Fate of two cities built on sinking ground: slow and fast submergence at Thônis -Heracleion and Canopus, Nile River Delta, Egypt

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Fate of two cities built on sinking ground: slow and fast submergence at Thônis – Heracleion and Canopus, Nile River Delta, Egypt

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Abstract

Deltas are, by nature, places affected by widespread ground subsidence. From the day they are settled, the cities that are built on deltas must cope with a number of issues arising from subsidence. These issues become more and more concerning as centuries go by, and may eventually leave no other choice than the abandonment of the cities. The most dramatic, if not the most common outcome, is the submergence of a city in the sea. The rediscovery of the sunken cities of Thônis-Heracleion and Canopus in 2,000 AD in Abu Qir Bay, for this reason caught the world's attention. Even more dramatically, it was soon proposed that their submergence did not take the form of a slow, ineluctable flooding, but a rapid process that forced the inhabitants to hastily abandon the cities. If such a rapid submergence event occurred today, it would affect a much more densely populated delta, and would have catastrophic consequences. Other studies have since questioned the occurrence of fast submergence in the bay of Abu Qir. Some archaeological data from the submerged sites are difficult to explain, however, without resorting to fast submergence. Besides, rapid ground subsidence has also been documented at Alexandria, at the time proposed for the submergence of Thônis-Heracleion and Canopus.

Considering the enormous hazard that fast submergence represents in such a heavily populated delta, more work is needed to establish its existence and quantify its amplitude. The present paper aims at clarifying the geological background in which it would take taken place, considering that a variety of different geological phenomena have been invoked to account for fast or slow subsidence. The paper reviews and analyses the strength and witnesses of the various evidence put forward in support for slow and fast subsidence. Although no definitive conclusion is reached, the most likely scenario that arises from the available data is that of rapid, localised ground collapse restricted to the cities, possibly by liquefaction as the result of ground shaking, superposed to long-term, slow delta subsidence.

Introduction

The sunken ancient cities of Canopus (C) and Thônis-Heracleion (TH) were rediscovered in 2000 in the western part of the Nile Delta, on the floor of Abu Qir Bay (Toussoun 1934, Stanley et al. 2004). They currently lie 1.5 and 4 km offshore, at water depths of 4 to 6 mm respectively (fig. 1). During antiquity, Abu Qir Bay provided sheltered access to the mouth of the now-disappeared Canopic Branch of the Nile River, which, at the time, was likely the largest distributary channel of the Nile. During the few millennia preceding the settling of both cities, the Canopic branch had filled the sea with sediment, pushing the shoreline several kilometres seaward (Flaux *et al*. 2017). Both cities grew as fluvial ports, 1-2 km inland from the mouth of the Canopic Branch (Frihy 1992). The Nile delta, like most deltas in the world, experiences continuous ground subsidence, such that any land reclaimed from the sea remains affected by slow foundering. The deposition of sediment across the delta plain during floods counterbalances subsidence, allowing the delta plain to stay emerged. Continuous subsidence in Abu Kir Bay has contributed 4.6 m of ground lowering at the two cities over the past 25 centuries (Stanley et al. 2004). The sediment discharge of the Canopic branch started to dwindle soon after the founding of the cities, as the flow of the Nile started being focused into the

Damietta and Rosetta branches. The Canopic branch vanished after the 5th century CE, allowing the sea to invade its subsiding floodplain (Flaux et al. 2017). In response to coastline retreat, the centre of TH was displaced a few hundreds of metres to the south of its original location, between 480 and 350 BCE, to a new site known as the Central Island (Robinson and Goddio 2015), 2-4, (Goddio 2015), 45, Fig 1.41). The date of submergence of the two cities is constrained by the discovery of Islamic coins in both cities, the latest coin being an Abbasid dinar dated to 785 AD (169 AH) (Goddio 2007, p. 75). Since the submergence of the cities, the coastline has retreated another 4 km to its present location.

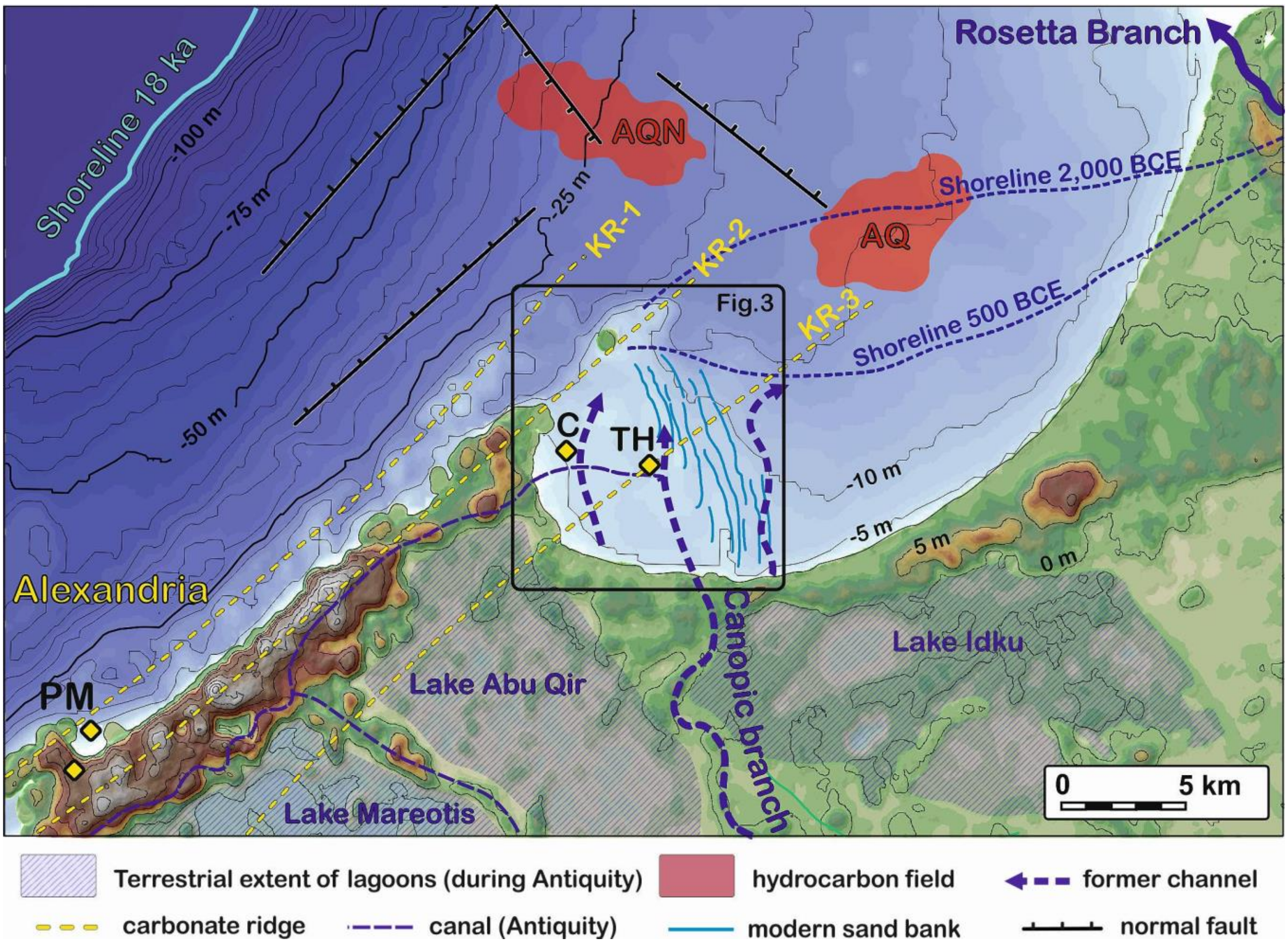

Figure 1: Topographic and bathymetric map (contour spacing: 5 m) showing the westernmost part of the Nile Delta between Alexandria and the Damietta Branch, and the geological and archaeological setting of Abu Qir Bay, with indication of the locations of Thônis- Heracleion (TH), Canopus (C), and of the Portus Magnus (PM) of Alexandria. See Fig. 2 for the location of this map within the Nile Delta. KR1-3 : kurkar ridges, using the existing numbering convention (Stanley and Hamza 1992). Hydrocarbon extraction fields: AQ: Abu Qir; AQN: Abu Qir North. Onshore altimetry data: ALOS World 3D digital elevation model (AW3D30, © JAXA) at 30 m resolution. Offshore bathymetric data extracted from the Global Multi-Resolution Topography grid using GeoMapApp (www.geomapapp.org) / CC BY / CC BY (Coplan et al. 2009). The shorelines depicted at 2,000 BCE and 500 BCE are from Chen et al. (1992). Locations of the Canopic channels from Stanley et al. (2004). Manmade canal locations from Flaux et al. (2017). Active fault traces from Abd-Allah et al. (2012).

Stanley *et al*. (2001) advocated that long-term subsidence alone cannot account for the total amount of lowering that some of the submerged buildings have experienced. Besides, they found that the cessation of archaeological evidence was synchronous at C and TH during 8th century CE, according to the latest Islamic gold coins found at the two sites: Canopus: 729-730 CE, TH: 775-785 CE (Goddio

2007, Table 1, fig. 4). Besides, no attempt was made to extract valuable materials from the collapsed buildings, suggesting substantial submergence. They proposed that a fast subsidence event affected both sites at the same time, and led to their synchronous submergence (Stanley et al. 2001, 2004). They put forward several potential causes of fast subsidence. They first invoked the indirect effects of large floods of the Nile River, before giving preference to tsunamis or/and earthquakes (Stanley et al. 2001, 2004). The occurrence of sudden ground lowering events, and the fact that they would affect the entire bay have since been questioned (Flaux et al. 2017). Yet the discovery of a rapid subsidence event in the harbour of Alexandria (Goiran al. 2018), and the recovery of additional archaeological evidence at the sunken cities show that the case for fast subsidence cannot be so hastily dismissed. We review and assess here the current lines of evidence that have been put forward in support for fast and slow subsidence.

1. Geographic background: coastline evolution of Abu Qir Bay

1.1. Life amidst the sandy coastline of the delta

The Nile sediment load is deposited onshore over the Nile delta plain and offshore over the delta cone (fig. 2). Three kilometres of sediments have thus accumulated over the delta during the past five million years (Cross et al. 2009). Those sediments that reach the sea are dispersed either far offshore in buoyant plumes that settle diffusely over the submarine cone, or funneled into confined submarine channels by high-density currents (Kneller et al. 2016, Li et al. 2021). Some sand is washed back to the shore, and then spread along the shore by coastal drift, downdrift of the river mouths that deliver these sediments (Frihy and Lawrence 2004). The Nile River feeds distributary channels (or branches), which positions and number across the delta have changed since Antiquity. Rather than migrating laterally, these branches tend to be abandoned and replaced by new ones during overflows or avulsions (Sestini 1989). Up to seven branches are thought to have coexisted during Antiquity. Only the Canopic and Pelusiac branches, on the western and eastern delta margins, were then considered to be navigable (Herodotus Historia II.17, Strabo Geography XVII.1.18, (Cooper 2008, p. 29-42, (Toussoun 1925). The number of simultaneously active branches had already shrunk to two by the 10th Century CE (Stanley and Warne 1998). The constant shifting, and reduction in the number of active branches profoundly impacted sediment delivery to the coast. This affected the shape of the coastline, which advanced seaward down-drift of the active outlets, and subsequently retreated landward once such outlets had been abandoned (Frihy and Lawrence 2004). In Abu Qir Bay, the demise of the Canopic Branch was coeval to landward retreat of the coastline (fig. 1), and was attributed to the dwindling delivery of Nilotic sediments (Chen et al. 1992, Stanley and Warne 1998, Flaux 2017). It prompted a landward retreat of the coastal cities. This is archaeologically observable across the Late Period and the early Ptolemaic period in the northern area of Thônis-Heracleion, where the temple to Amun, which was equated to Herakles by early visiting Greeks, was most likely located (Herodotus Historia 2, 11 (Robinson and Goddio 2019). In that area were found the likely remains of a temple cache of statuettes, dated by associated ceramics to the 6th and 5th centuries BCE (site G1: Goddio 2007, p. 120, fig. 3.93, Heinz 2015, p. 56-7, fig. 2.1). Today, the remains of the dismantled temple cover over three hectares, consisting of limestone blocks, many of which are carefully and neatly arranged in ordered rows. In another part of the temple, architectural and decorative elements were cut up for recycling and reuse (Goddio 2015, p. 45-46, fig. 1.41). A smaller sanctuary from the Saïte period, dedicated to Khonsu-Thoth, and also located in the northern area of TH, suffered a similar fate: it was dismantled and then abandoned (site M8: von Bomhard 2017, p.17-22, (Goddio 2015, p.26-28, fig. 1.18). The archaeological stratigraphy at this latter site indicates that the remnants were sealed by successive layers of clay and sand brought in by currents, with no signs of human occupation, indicating that the area became inaccessible and was most probably submerged. It is likely that both temples were re-founded further to the south on the Central Island where, as noted above, between 480 and 350 BCE, a new phase of construction saw the erection of the temple of Anun-Gereb and the relocation of the monumental religious core of the port-city to this island (Robinson and Goddio 2015, p. 2-4, Goddio 2015, p. 45, fig 1.41). The North-East Channel, a waterway that connected the port of TH to the Canopic Branch, silted up during the 5th to the 4th century BCE. As a response, the activities from the Central Port were relocated farther to the southeast of the city, where a connection to the Canopic Branch remained (Goddio 2015, p. 45).

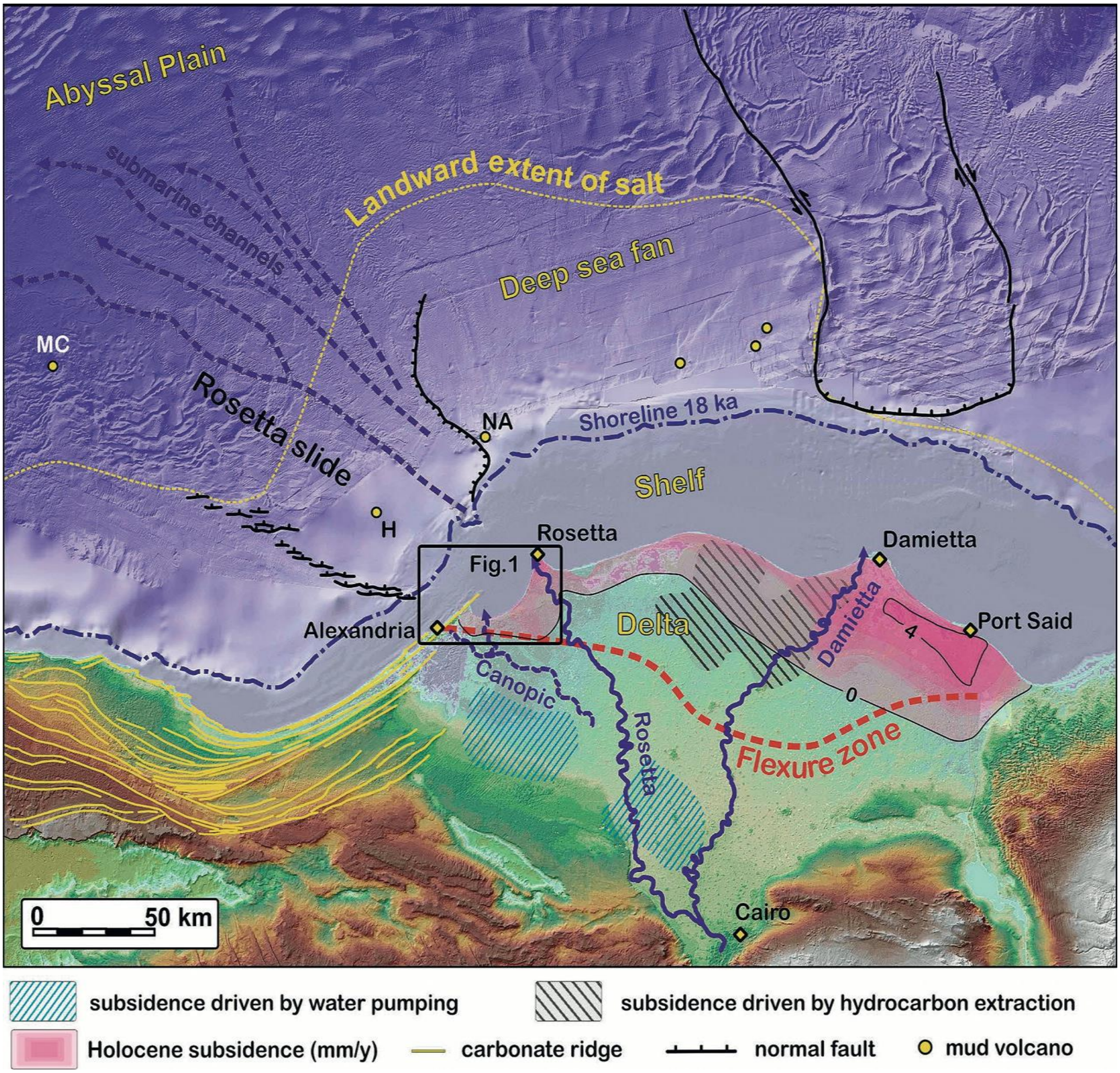

Figure 2: Map showing the entire delta and cone of the Nile River, with the two currently active branches, the former Canopic branch, kurkar ridges, landslides at sea, mud volcanoes, submarine channels, and the distribution of subsidence on land, with indication of the "Hinge Zone", and areas of highest subsidence, as well as the regions of water and hydrocarbon extraction.

On land altimetric data: JAXA ALOS World 3D digital elevation model (AW3D30) at 30 m resolution. Bathymetric data extracted from the Global Multi-Resolution Topography grid using GeoMapApp (www.geomapapp.org) / CC BY / CC BY (Coplan et al. 2009). Flexure zones and areas of fast subsidence triggered by water pumping and hydrocarbon extraction from Gebremichael et al. (2018), modified, Holocene coastal subsidence from Stanley and Warne (1993). Nile cone tectonic deformation and landward extent of salt from Loncke et al. (2006), modified. Location of mud volcanoes from (Bayon et al. 2009, Huguen et al. 2009).

Site	# on graph	Sample name	RSL indicator	Nature of the sample	Dating: radiocarbon laboratory number	Depth bsl	Radiocarbon age	Calibrated calendar age
						m b.s.l.	Year BP	Year CE
A	**1**	IX 28	marine bottom	cladocora	Ly-10617(1)	> -7.5 ±0.05	5,485 ± 50	-3,733 ± 183*
A	**2**	II 25	marine bottom	cladocora	Ly-8870(1)	> -7.3 ±0.05	5,360 ± 55	-3,576 ± 188*
A	**3**	XI 27	marine bottom	marine shell	Poz-1640(1)	> -7.0 ±0.05	4,625 ± 40	-2,726 ± 152*
A	**4**	II 20	marine bottom	cladocora	Ly-10570(1)	> -6.9 ±0.05	4,640 ± 50	-2,710 ± 188*
A	**5**	XI 24	marine bottom	marine shell	Poz-1638(1)	> -6.2 ±0.05	4,430 ± 45	-2,452 ± 202*
A	**6**	II 18	marine bottom	cladocora	Ly-8871(1)	> -6.15 ±0.05	4,195 ± 50	-2,140 ± 210*
A	**7**	XI 23	marine bottom	marine shell	Ly-1366 (1)	> -5.9 ±0.05	3,890 ± 50	-1,733 ± 196*
A	**8**	II 17	marine bottom	marine shell	Ly-10569(1)	> -5.6 ±0.05	2,085 ± 45	458 ± 167*
A	**9**	IV 28	marine bottom	marine shell	Poz-1636(1)	> -5.5 ±0.05	2,305 ± 35	209 ± 163*
A	**10**	IX 19	marine bottom	marine shell	Ly-15386(1)	> -5.5 ± 0.1	1,925 ± 40	626 ± 149*
A	**11**	I 8	pebble beach	pebble beach	Archeological	-5.4 ± 1.5	5th-6th AD	500 ± 100
A	**12**	XI 21	marine bottom	marine shell	Poz-1637(1)	> -5.4 ± 0.1	3,665 ± 40	-1457 ± 166.5*
A	**14**	II 16	marine bottom	marine shell	Poz-1643(1)	> -5.1 ± 0.1	2,065 ± 40	490 ± 155*
A	**15**	XI 18	marine bottom	marine shell	Poz-1658(1)	> -4.9 ± 0.1	2,150 ± 35	397 ± 155*
A	**16**	II 15	marine bottom	marine shell	Ly-10567(1)	> -4.8 ± 0.1	1,935 ± 55	611 ± 166*
A	**17**	V 17-18	aegagropiles	charcoal	Ly-10737(1)	> -5.4 ± 0.8	1,330 ± 35	711 ± 63†
A	**19**	II 14	marine bottom	marine shell	Ly-1305(1)	> -4.5 ± 0.1	1,845 ± 45	722 ± 149*
A	**20**	II 13	marine bottom	marine shell	Ly-1465(1)	> -4.2 ± 0.1	1,890 ± 45	670 ± 155*
A	**21**	II 9	marine bottom	marine shell	Ly-8873(1)	> -2.7 ± 0.1	1,720 ± 45	838 ± 153*
A	**22**	II 8 G	pebble beach	pebble beach	Between II 9 and II8S	-2.0 ± 1.5	1,683 ± 83	879 ± 191
A	**23**	II 8 S	macrofauna	marine shell	Ly-1522(1)	-1.0 ± 1.0	1,635 ± 35	919 ± 147*
A	**24**	II 7	macrofauna	marine shell	Ly-1521(1)	-0.6 ± 0.6	1,530 ± 35	1038 ± 152*
A	**25**	V 9-11	aegagropiles	marine plant	Ly-10736(1)	-0.4 ± 0.4	1,175 ± 30	1367 ± 106*
A	**N1**	N1	Sea level	notch	Relative to @	-6.7 ± 0.2	> 2,850	> @
A	**N2**	N2	Sea level	notch	Relative to @	-6.8 ± 0.2	> 2,850	> @
A	**Q1**	Q1	harbour	quay	Archeological	<-5.0	5th-6th AD	500 ± 100
C	**C1**	SCA100	delta plain	coin	gold coin, site T(2)	< -4.8 ± 0.5	archeological	719 ± 1
C	**C2**	SCA101	delta plain	coin	gold coin, site T (2)	<-4.8 ± 0.7	archeological	730 ± 1
C	**26**	GODDIO#1	delta plain	wood	Beta-145896(3)	<-4.8 ± 0.5	2,270 ± 60	-292 ± 130†
C	**27**	GODDIO#2	delta plain	plant material	Beta-145897(3)	<-3.8 ± 0.7	2,370 ± 40	-560 ± 178†

C	**28**	GODDIO#3	delta plain	charred seeds	Beta-145898[3]	<-5.0 ± 0.7	1,980 ± 40	38 ± 92†
C	**29**	GODDIO#4	delta plain	charred material	Beta-145899[3]	<-5.0 ± 0.5	3,140 ± 40	-1,399 ± 103†
C	**30**	GODDIO#6	delta plain	wood	Beta-145900[3]	<-4.0 ± 0.5	2,030 ± 40	-37 ± 116†
C	**31**	GODDIO#7	delta plain	peat	Beta-145901[3]	<-3.6 ± 0.7	6,500 ± 70	-5,469 ± 145†
C	**32**	GODDIO#10	delta plain	wood	Beta-145902[3]	<-5.0 ± 0.7	2,060 ± 40	-72 ± 103†
C	**33**	GODDIO#11	delta plain	wood	Beta-145903[3]	<-4.5 ± 0.5	5,530 ± 50	-4,360 ± 99†
C	**34**	GODDIO#12	delta plain	peat	Beta-145904[3]	<-3.8 ± 0.5	6,760 ± 60	-5,661 ± 104†
C	**35**	GODDIO#13	delta plain	wood	Beta-145905[3]	<-4.6 ± 0.5	2,090 ± 40	-96 ± 105†
C	**36**	STANLEY SITE T	delta plain	wood	Beta-145906[3]	<-4.6 ± 0.5	2,300 ± 50	-341 ± 141†
C	**37**	STANLEY T ZONE	delta plain	plant material	Beta-145907[3]	<-4.6 ± 0.2	2,390 ± 40	-568 ± 178†
C	**38**	AQ13A65	delta plain	plant material	Beta-159431[3]	<-3.7 ± 0.2	1,980 ± 40	51 ± 105†
C	**39**	AQ13152-157	delta plain	plant material	Beta-169957[3]	<-4.6 ± 0.2	2,320 ± 40	-280 ± 72†
C	**40**	AQ13323-329	delta plain	shell	Beta-169958[3]	<-6.3 ± 0.2	3,770 ± 40	-1,587 ± 167*
C	**41**	AQ13BI36-39	delta plain	plant material	Beta-159825[3]	<-3.4 ± 0.2	2,220 ± 70	-249 ± 153†
C	**42**	AQ-13B 68-72	delta plain	plant material	Beta-168608[3]	<-3.7 ± 0.2	2,120 ± 40	-196 ± 155†
C	**43**	AB-13C 18cm	marine bottom	plant material	Beta-168609[3]	<-3.2 ± 0.2	2,240 ± 40	-296 ± 99†
C	**44**	AQ13AI32-36	marine bottom	plant material	Beta-159824[3]	<-3.4 ± 0.2	2,050 ± 70	-112 ± 240†
C	**45**	AQ1550-54	delta plain	shell	Beta-169961[3]	<-4.0 ± 0.2	2,880 ± 40	-540 ± 178*
C	**46**	AQ1741-51	marine bottom	shell	Beta-169962[3]	<-4.0 ± 0.2	2,860 ± 40	-524 ± 183*
C	**47**	AB1797-102	delta plain	shell	Beta-169963[3]	<-4.5 ± 0.2	3,340 ± 40	-1,066 ± 180*
TH	**C3**	SCA317	delta plain	coin	gold coin, site H9 [2]	<- 4.6 ± 0.5	archeological	786 ± 1
TH	**48**	AQ452-65	delta plain	organic sediment	Beta-169952[3]	<-4.9 ± 0.1	3,330 ± 60	-1,623 ± 129†
TH	**49**	AQ921-24	marine bottom	marine shell	Beta-169955[3]	<-4.0 ± 0.1	120 ± 40	1,910 ± 41*
TH	**50**	AQ110-7	marine bottom	marine shell	Beta-169971[3]	<-4.1 ± 0.1	1,140 ± 40	1,392 ± 114*
TH	**51**	AQ1122-40	delta plain	organic sediment	Beta-169956[3]	<-4.3 ± 0.1	3,180 ± 40	-1,454 ± 66†

Table 1: Radiocarbon and archaeological ages of paleo-sea level indicators used to constrain the subsidence rates at Alexandria (A), Canopus (C), and Thonis-Heracleion (TH). Data from: (1): Goiran J.-P., Vittori C. *et al.* (2018), (2): Goddio F. (2007), (3): Stanley D., Bandelli A. *et al.* (2007). Calibrated ages (2σ) derived from the radiocarbon ages using (*): the marine calibration curve of Heaton T.J., Köhler P. et al. (2020), (†): the continental calibration curve of Reimer P.J. *et al.* (2020).

The strategic importance of the location of the city, however, outweighed issues arising from ground subsidence. At the edge of the 'Sea of the Greeks', the site of TH was carefully chosen as a border post between the state of Egypt and the outside world: a defensive bastion both militarily and theologically, a choke point at which to extract taxes, and, during the Persian period, the major trading emporium of Egypt (Robinson and Goddio 2019). The port and its city grew to prominence in the context of increasing contacts with the Greek world, at a strategic location near the mouth of the westernmost navigable branch of the Nile. It was a gateway to the land of Egypt beyond. The inhabitants of TH coped and adapted to the changing coastline, undertaking radical changes when necessary. Such endurance and adaptability, however, only lasts as long as compelling reasons remain to continue to inhabit the site. With the coming of the Ptolemies to Egypt, these reasons evaporated: the emporium, the economic lifeblood of the port, was transferred to Alexandria, and the strategic importance of its location waned. Following the collapse of the temple of Amun-Gereb on the Central Island in the years around 100 BCE, there was neither the political will, nor economic impetus to fund its reconstruction, and the city was largely abandoned to those who would rob and recycle its buildings. The final inhabitants were from a small religious community, living in the remains of one of the former temples on the Central Island (Goddio 2015, 48). Rather than a teaming, cosmopolitan port, TH in the Byzantine period was instead a lonely, isolated place at the edge of the sea, a location perfectly suited to the developing ideals of early Christian monasticism (Hedstrom 2017).

1.2. The rocky shoreline

The warm waters of the south eastern Mediterranean Sea favour abundant production of biogenic carbonates by planktonic and benthic marine living organisms. Sand-sized fragments of these biogenic carbonates are transported by coastal currents and waves, and deposited over shallow submarine sand banks, beach ridges, and dune fields (Sestini 1989). Sea level has oscillated several tens of metres up and down during the past two million years. The ridges formed during marine high stands have been exposed to weathering and erosion during lowstands. Their carbonates have been subjected to dissolution and re-precipitation, which cemented and hardened these ridges. The cemented bioclastic carbonate sand that makes the ridges is known as kurkar in Egypt and as ramleh along the Levantine coast. During highstands, the cemented ridges form rocky shorelines that host numerous naturally sheltered harbours. The kurkar ridges have thus determined the location of many ports, from Alexandria in Egypt (Goiran et al. 2014) to Arwad in Syria (Dodonov et al. 2008), via Cesarea Maritima in Israel (Galili et al. 2021), and Tyre or Sidon in Lebanon (Badawi 2016). The carbonates produced west of the Nile Delta are transported toward the delta, and accreted along its western side (fig. 2) where they form kurkar ridges (Stanley and Hamza 1992). Alexandria was built on a kurkar ridge complex (fig. 1), using a natural harbour between a partly submerged ridge and a ridge that corresponds to the mainland coast. The stable setting of Alexandria, however, contrasts with the more troublesome site of Thônis-Heracleion, built directly over the flat delta plain. The ridges at Alexandria prevented the branches of the Nile River which flow west across the delta from reaching the coast, as their water ponded up behind the ridges, forming lakes such as Lake Mariott. The water evacuation was deflected eastward, as far as the point where the ridges disappear. This place, during the Holocene, corresponds to Abu Qir Bay. The Canopic branch of the Nile, one of these west-flowing branches, was thus located at the westernmost possible location for a Nile outlet, in Abu Kir Bay (Stanley and Hamza 1992).

2. Geological background: origin of subsidence

Delta plains generally subside at rates that do not exceed a few millimetres per year (Ericson *et al.* 2006). Although slow, such rates are large enough to entail the repurposing or abandonment of manmade structures within a few centuries from their construction. As exposed in detail hereafter (see discussion), the sinking of TH and Canopus are thought to have combined slow subsidence and rapid events, with a cumulated amplitude of several metres. Rapid, is here understood as an event which duration is shorter than the resolution of radiocarbon dating and of other archaeological constraints available. The rapid events may therefore have lasted between a few minutes and a century. We review first the processes that generate slow, continuous subsidence (namely, sediment loading and compaction, gravitational spreading, and fluid escape) and then review the processes that can produce quasi-instantaneous foundering (namely, tectonic displacement, ground liquefaction, shallow gravitational spreading).

2.1 Slow subsidence

2.1.1. Sediment loading and sediment compaction

The sheer amount of sediment deposited on the delta represents a large load over the lithosphere on which the delta is built. Sediment loading pushes the lithosphere down into the underlying asthenospheric mantle. Below the Nile Delta, the lithosphere has hence sunk several kilometres into the asthenosphere (Cross *et al.* 2009). The mechanical response to this loading takes the form of a flexural sag of the lithosphere, centred on the delta (Gebremichael *et al.* 2018). The flexure generates bending stresses that reactivate old tectonic faults. These old faults then expand upward into the over- lying sediment pile, deforming the delta (Sestini 1989, Cross et al. 2009). West of the delta, this long wave- length flexure has been invoked in the bending of the kurkar ridges (Sandford and Arkell 1939, Hassouba 1995), the elevation of which decreases from 250 m a.s.l., 160 km west of Abu Qir, down to sea level at Abu Qir, and finally down to 100-120 m below the delta surface, 40 km east of Abu Qir (Stanley and Hamza 1992).

Sediment compaction across the Nile delta plain is another source of slow subsidence. It is particularly fast during the first thousands of years following sediment deposition (Stanley and Warne 1998, Marriner et al. 2012). Therefore, in the Nile Delta, it mostly affects sediments deposited over the past 10 ky (during the Holocene), that is, since the return of sea level within a few metres from its present-day level. The thickness of these Holocene sediments across the delta increases eastwards, from 3-15 m in Abu Qir Bay (Stanley et al. 2004), to up to 40 m at Port Said (Stanley and Warne 1993). This lateral increase in thickness is mirrored by an increase in subsidence rates averaged over the millennia elapsed since deposition (fig. 2). These increase from 1-2.5 mm/y in Abu Qir Bay (Chen et al. 1992, Flaux et al. 2017) to up to 5 mm/y at Port Said (Stanley 1988). The eastward increase in subsidence, therefore, likely results, at least in part, from the compaction of an increasingly thick pile of Holocene sediment. The fact that a thicker succession has accumulated in the east, however, calls for a deeper driver of subsidence in the east (Stanley 1988), of either tectonic or gravitational origin. These deeper drivers are now reviewed.

Gravitational spreading vs. regional tectonics

The tectonics of Northern Egypt is controlled by slow, protracted continental convergence between Africa and Eurasia. In Cyrenaica (western Egypt) and in the Northern Sinai (eastern Egypt), platergence has produced contractional folding until the Eocene, 35 My ago (Arsenikos *et al.* 2013, Bosworth and Tari 2021), before the birth of the Nile Delta in the Oligocene. No large-scale deforma- tion can be subsequently ascribed with certainty to continental convergence. Instead, the deformations observed across the delta can be all explained, in a way or another, by flexural loading or by gravitational collapse in the delta.

Many of the faults that disrupt the delta accommodate generalized gravitational spreading of the delta toward the abyssal plain of the East Mediterranean Sea. The most prominent features produced by delta spreading are giant landslides, rooted on décollement levels at depths of 1-2 km beneath the seafloor (Loncke *et al.* 2009). The most important décollement is hosted by evaporites (precipitated marine salts) layers, depo- sited ~5.5 My ago, during the Messinian Salinity Crisis (MSC), at depths in excess of 2,500 m. After the MSC the Nile Delta expanded above the evaporites, which yielded under the weight of the delta, initiating its collapse. Other décollement levels are located farther up the sedimentary succession, affecting clays and silty-sandy levels, which resistance to shearing is reduced by the high fluid pressure of the delta sedi- ments (Loncke et al. 2006). Sliding and creeping generates deformation at a variety of scales, from deep, slow creep affecting 1-2 km thick translational slides, up to shallow, instantaneous mass-wasting events affecting the submarine cone surface (Loncke et al. 2009). Slides rooted in the Messinian evaporites extend to the landward limit of deposition of the evaporites (Loncke et al. 2006), which currently lies 50-100 km offshore (fig. 1). Faults rooted in higher décollements are found in much closer proximity to Abu Qir Bay. An alignment of such en-échelon, cuspate, normal faults lies within 15 km of Alexandria (fig. 2). It forms the southern border of the Rosetta Slide, a 60 km wide submarine landslide that accommodates the NW-directed collapse of the Nile cone. The head scarp of the Rosetta slide progressively migrates toward the current coast by retrogressive failure (backwearing). It currently lies at depths of 120-150 m, within 30 km of the Cape of Abu Qir (Garziglia et al. 2008). The surface of the slide is covered with debris deposited by large mass-wasting events that individually rework between 3 and 500 km^3 of head scarp sediments. These large landslides have an average return period of 27 ky (Garziglia et al. 2008). The deformation associated with delta collapse, therefore, does not seem to extend as far south as Abu Qir Bay and is not directly involved in the sinking of the ancient cities. It is, however, a potential source of earthquakes and tsunamis (see discussion).

Closer to TH and Canopus lies an array of normal faults that stretches from offshore near the Rosetta slide offshore, to onshore, at the so-called Hinge Zone, a flexural bend located south of Abu Qir Bay (fig. 2). The Hinge Zone marks the southern border of the area affected by long-term, load-generated subsidence (Sestini 1989, Gebremichael et al. 2018). Seismic imaging shows that f lexure-related faults are active immediately north of Abu Qir Bay (fig. 1), cutting through the most recently deposited sedi- ments (Abd-Allah et al. 2012). Other faults, located within the bay, also offset Quaternary sediment layers (Stanley 2005, Abd-Allah et al. 2012). Seismic imaging, however, lacks the necessary resolution to determine whether the topmost Holocene sequence (<10 ky) is also disrupted by these faults, and there- fore whether such faults have contributed to ground subsidence since the settlement of the cities. Higher resolution seismic profiles acquired in the bay around the sunken cities (Stanley et al. 2007) reveal that Holocene sediments drape or wrap around the pre- existing kurkar ridge KR3 (fig. 1), which irregular topography has been variously interpreted, depending on location, as a subaerial erosion surface predating sea level rise, or as a surface disrupted by tectonic faults (Stanley 2005). The high resolution seismic profiles, however, fail to directly image fault planes or tectonically offset layers inside the ridge, such that definitive evidence for historical disruption of this ridge remains to be provided.

2.1.3 Salt and fluid escape.

Sediment compaction and deformation promote the upward escape of salts and fluids from within the delta, a process that can contribute to surface subsidence. Dewatering occurs by compaction at shallow depth, within a few thousands of years following deposition. It can be accelerated by the artificial pumping of the interstitial sediment pore water for irrigation (fig. 1). Pumping today entrains rapid (1cm/y) subsidence on some parts of the delta floodplain (Gebremichael *et al.* 2018). Offshore, the natural compaction of sediment generates high hydraulic pore pressure, which is regarded as the main contributor to the sudden failure of submarine slopes (Garziglia et al. 2007). The organic matter trapped in the Nile sediments is biodegraded after deposition and expelled as methane, either diffusively, or at seeps, hundreds of which have been identified offshore (Bayon et al. 2009). A fraction of the organic matter is decomposed at greater depth by thermal maturation, releasing hydrocarbons that percolate either diffusely through the delta, or are released at large submarine mud volcanoes, such as the Horus volcano, 40 km north of Abu Qir (fig. 2), or the North Alex volcano, 60 km north of Damietta (Feseker et al. 2010). Part of the hydrocarbons are intercepted by geological traps onshore and offshore, from which they are extracted today. One extraction field, Abu Qir, is located within 10 km of TH (fig. 2), and one of its pipelines passes within 600 m of the archaeological site (Stanley et al. 2007). Onshore extraction (fig. 1) generates up to 1 cm/y of ground subsidence (Gebremichael et al. 2018). Offshore extraction, therefore, likely affects the seafloor around the sunken cities.

2.2. Fast subsidence

Fast ground subsidence is here defined as an event that spans a few minutes to a century, the imprecision in its duration being determined by the limits of dating at the archaeological sites, which varies with time, location, artefacts and dating techniques (coins, shards, radiocarbon dating, and the geometric relationships encountered by trenching, see discussion). Several geological drivers of fast subsidence can be recognized in the Nile Delta.

The presence of active faults up to 10-20 km in length, in close proximity to, and potentially within Abu Qir Bay, opens the possibility for rapid vertical ground displacement during fault slip events. However, the faults may slip by continuous creep, and not necessarily rupture during discrete events. If they do slip during discrete events, such events are not necessarily seismogenic. Reviews of ground shaking and slope stability on the submarine cone (El-Sayed et al. 2004, Garziglia et al. 2007) suggest that the faults that affect the delta could trigger earthquakes as large as Ms 6.7 (El-Sayed et al. 2004). Based on the lengths of the faults mapped so far, displacements on the faults located the closest to Abu Qir Bay cannot exceed a metre, in the immediate vicinity of the ruptured fault planes (Schultz and Fossen 2002), and much less at TH and Canopus, which are located several kilometres away. Larger, teleseismic earthquakes (>Ms 7.0) are generated along the Africa-Arabia (Israel, Lebanon, Syria) and Africa-Eurasia (Turkey, Greece) plate boundaries, hundreds of kilometres from the Nile Delta. Despite their remoteness, these earthquakes have caused substantial damage to settlements in the Nile Delta (Ambraseys and Adams 1998, El-Sayed et al. 2004). The longer duration, and lower frequency shaking generated by these distal earthquakes tends to promote ground liquefaction (El-Sayed et al. 2004, Bradley et al. 2019). In the fluid-saturated and poorly compacted layers of the delta, ground shaking is subject to site amplification, shaking duration lengthening, and a shift of shaking toward lower frequencies. Low frequency shaking is susceptible to trigger ground liquefaction by sand dewatering and compaction. It has been regarded as the main factor triggering the large mass-wasting events documented in the Rosetta slide (Garziglia et al. 2007). Liquefied soils yield under downward and upward applied stress, flowing away from building loads. As a result, buildings sink, tilt, and collapse into liquefied ground. Conversely, liquefaction triggers upward displacements of canal floors relative to canal sides. Earthquakes have, therefore, been regarded as the dominant process that generated fluidized sediment layers and convoluted beds in the delta plain sediments cored around TH and Canopus, and one of the causes of building collapse at both sites (Stanley et al. 2004).

The presence of water-saturated sand layers trapped at shallow depth (5-10 m) below a sealing cap of impervious silts and muds is common in deltas, where it promotes widespread lateral ground displacement (gravitational spreading) during the liquefaction of underlying sands. The impossibility for water to escape from the compacting sand leads to the formation of a "water mattress" over which the clayey sealing layer can move laterally, away from loads and towards free borders, such as river banks (Obermeier 1996, Hughes *et al*. 2015). In the Nile Delta, this configuration is frequent, as it corresponds to muddy layers deposited in coastal lagoons and floodplains after the filling of the sea by marine sands. This is the case in Abu Qir Bay (Sestini 1989, Stanley and Warne 1998, Flaux *et al.* 2017). Pressurisation of the sands may be aggravated by the retention of gas escaping from below, accumulated earlier into the subsurface by diffuse hydrocarbon outgassing (Garziglia *et al*. 2007). Upon shaking, the sealing layers are susceptible to spread laterally into nearby river channels, driving river bank failure and the stretching, faulting, and collapse of the floodplain located behind (Obermeier 1996, Hughes *et al.* 2015). The load exerted by buildings next to riverbanks further promotes lateral spreading.

Ground deformation can also happen without any ground shaking in response to the rapid loading of soft, fluid- saturated silts and muds only a few decades old, at the mouth of rivers. Rapid loading, in this case, is exerted by thick layers of silts and mud deposited by a flood. This was initially considered as the most likely cause of deformation at TH and Canopus (Stanley *et al.* 2004, Stanley *et al.* 2007).

3. Discussion: evidence for slow and fast subsidence in Abu Qir Bay

In light of the geological context described in the previous section, we review here the evidence for subsidence in Abu Qir Bay and how it is seen in the archaeological record of TH and C. The case for fast subsidence has been made using arrays of observations, rather than on one single type of observation. These observations are presented here in succession, to assess their relative contribution to the debate. We review, first (3.1), the geological evidence for slow subsidence in Abu Qir Bay, its spatial variability, amplitude, rate, and drivers. We then review the evidence for urban adaptation to slow subsidence at the archaeological sites (3.2). The evidence for rapid subsidence is based on three sets of observations that are successively reviewed. First, we review rapid deformation of the delta plain sediments around the cities (3.3), second, rapid building collapse and its relationship to previously discussed ground deformation (3.4), and third, the amount of excess subsidence expected to result from rapid subsidence events and its extent across the bay (3.5). Finally, we discuss the chronology of the proposed fast subsidence events in light of a fast foundering event recently documented at Alexandria (3.6).

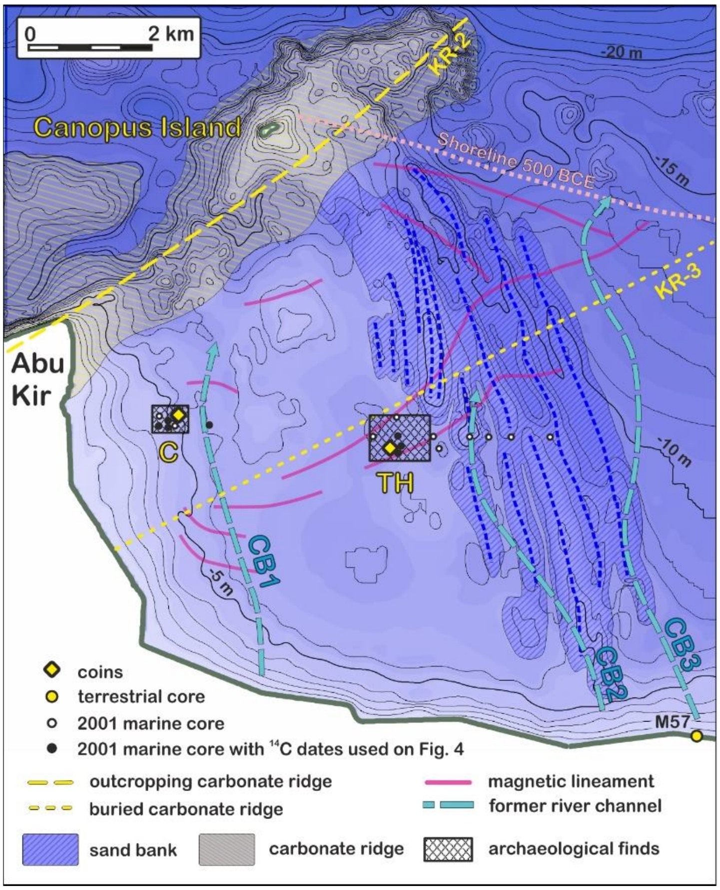

Fig.3. Bathymetry of the western part of Abu Qir Bay, showing the location and extent of Canopus (C) and Thonis-Heracleion (TH), the extent of carbonate ridge KR2 underwater, the projected trace of the buried carbonate ridge KR3, and the location of sand banks emplaced since the flooding of Abu Qir Bay. CB1-CB3 : channels imaged by sea-bottom imaging and interpreted as successive Canopic channels (Goddio F. 2007, Stanley D., Bandelli A. et al. 2007). Shoreline at 500 BCE from Chen Z., Warne A.G. et al. (1992). Magnetic lineaments from (Stanley D., Bandelli A. et al. 2007). Locations of Arabic gold coins from (Goddio F. 2007) and of radiocarbon samples from Stanley D., Bandelli A. et al. (2007). Core M57 from Flaux C., Marriner N. et al. (2017).

3.1 Slow subsidence in Abu Qir Bay

3.1.1. Flooding of Abu Qir Bay: evidence for flexural loading

The age of deposition of delta plain sediments on the floor of Abu Qir Bay has been used to calculate rates of ground subsidence (Chen *et al.* 1992, Flaux *et al.* 2017). The age of the Holocene sediments deposited in the delta shows that subsidence increases across the bay, from 0.1 m/ky at Abu Qir up to 4.5 m ky under the Rosetta Branch promontory (Chen *et al.* 1992). This eastward increase is thought to result from the downwarping of the bay under the load of the Rosetta promontory (Stanley 2005). This increase in subsidence is mirrored by an increase in the depth on the sea floor (figs. 1 and 3), suggesting that the infilling of the bay by marine sediments does not fully counterbalances subsidence. As a matter of fact, cores collected around Canopus and TH (fig. 3), and at the present day shoreline (Stanley et al. 2007, Flaux et al. 2017), show that the bay is still directly floored by the lagoonal and floodplain sediments deposited before submergence. They are covered by a mobile veneer of marine sands, which is generally thin, except between the island of Canopus and the south coast, where a field of submarine sand banks has developed (fig. 3). The delta plain sediments exposed in the vicinity of the archaeological sites are either contemporary to the settlements (fig. 4), or much older (Stanley *et al.* 2007). The exposure of the older sediments is thought to result, in part (Stanley *et al.* 2007), or predominantly (2017), from the erosion of softer, overlying layers by the marine currents that sweep the bay. Deformation of the delta plain layers also brings these deeper layers to the surface (Stanley *et* *al.* 2004). Acoustic sub-bottom profiling (Stanley *et al.* 2007) also evidences an overall north-eastward dip of the delta plain layers, parallel to the sea floor, implying that the overall north-eastward increase in depth of the seafloor results from the increase in the amount of ground subsidence toward the northeast since Antiquity, rather than seafloor erosion by marine currents or marine sediment accumulation.

3.1.2. Rate and amplitude of the subsidence

Canopus lies at depths of 4.0-6.5 m and Thônis- Heracleion at depths of 5.5-6.0 m (Goddio 2007). Using, as milestones, a tentative initial phase of habitation in the 6th century BCE, and a historical report by Sophronius noting that the Church of the Evangelists stood at the shoreline in the 7th century CE, and further assuming that buildings located at sea level during the 7th century CE were initially built in the 6th century BCE two metres above sea level, Stanley *et al.* (2004) estimated that subsidence took place at 2 m/ky over the 13 centuries that separate city foundation from submergence (fig. 4). Flaux *et al.* (2017) noted that, on the southern coast of the bay, their coring site (fig. 3) was invaded and vacated by the sea four times during the past four millennia. This pattern of advances and retreats is much more complex than the continuous landward retreat of the coastline previously envisioned (e.g. Chen et al. (1992), fig.1). They proposed that these retreats and advances were driven by variations in the amount of sediment delivered by the Canopic branch to the delta plain and to the sea, concurring with Stanley *et al.* (2004) that the final flooding was driven by the complete demise of the Canopic branch. The rate of long-term subsidence at this coastal coring site (1-1.6 m per millennium) is similar to earlier estimates (Sestini 1989, Stanley and Warne 1998, Marriner *et al*. 2012). It is also consistent with the subsidence rate (<2.3 m per millennium) of the floodplain sediments surrounding the sunken cities (Flaux *et al.* 2017). It is even consistent with the long-term subsidence rate of 0.8 m per millennium measured at Alexandria (Goiran *et al*. 2018), if one considers that subsidence is primarily driven by flexure under the load of the growing Rosetta Promontory. We recalculated the age-depth distribution of the youngest delta plain sediments cored around the sunken cities (fig. 4), as well as the ages of sea level markers at Alexandria (Goiran et al. 2018) using present-day radiocarbon calibration curves (see Table 1 for details). Radiocarbon samples are terrestrial in Abu Qir Bay and marine in Alexandria. The latter were calculated assuming a global marine reservoir age of ~450-550 y with no additional reservoir correction. Irrespective of their marine of continental origin, radiocarbon ages provide an average subsidence rate of 0.6 ± 0.1 m/ky over the past 6 ky (fig. 4). Such rates must be corrected for sea level rise in the Eastern Mediterranean Sea since Antiquity in order to retrieve true subsidence relative to a fixed vertical reference frame. This aspect is discussed in section

3.1.3 Archeological evidence for slow submergence

At Thônis-Heracleion, slow subsidence forced the dismantling of the main temple of Amun, and the relocation of the city centre to the Central Island, south of its initial location. The new location was presumably sufficiently distanced from the encroaching sea and/or stood on a patch of ground high enough to give the priests confidence to build their temple anew, and to plan for future generations of life there. The archaeological signature for this is seen in the deconstructed remains of the temple of Amun and of the sanctuary of Khonsou-Thoth, which gives a sense of long-term planning and of coordinated activity that contrasts sharply with the evidence associated with rapid events: temples were here carefully taken down, recycled, and ritually deconsecrated. The destruction of the successor to this temple, that of Amun-Gereb, around 100 BCE resulted in the cessation of urban life, but it did not mean that the city was entirely abandoned. There are, for example, a small number of coins from across the Roman and into the Byzantine and Islamic periods, that would suggest possibly sporadic and certainly low levels of habitation (Meadows 2015). It is likely that many of these people were involved in the wides- pread dismantling and removal of materials from the sites, but at least some would have lived amongst the remains of the former city. The pendants in the shape of the cross found at both Canopus and TH (Goddio and Masson-Berghoff 2016, p. 302, p. 340) are unambiguously related to Christian communities living in these remote, and increasingly watery locations at the edge of the sea. On the Central Island of TH for example, a group of nuns built a convent with blocks reused from the pagan sanctuaries (Sophronius of Jerusalem Miracles of Cyrus and John 44, (Peltier 1978) 178, (Goddio 2015), 48), while in Canopus, columns were reused and hard decorative stone was repurposed in the construction of Site T, tentatively identified as the martyrium of St Cyrus and St John (Goddio 2007, p.

33-68). Sophronius furthermore noted that a Church of the Evangelists, which had taken the name of the saints, was standing in the 7th century CE, although, at that time, it was located 'près du rivage de la mer, sur un sol qui n'est ni très ferme. Placée entre les sables et les flots, elle reçoit le choc des uns et des autres' ('Near the seashore, on a ground that is not very firm. Placed between the sands and the waves, it is pummelled by both of them', Miracles of Cyrus and John 29, (Favre 1917), 44-45, (Toussoun 1934), a vivid reminder of the continuation of the slow subsidence of this landscape.

3.2. Deformation in the delta plain: slow or rapid?

The main geological phenomenon susceptible to drive rapid subsidence at the scale of the delta plain is slip on regional faults. However, these faults are too distant from the archaeological sites and of limited lengths to produce metre-scale rapid subsidence at the archaeological sites. The delta plain, on the other hand, bears evidence of soft sediment deformation, which has been used to advocate the occurrence of rapid foundering. We review here the observed deformations at C and TH to assess whether deformation was slow or rapid.

Fluidised layers have been found in sediment cores across the delta plain, near the archaeological sites (Stanley *et al.* 2007). Fluidised layers are unambiguous evidence of rapid ground deformation produced by liquefaction. Fluidisation can be generated by ground shaking, but also by a number of other processes, such as ground stomping by animals, or water table pressurisation of rivers during floods (Li *et al*. 1996, Nelson and Leclair 2006). Soon after the rediscovery of TH and Canopus, rapid loading of the floodplain with sediments during floods was regarded as the main cause of building collapse. Stanley et al. (2004) advocated that mud deformation of the kind observed in the sediment cores was produced by fast loading of delta plain clays, based on observations made along the submarine shoreface of the Mississippi River Delta (Coleman 1988). Deformation there occurs at sea in recent, unconsolidated clays. This setting is not directly transposable to TH and C, because the cities were built on a delta plain already several thousands of years old, and therefore much more compacted. Floods have triggered cracking and upward expulsion of pressurised sands (sand blows) by over-pressurisation of the water table, (Li *et al*. 1996, Nelson and Leclair 2006), but this has only been observed thus far behind flood protection dykes. The dislocation patterns of the sort observed at Canopus are actually often produced by lateral spreading (Obermeier 1996, Hughes *et al.* 2015). Liquefaction and gravitational spreading produce metre-scale, but spatially restricted subsidence in delta plains, and diagnostic patterns of deformation (Obermeier 1996, Hughes 2015, Bradley *et al.* 2019). Arrays of parallel magnetic alignments have been recognized at both Thônis-Heracleion and Canopus (Stanley et al. 2004). The lineaments are produced by contrasts in either the concentration or in the composition of the magnetic minerals present at shallow depths within the ground (0-20 m). The monotonous sedimentation of the delta plain is not expected to produce linear magnetic anomalies in map view. The magnetic lineaments were, therefore, interpreted as evidence for widespread faulting (Stanley *et al.* 2004). At Canopus, they strike N-S, parallel to alignments of building remains, which implies that the anomalies are generated, at least in part, by the buildings them- selves. Nonetheless, a 400 m wide array of tightly stacked, 10 to 25 m wide magnetic lineaments extends to the SW of Canopus, over mostly unexplored areas. The geometry of this tight array is reminiscent of the fault patterns typically produced by gravitational spreading near river channels (Obermeier 1996, Hughes *et al*. 2015). If this is the case, at Canopus, it would then be the result of E-W stretching, likely toward the banks of the north-flowing Canopic channel CB1 (fig. 3).

An array of parallel linear magnetic anomalies is also present at Thônis-Heracleion. The anomalies are 40-wide, and form an ampler array than at Canopus. They strike N50-N75, oblique to the S-N courses of the Canopic Branches CB2 and CB3. The array, therefore, is less likely to result from gravitational spreading. Tilted floodplain layers have been imaged in excavations at TH (von Bomhard 2017, p. 17-19, fig. 2.14). An array of N60° striking, low-lying and narrow ridges with a slightly tighter spacing than the magnetic anomalies (Stanley *et al.* 2007, p. 37) have been found by acoustic imaging 1 km to the NE of TH, behind a modern sand bank (Stanley *et al.* 2004). These ridges are likely made of tilted alternations of resistant and erodible beds of delta plain sediments. They could have been generated by rapid deforma- tion of the delta plain, in association with building destructions at TH (see 3.4). Alternately, they could result from slow deformation. Indeed, the anomalies at TH belong to a much larger, 6 km long magnetic lineament that straddles Abu Qir Bay (fig. 3). This lineament is located above the buried extension of kurkar ridge KR3. The spatial coincidence between the magnetic lineaments and KR3 suggests that the layers that produce the magnetic signal are influenced by the underlying ridge. In TH, the anomalies are stronger in the urban districts than farther afield, possibly because they are reinforced in town by walls and canals. The natural features, therefore, appear to have influenced the choices of the inhabitants of TH with regards to how they developed their lands- cape. Acoustic imaging of the sediments shows that the kurkar ridge lies buried at depths of only 3.5 m to 10 m below TH (Stanley *et al.* 2007). Given that compaction strongly increases with the thickness of Holocene sediments (Stanley and Warne 1998, Marriner *et al.* 2012), the cause of deformation, in this case, could be the contrast between the limited compaction of the thinner Holocene deposits cove- ring KR3 and the thicker Holocene deposits located farther away. Over time, the layers would develop a dip away from the buried ridge crest. They would also provide slight ground prominence in TH, the layout for which might have been designed accordingly. The tilting of the layers above the kurkar ridge has been used as evidence for rapid deformation, if faulting and spreading affect the underlying kurkar ridge (Stanley *et al.* 2004, 2007, Stanley 2005). The acoustic data lack the resolution necessary to directly image fault planes or tectonic separations within the kurkar, such that the data do not provide definitive evidence for the proposed widespread, deep deformation of Abu Qir Bay. If such deformation exists, anyway, it cannot result from soil liquefaction, because the stiff kurkar lies on sediments too deep to be affected by liquefac- tion (Obermeier 1996).

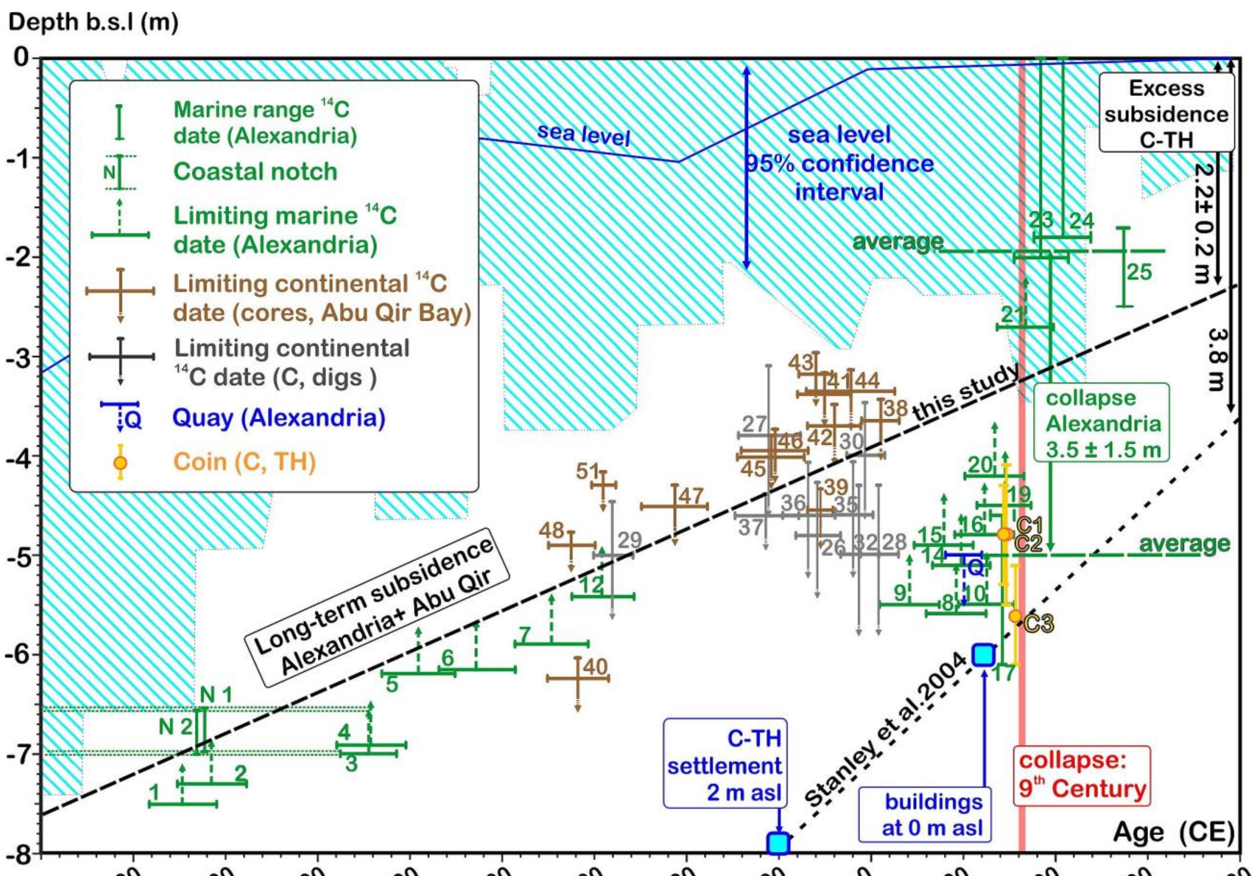

Figure 4: Subsidence chronology at Thônis-Heracleion, Canopus, and Alexandria (combined curve). Sea level marine blue curve from Dean *et al.* (2019), with blue shaded areas in % probability. Numbers refer to samples in Table 1.

3.3. Building collapse and ground deformation in the sunken cities

Canopus bears the strongest evidence of building deformations associated with rapid ground deformation. Building TW2 possesses a 30 m long outer wall, likely built as part of a Byzantine Christian complex. The wall seems affected by a sag in the underlying sediments. The sag, therefore, seems to postdate wall construction (Goddio 2007, p. 61-65). The wall was subsequently levelled, and its stonework reused elsewhere, prior to the disappearance of Canopus in the 8th century CE, indicating that the building had been damaged much earlier. At site T, a 2.3 m deep, 20°N-striking trench was cut into the delta plain muds. Its floor was trampled by animals and covered with plants during the 1st to 2nd century CE, before being filled by sand (Goddio 2007, p. 36-9, figs. 2.10-2.14). The trench has been regarded either as man-made (Stanley et al. 2004), or as a natural crack (Goddio 2007). Vertical cracks affect stiff clays at the bottom of the trench. These are a clear indica- tion of deformation. The trench is filled by a thick, artefact-free infill of fine sand that contains marine shells. The overall scene is potentially compatible with gravitational spreading. Indeed, a man-made trench, cutting through a substantial thickness of delta plain clays, reduces the clay layer resistance to stretching, and can be expected to focalise the formation of tension cracks into the clay during spreading. These cracks can then act as escape ways for the underlying, fluidised marine sands (sand blows), that would then fill in the trench. At least two phases of occupation follow the infilling of the trench, the most important being a Byzantine religious structure constructed in a monumental fashion, reusing older architectural and decorative elements. Islamic coins were discovered in the excavations of this later building, suggesting that it was still in use during the final submergence of Canopus in the 8th century CE. Both sites TW1 and T, thus reveal ground deformation events prior to the 8th century CE. Deformation remained localised and was dealt with by the population of Canopus who continued to live in the city.

At Thônis-Heracleion, indices of ground deformation are less obvious, but building collapse is more clearly documented by catastrophic deposits associated with the destruction of the temple of Amun-Gereb at the end of the 2nd century BCE. The destruction of the temple on the southern edge of the Central Island, appears to be associated with a landslide to the south, which resulted in the slumping of a stone-built quay over a ship, which was tied up against it, sinking the ship beneath the waters of the South Temple Channel, and covering it with debris (Robinson 2018, p. 327-328, fig. 2). The material from the destruction of the quayside, notably coins and pottery, provides a clear dating horizon from the middle to the end of the 2nd Century BCE (Robinson and Goddio 2015, p. 3-4), which also accords with other destruction deposits from around the temple. The profound impact of this event on the city can be seen in studies of the entire corpus of numismatic and ceramic materials, which suggests that it resulted in the abandonment of the city. Numismatic evidence reveals a break in the pattern of circulation of coinage in the mid-2nd Century BCE (Meadows 2015, p. 131). A similar break is noticeable among ceramics, but at a slightly later date, between 150 and 125 BCE (Grataloup 2015, p. 145). A final temporal constraint on the abandonment of the city is provided by the 6 m tall bilingual stele of Ptolemy VIII, which was erected most probably shortly after 118 BCE (Thiers 2008, Goddio 2015, p. 46-47), although it could date to either 141/140-131 or 124-116 BCE; the periods when Ptolemy VIII was in power. Given that this stele records a reinstatement of land to the priesthood of the temple, it seems unlikely that this would have been done while the temple itself was in ruins and the city in the process of being abandoned. Taken together, these data document slumping in the final quarter of the 2nd century BC, followed by large-scale abandonment of the temple, the city, and its port. Submergence of the slumped material into the waterways around the Central Island protected them from centuries of scavenging, recycling, and reuse that would have otherwise removed much of the datable material associated with these ground failures.

The general corpus of data available in Abu Qir Bay supports widespread deformation of the delta plain around TH and Canopus, as well as below Canopus. Some of this deformation was undoubtedly instantaneous (fluidisation of delta plain sediments, quay collapse in TH). Some deformation at Canopus clearly occurred during its occupation. That defor- mation was quite likely instantaneous (cracks at the bottom of trenches feeding putative sand blows, magnetic array of tight lineaments), and overall, well accounted for by gravitational spreading.

Deformation at Canopus affects Byzantine constructions, while at TH, the collapse of the temple occurred at the end of the 2nd century BCE. If both events were triggered by rapid ground deformation, then either each event was restricted to one city, or affected both cities but evidence for successive events in each city has not been found yet. This is plausible, considering that perhaps as little as 5 % of TH has been investigated (Goddio and Robinson 2016). Much of the evidence at TH points to fast foundering events taking place during the Ptolemaic period (305 to 30 BCE). What may appear to be a lack of evidence of damage during later times may relate to excavation strategies and priorities at the site. Excavations have concentrated on the collapse of the temple of Amun- Gereb because of its major influence in the history of the port city. This does not preclude later events, contemporary those affecting Canopus during the early Byzantine period (330-700 CE), which in TH would affect the more ephemeral remains of Late Antiquity.

The best candidate for rapid collapse, therefore, rather than downfaulting of the entire delta plain, is localised, soft-ground deformation. Soft-ground deformation events could be localised, randomly occurring events affecting Abu Qir Bay, or synchro- nous events with a regional trigger. The regional trigger is most likely ground shaking by teleseismic earthquakes, because, over the past few centuries, teleseismic earthquakes have been able to damage settlements in the Nile delta, and have the potential to trigger submarine landslides over the delta cone (see section 2.2).

3.4. Excess subsidence at the sunken cities

As exposed in section 3.1, long term subsidence in Abu Qir Bay was calculated by Stanley et al. (2004) using a putative original elevation for architectural elements built around the time of settlement of the cities. Using that estimate, they found that subsidence proceeded at 2 m/ky over the 13 centuries that separate settlement from submergence. Continuation at such rates, up to today (fig. 4), then accounts for 4.6 m of the total 8 m of inferred total subsidence. The missing 3.4 m of subsidence were ascribed to fast subsidence during the 8th century CE (Stanley *et al*. 2004). Recalibration of the radiocarbon ages of delta plain sediments deposited around the cities before the marine transgression from 2 ,000 BCE to 100 CE (Table 1) suggests that the delta plain subsided at ≤ 1.1 m/ky. If subsidence proceeded at the same rate up to today, then 2.0-2.5 m submergence are not accounted for by slow subsidence of the delta plain (fig. 4). The closest assessment of glacio-eustatic sea level rise straddling the period of interest comes from the tectonically stable southern part of the Levantine coast (Dean *et al*. 2019). It indicates that glacio-eustatic sea level has risen 0.8 ± 0.4 m since the settlement of the cities (fig.4). Here, this glacio-eustatic sea level rise incorporates the rise in sea level resulting from the increase in the volume of the oceans, and the downward adjustment of the lithosphere to the load represented by the water that has entered the Mediterranean Sea since the last Glaciation, combined with a distal response, the melting of the Scandinavian ice cap. The remaining 0.8-2.1m of subsidence therefore, represents the amount of subsidence restricted to the bay itself, not accounted for by constant, slow subsidence, which could result from rapid foundering. The excess subsidence of the cities with respect to the surrounding delta plain could result from ampler and more localised foundering below the buildings. In Canopus, floodplain muds lie at a depth of 5 m at site T (Goddio 2007), a bit deeper that the surrounding delta plain (4.1 ± 0.9 m, Table 1). Not enough information is available at TH to assess the amount of excess subsidence relative to the surrounding plain, but Goddio (2007) stresses that the sinking of the buildings and quays relative to channel fills makes it difficult to appreciate the former topography of the site.

The excess subsidence of the archaeological sites has been ascribed to ground compaction below buildings during the centuries following their construction. Compaction would account either in part (Stanley *et al*. 2004) or in whole (Flaux *et al*. 2017) for excess subsidence. If compaction is entirely responsible for excess subsidence, then no fast subsidence is required (Flaux *et al.* 2017). Ground deformation and building collapse led Stanley *et al.* (2004) to propose instead that part of this excess subsidence was instantaneous. We propose that excess subsidence could result from lateral spreading toward the channels of the Canopic Branch and the harbour basins. To accommodate such a large amount of subsidence, the channel or basins would have to reach depths of 4 m at bankfull discharge, to allow for the banks to collapse by a similar amount. This requirement is compatible with the depth of the Nile today (Helal *et al.* 2020), if one assumes that the Canopic branch was then the main distributary channel of the delta (Stanley *et al*. 2004).

It has been argued that rapid subsidence of the entire floodplain is not required to account for the more moderate subsidence of the delta plain. First, because marine erosion may have removed the most recent delta plain sediments (Flaux *et al.* 2017). These missing layers would plot on Figure 4 above the displayed limiting continental dates, shifting the curve upward. Also, the most recent, hence most easily erodible sediments of the floodplain, are likely to plot within the 500 BCE-500 CE interval, steepening the slope of the subsidence curve, thus decreasing or even annealing the need for fast subsidence. Second, they argued that slow subsidence is not steady over the duration of the record, because the location of the Nile branches has changed over the period, and with them, the locus of sediment loading (Stanley 2005, Flaux *et al.* 2017). In the absence of definitive evidence for tectonic faults or large slides affecting the bay, no clear driver of wholesale lowering of the delta plain can be identified. As a result, and with the available knowledge, fast subsidence in the cities is more easily accounted for by ground failure below the buildings by soil liquefaction, and by lateral spreading, than by wholesale rapid lowering of the entire delta plain.

3.5. Fast subsidence and fast submergence during the 8th Century CE

Soon after the rediscovery of the sunken cities, it was noticed that the cessation of archaeological evidence was synchronous at C and TH. This event was dated to the 8th century CE by their latest Islamic gold coins (Canopus: 729-730 CE, TH: 775-785 CE (Goddio 2007, Table 1, fig.4). It was, therefore, proposed that a fast subsidence event was responsible for their synchronous submergence (Stanley *et al*. 2001, Stanley et al. 2004). At Canopus, the evidence comes from the Church of St John and St Cyrus at site T (Goddio 2007, p. 67). A catastrophe-like set of remains creates the impression of a building stopped at a moment in time (Goddio 2007), p. 47). Elements of sculpture, columns, and other architectural elements were in the process of being reworked and recycled into the construction and decoration of the religious building. Jewelry, which included both finished and unfinished pieces, as well as the materials from which to manufacture them, indicates the presence of a workshop (Petrina 2010). The quantity of gold from site T – over 250 pieces found so far – appears to be a clear indicator of a catastrophic event. If the site was abandoned due to a slow rise in sea level (Flaux *et al.* 2017) one would expect the artisans to have taken their valuable gold with them. Flaux *et al*. (2017), upon challenging the existence of the fast subsidence events, proposed that abandonment of the cities resulted from shifting trade routes. The interpretation seems at odds with the ascetic tradition at the heart of the growth of monasticism in Late Antique Egypt (Hedstrom 2017) and the impulse for people to move to TH and C in order to remain at the fringes of society during the Byzantine period. It is also at odds with the importance of buildings such as the Church of St Cyrus and St John, as places of pilgrimage, before the final abandonment of the cities.

The recent discovery of a rapid foundering event in the harbour of Alexandria (Goiran *et al*. 2018), provides some support for a rapid final submergence of TH and Canopus in the 8th Century CE. In Alexandria, the event is marked by a 3.5 ± 1.5 m drop in the elevation of Roman quays, pebble beaches, and strandlines (Goiran *et al*. 2018). The recalibrated ages (fig. 4) indicate that this event occurred between 720 ± 150 CE and 840 ± 150 CE, which makes it coincide with submergence of TH and C in Abu Qir Bay. The event particularly affects areas supporting heavier buildings and structures (Goddio 2021, p. 45-47). The geological context is markedly different from that of TH and C, however, in that many elements of infrastructure and buildings rest directly on the cemented carbonate (kurkar) ridges. These are not susceptible to collapse by gravitational spreading, nor to deformation by large floods from the Canopic Branch. The quays that sank in the 8th century, however, may have been built on soft, fine-grained marine sediments deposited in a relatively quiet natural harbour, sheltered from the open sea by the outer kurkar ridge (ridge I, fig.4). Shaking of port structures triggers underlying sediment compaction and their lateral expulsion (Waltham 2002). At exposed locations, a strong swell is able to entrain structure foundering (Galili *et al.* 2021). In Alexandria, however, the quays are sheltered from strong swells, which makes foundering by ground shaking more likely. The source of the shaking could be a distal (teleseismic) earthquake, sourced north of the Eastern Mediterranean Basin, in Anatolia, Cyprus or the Aegean Sea, which have been shown to affect structures in the Nile Delta (Ambraseys and Adams 1998, El-Sayed *et al.* 2004), or a local earth-quake, although such earthquakes are not expected to generate strong shaking. In this later, less likely case, shaking could be associated with the activation of growth faults in the delta plain north of the flexure zone (fig. 2), either on land or at sea. It could also result from the activation of the Rosetta Slide to the north of Abu Qir and Alexandria, with associated far field lowering of the coast, or release of deep fluids, such as brines, or hydrocarbons. The rapid sinking of structures on harder ground, however, implies whole- sale rapid subsidence of the kurkar ridge, and would require the activation of faults associated with the deep deformation of the delta, much farther south than the Rosetta Slide. Such an event would account for the component of subsidence in Abu Qir Bay not directly accounted for either by the excess subsidence of the sunken cities, or by constant, long-term subsidence. The structures associated with such deep deformation, involving Alexandria and the sunken cities, remain to be identified.

Conclusions

The Nile delta plain is subjected to slow, long-term land subsidence driven by sediment loading, sediment compaction, and the creeping of the delta toward the Mediterranean Sea. Additional, recent subsidence results from water and hydrocarbon extraction. Rapid, quasi-instantaneous subsidence of regional extent may result from displacements across growth faults and giant slides. More localised rapid subsidence may result from riverbank collapse, ground liquefaction, and fluid escape. These later are likely to be triggered by floods or earthquakes.

In Abu Qir Bay, slow subsidence appears to be driven by sediment loading and sediment compaction. There is a general consensus that the demise of the Canopic Branch of the Nile reduced the amount of sediment deposited across the delta plain and the foreshore. In the absence of natural land regrading of the delta plain by sediment, subsidence was the main driver of marine transgression into the bay. In the now submerged cities of Canopus and Thônis-Heracleion, there is evidence that progressive invasion of the sea was responsible for a repurposing of structures, reorganisation of the cities, and for their progressive demise.

It has been proposed that a component of fast subsidence also affected the sunken cities of Thônis-Heracleion and Canopus. Fast subsidence was called upon to explain the synchronous submergence of both cities, and their sudden abandonment. Additional evidence would include an excess amount of subsidence, compared to the amount of subsidence expected from long-term subsidence alone, deformations of the ground, regarded as rapid events, and other, earlier catastrophic collapses in the cities.

Taken individually, the additional evidence can be disputed. The overall subsidence of the floodplain surrounding the sunken cities can be explained by floodplain erosion and uneven long-term rates of subsidence, driven by the shifting pattern of sediment loading across the Nile Delta. Some of the deformation observed in the floodplain and in the cities may have developed slowly, and fast deformation and building collapse do not require fast ground subsidence.

Some of the deformation in Canopus, however (fluidized layers, arrays of parallel faults near river banks, cracks at the bottom of trenches) is highly reminiscent of the lateral spreading produced by soil liquefaction. Building and quay collapse in TH may, therefore, also result from soil liquefaction. Soil liquefaction is enhanced by the presence of building loads, and may, therefore, account for the excess subsidence documented into the two cities, with respect to the surrounding delta plain, and the observation of a general levelling of the ground surface in TH. The recent discovery of a fast subsidence event in the harbour of Alexandria, synchronous with the submergence of the two cities, over structures potentially built partly on marine sediments supports the view that the fast deformations observed at the two cities, affecting the ground and the buildings, did not strike randomly in time and space, but were synchronous, and triggered by a regional phenomenon. The most likely trigger is ground shaking during earthquakes. The most likely source of potent, low frequency shaking is distal earthquake, located along the Aegean-Anatolian subduction zone, rather than a seismic source located in the delta proper.

Less evidence comes in support for a rapid subsi- dence affecting the entire floor of Abu Qir Bay. The deep seated deformation of the Nile Delta may, at times occur rapidly, driving rapid ground subsidence. Thus far, however, none of the active structures asso- ciated with that deformation extends close enough to Abu Qir Bay to drive wholesale lowering of the floor of the bay. Some of the structures affected by fast subsidence in Alexandria appear to be set on a hard substrate. Their rapid foundering, conversely, requires displacement of such structures. Part of the rapid foundering, in this case, could be of regional extent, and not only restricted to the cities, driven by defor- mation on structures that have not yet been identified.

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