 3b).

2.3 Indicators dated to the 8th–13th century AD, above –2.70 m

For this period, five measurements, II 7, II 8 G, II 8 S, II 9, V 9–11, were obtained from two cores, CII and CV. Three types of indicators for sea level were combined (Fig. 3c). A sedimentological indicator, marked by a pebble beach, is presented in core CII at about -2 m (± 1.5 m) bpsl. This sample, CII 8 G, is dated in a relative way by two other samples, CII 9, situated at –2.70 m and dated to 591–777 cal. AD, and CII 8 S, situated at –2 m and dated to 674–843 cal. AD. It is thus deduced that this pebble beach was in place between the end of the 6th century AD and the middle of the 9th century AD. In this period, the relative sea level was situated -2 m (±1.5 m) bpsl. Two levels in core CII (II 8S and II 7) present a biological indicator for the relative sea level, characterised by abundant biocenosis related to Fine Sands of High Levels (FSSW). These two samples are positioned at about –2 m for II 8S and about –1.80 m for C II 7. They are dated by radiocarbon to 1635 ± 35 BP, that is, 674 to 843 cal. AD, and to 1530 ± 35 BP, that is, 773 to 977 cal. AD, respectively. FSSW biocenosis develop between 0 and –3 m bpsl, thus these two samples reveal that the sea level was situated above them, between –2 m and the present sea level and between –1.80 m and the present sea level. A mass of *egagropili* was found in core CV. It indicates a fossil high edge of beach at about –1.70 m for CV 9–11, radiocarbon dated to between 1167 and 1294 cal. AD. Finally, the last sample, CII 9, corresponds to marine biocenosis in place that lived on a sea bed situated at –2.70 m bpsl and radiocarbon dated to between 591 and 777 cal. AD.

3. Discussions

The compilation of all the age/depth points on the graph (Fig. 4) presents a concave shape. This indicates an abrupt rise in relative sea level during the second part of the 1st millennium AD. Three successive positions of ancient sea levels have been identified.

3.1 A relative sea level before 4800 BP at about –6.75 m bpsl

The three samples of *Cladocora,* 1, 2, and 4, were collected on underwater reefs in place from positions at about –7.50 m, –7.30 m and –6.90 m respectively. They are all dated to the beginning of the 4th millennium BC. They correspond to a biological indicator on the sea bed resting on a hard substratum and indicate that the sea level in this period was above –6.90 m. Sample 3 corresponds to shells on a soft seabed dated to 3021 to 2821 cal. BC (4970 to 4770 cal. BP) which converges with the observations made on the *Cladocora*. In the same depth range, about –6.7 m and –6.8 m, two notches of marine erosion were discovered by the team of F. Goddio (2006) on the reefs, submerged today, which are situated in the eastern harbour (Fig. 1). They are thought to be of mediolittoral origin. The combination of these dated biological indicators and these forms of mediolittoral erosion enable identification of an ancient relative sea level at about –6.7 m/–6.8 m at the beginning of the 4th millennium BC (Fig. 4). However, as said in part 1, we cannot affirm that the notches have a mediolittoral origin. As a consequence, they could reveal an ancient sea bed prior to the 3rd millennium BC.

3.2 An ancient relative sea level between –5 m and –5.40 m bpsl

All eight samples of sea shells characteristic of an infralittoral sea bed were taken in cores CII, CXI, CIV and CIX. These cores were all drilled near the *tombolo* (Fig. 1). In the graph, the samples are densely represented for the period between the 2nd century BC and the 7th century AD, and are distributed between –5.60 and –4.20 m, which shows the strong sedimentation that occurred throughout this period. These *in situ* biocenosis confirms that the sea level was situated above each of them. Therefore, they are not accurate proxies to measure ancient sea levels. However, three pieces of evidence have enabled an estimation of the position of the upper envelope curve of the water body in this period. (i) The top facing of wharves dated to the 5th–6th century AD is perfectly preserved and is situated at –5 m bpsl. This is a solid archaeological indicator that provides confirmation that the sea level was situated below –5 m. (ii) The pebble beach positioned at –5.40 m (±1,5 m) and dated to the 5th–6th century AD indicates a sea level which is in accordance with the levels of the wharves. (iii) The mass of *egagropili* from the top of the beach, situated at –4.60 m, indicates that the relative sea level was situated below its position, between –4.60 m and –6.10 m. (iv) An infralittoral marine bed (sample 12, shells) indicates a sea level above –5.4 m, at about 1734–1504 cal. BC. From these four observations, we can infer the presence of a relative sea level of between –5 m and –5.4 m in the 5th–6th century AD. Subsequently, the infralittoral sea beds (data 15, 16, 19 and 20 in Fig. 4) appear to show the beginning of a rapid rise of the relative sea level. In fact, the data clearly indicate a sea level above the top facing of the quays during the 5th–7th centuries AD. It is, however, impossible in the present state of our knowledge to estimate its precise position in relation to the present sea level. This is important archaeological evidence as it shows a rapid immersion of the harbour structures, in the 7th century AD at the latest.

3.3 A relative sea level of about –1.75 m bpsl dated to between the middle of the 8th century AD and the end of the 13th century AD

Concerning the latest scatter plots, the pebble beach (sample 22) indicates an ancient sea level at about –2 m (±1,5 m) which is dated between the end of the 6th century AD and the middle of the 9th century AD. Four other samples are within this range (21, 23, 24, 25). They are dated between the end of the 6th century AD and the end of the 13th century AD. The dates are mostly concentrated in the 8th century AD. Sample 21, which corresponds to an infralittoral sea bed, is positioned at –2.70 m bpsl and thus indicates that its contemporary sea level was above –2.70 m. Samples 23 and 24, characteristic of the FSSW fauna (0–3 m), show that the relative sea level was definitely above –2 m and –1.80 m during this period. Finally, sample 25, consisting of *egagropili*, enables the definition of the upper envelope curve of the sea level in this period, at about –1.70 m bpsl. The combination of these data in terms of age and depth enables an estimation of a relative sea level of about –1.75 m for the period between the middle of the 8th century AD and at least the end of the 13th century.

3.4 Possible explanations for the change of the three ancient relative sea levels

Figs. 3 and 4 allow to distinguish at least three ancient relative sea levels as shown above. The relative sea level has risen 6.75 m during the last 5 to 6 millenniums. These sudden (centuries) and high changes (metres) in relative sea levels can be explained by a consistent seismic activity of the delta and a compaction of sediments, particularly clay sediments (Stanley 1997, 2005; Stanley and Pablo 2014; Pirazzoli *et al.* 1996; Ambrasseys *et al.* 1994; Guidoboni *et al.* 1994). Furthermore, it is possible to identify a sudden subsidence around the second half of the 8th to 9th centuries AD. This huge vertical land motion contrasts with the progressive relative sea level rise which took place between the 4th millennium BC and the first half of the 1st millennium AD.

3.5 Comparisons

When the entire age/depth graph is considered, the overall shape of the sea level curve takes a concave form opposite to the Fleming's (1998). If the second half of the 1st millennium AD is considered, we observe that the relative sea level rise was about 4 m (±1 m) between the middle of 8th century AD and the end of 9th century AD. This is the first time that a date has been provided for this major phenomenon of evolution in landscapes at Alexandria. This abrupt relative sea level rise at Alexandria is characterised in the sediments by infralittoral sandy bodies that covered the mediolittoral beaches with pebbles (Goiran 2001). The preservation of these beach facies (pebbles, *egagropili*), the good condition of the ancient quays and their facing (upper pavement) point to a rapid immersion in water, otherwise the waves and the surf zone would have destroyed the facing to a large extent. Recently, in Alexandria, archaeologist and historian showed a modification of the freshwater supplies and storages from the 10th century AD (Hairy and Sennoune 2006), probably marking a subsidence of the area causing an entering of sea water in the Alexandrian channel. Such events, like huge collapses due to coseismal subsidence (Long and Shennman 1994), and seismic uplifts (Morhange *et al.* 2006) have already been analysed for the Eastern Mediterranean Sea, but are older and occurred during the early Byzantine period (Pirrazoli *et al.* 1996; Kelletat 1991). On the scale of the Nile Delta, the relative sea level variations depend on several factors such as "seismicity, vertical land motion, effects of sediment compaction and remobilization, including liquefaction, affecting the substrate underlying human-built structures" (Stanley 1988; 1997; 2005; Stanley and Pablo 2014; Said 1993; Frihy 1992). A general shift affected the northern coastal section of the delta and became accentuated towards the east in the region of Manzala. There the strongest rate of subsidence in the delta occurred, with more than 4 mm per year (Warne and Stanley 1993). The bedrock in this region possesses a dense network of faults (Said, 1990). Thus, although the thickness of the Holocene sequence in the west of the delta is nearly 10 metres, these deposits are 50 m thick in the east of the delta. This lateral variation in thickness of the deposits is partly explained by compaction, but especially by the presence of active faults and many flexures which are active at river mouths. Added to this is the isostatic adjustment due to the thickening of the Pleistocene and Holocene sedimentary deposits (Warne and Stanley 1993). On the southern side of Alexandria, the Maryut Lake records a desiccation from about the 9th–10th century AD, when it became a Sebkha-like environment (Flaux 2012). It looks as if the same huge event affected the maritime and lacustrine facades of Alexandria. The data obtained can also be compared to the results from the ancient site of Heracleion, at the mouth of the ancient Canopic branch. This port city, 25 km east of Alexandria, is today –12 m underwater in the bay of Aboukir (Stanley *et al.*, 2001, 2004). The seismic profiles reveal the faults and the archaeological structures, which are almost intact, suggesting an abrupt immersion around the 8th century AD (Stanley *et al.* 2006). Thus, on the western edge of the delta, Alexandria "sunk" twice less rapidly than ancient Heracleion situated further east. This abrupt relative sea level rise, attributed to the 8th century AD at Heracleion and between the 8th and 9th centuries AD at Alexandria, appears to have affected the two sites simultaneously. Only the magnitude of the phenomenon differed.

Conclusions

For the study of the relative sea level variations in relation to Alexandria during the Holocene, an important margin of errors remains because of the imprecision inherent to the indicators used. The compilation of the existing data (Pirrazoli 1991; 1996) with the chronostratigraphical data presented in this article does, however, reveal three ancient relative sea levels. A first level is situated at about –6.75 m below the present sea level and is dated to 5000 BP. A second level, dated to the Roman period, is situated between –5.40 and –5 m bpsl. A third and final level, dated between the end of the 9th century AD and the 13th century AD, lies at –1.5 m bpsl. These data reveal a sudden rise of about 3.5 m +/– 1.5 m in the relative sea level between the end of the middle of 8th century AD and the end of the 9th century AD which can be correlated with what occurred at the site of Heracleion in the 8th century AD. The three sea levels revealed demonstrate three sets of dynamics inherent to the western fringe of the Nile delta: first, the classic rise of the sea level in the Holocene thanks to the *Cladocora* reef; second, a sudden relative rise in sea level in the middle 8th century AD / end of 9th century AD, and finally the rapid and continuous subsidence of this site when compared to Fleming's curve (1998). The evolution of these three sets of dynamics, which are today known and measured, implies a necessity for management and regional adaptation by today's societies in order to anticipate the risk of coastal immersion that could cause floods and put into question current planning. Such a kind of relative sea level variations should also lead to anticipate the salinisation of coastal lakes (Stanley, 2014) and arable lands as subsidence is still going on (Stanley, 2014).

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