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Deformation of the ancient mole of Palairos (Western Greece) by faulting and liquefaction

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A B S T R A C T

A submerged 2300 years-old mole or breakwater with a sigmoidal shape has been identified at the Palairos harbor (Akarnania, SW Greece mainland). Different possible scenarios could be proposed to explain this enigmatic shape for an ancient breakwater, such as selective erosion of the original structure, construction above existing shoals or reefs, gravity sliding and post-construction offset due to strike-slip faulting, but all these scenarios seem rather weak. Inspired by a large scale lateral offset of a retaining wall of a quay at the Barcelona harbor due to static liquefaction, by evidence of strike-slip earthquakes and of liquefaction potential in the study area, as well as by recent evidence for long-duration steady, nearly uni-directional dynamic displacements in the near-field of strike-slip faults, we propose an alternative scenario for this mole. An earthquake associated with strike-slip faulting and high acceleration produced liquefaction of the mole foundations and long duration, nearly unidirectional tectonic slip, while the later part of the steady slip produced additional secondary (surficial) slip on liquefied layers.

1. Introduction

In the framework of a marine archaeological survey in Akarnania, South Western Greece mainland, W. Murray identified and surveyed remains of an ancient submerged breakwater or mole at the Palairos Bay, near Pogonia (Fig. 1; Murray, 1982). A particularity of this breakwater is that it has a sigmoidal pattern and it seems to consist of two overlapping, or better en echelon segments (Fig. 2). This is an extraordinary pattern for an ancient breakwater (Blackman, 1982; Marriner and Morhange, 2007) and a question arises: does the present-day shape of the mole reflect the original structure, or its sigmoidal pattern is a result of post-construction deformation due to natural effects or to deliberate destruction/ modification of the ancient mole?

For years this ancient breakwater, >200 m long, was ignored and has only been regarded as evidence of sea-level rise (Pirazzoli and Pluet, 1991; Vött, 2007) and no clear explanation for its unusual shape was possible to be given. However, recently there have been three lines of evidence which may permit an alternative explanation for the unusual shape of the breakwater: (1) a recent failure of the Prat Quay in the Barcelona Harbor due to static (i.e. non-seismic) liquefaction which caused lateral offsets of tens of meters (Gens, 2015), (2) there was found evidence of strike-slip faulting and of liquefaction in the wider Palairos area (see below, Section 4) and (3) it was found that in the near-field of a strike-slip fault co-seismic dynamic displacements have a very particular pattern and correspond to a steady, nearly unidirectional movement covering a considerable part of the strong motion (Fig. 3a; Saltogianni et al., 2016). Evaluation of this evidence permits to propose an explanation for the Palairos harbor: that the sigmoidal failure of the ancient mole is due to a combination of strike-slip faulting during an earthquake, liquefaction and destruction by wave action. This explanation seems more likely than other alternative explanations.

2. The Palairos ancient breakwater

During his survey in the wider Palairos area and close to the coast marked by ancient remains at Pogonia Murray (1982) identified a nearly linear mass of rocks offshore, extending up to a distance of approximately 250 m from the modern shore. The upper part of this structure is limited between the depths of 1 and 3 m below mean sea level. Several lines of evidence indicated that it could be identified with remains of an ancient breakwater or mole, partly silted: (i) It consists of irregular boulders aligned to a nearly E-W direction, very favorable to produce a harbor protected by the southerly winds and is parallel to a modern mole farther south (Fig. 2); (ii) it does not correlate with any natural ridge which could trap boulders; (iii) the dimensions of the structure are compatible with those of ancient Greek moles (up to 600 m long; Blackman, 1982); (iv) it is located very close to ancient coastal remains and its northern, wave-protected part is marked by abundant fragments of datable pottery (amphorae fragments), evidence of marine transportation of goods in antiquity.

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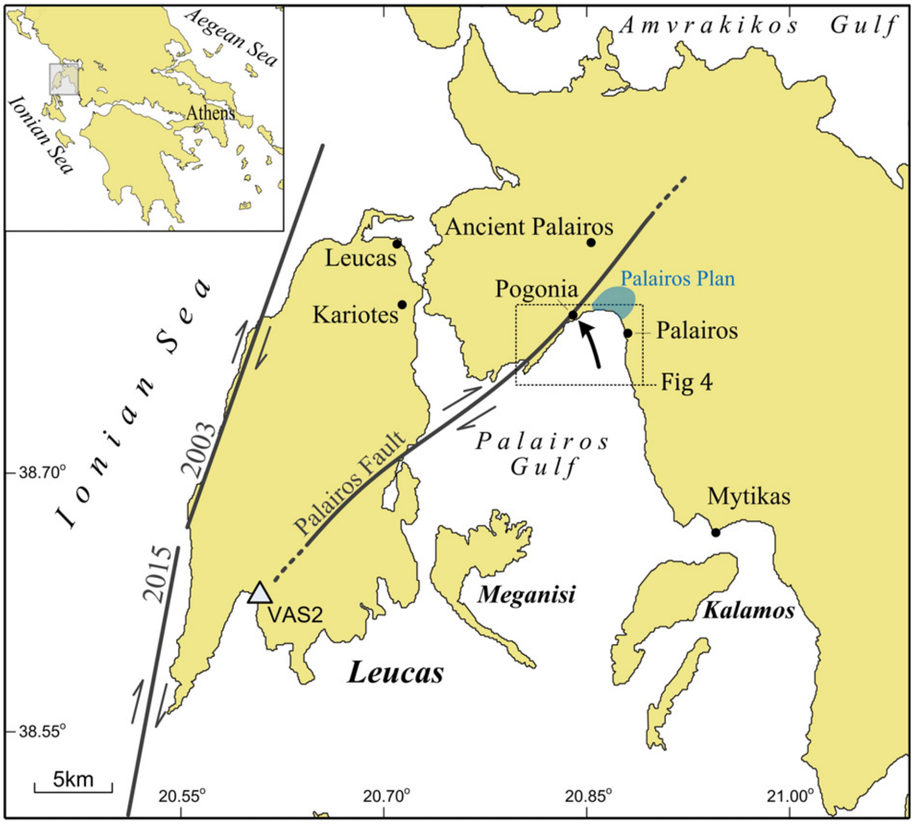

Fig. 1. Location map. An arrow indicates the location of the ancient mole along the Palairos Fault, for simplicity shown as a single line, but in reality corresponding to a shear zone. A square marks the area of Fig. 4. The strike-slip faults of the 2003 and of the 2015 earthquake (after Saltogianni and Stiros, 2015 and unpublished data), the most recent and documented strike-slip faults in the area, are shown. A triangle indicates the VAS2 accelerometer.

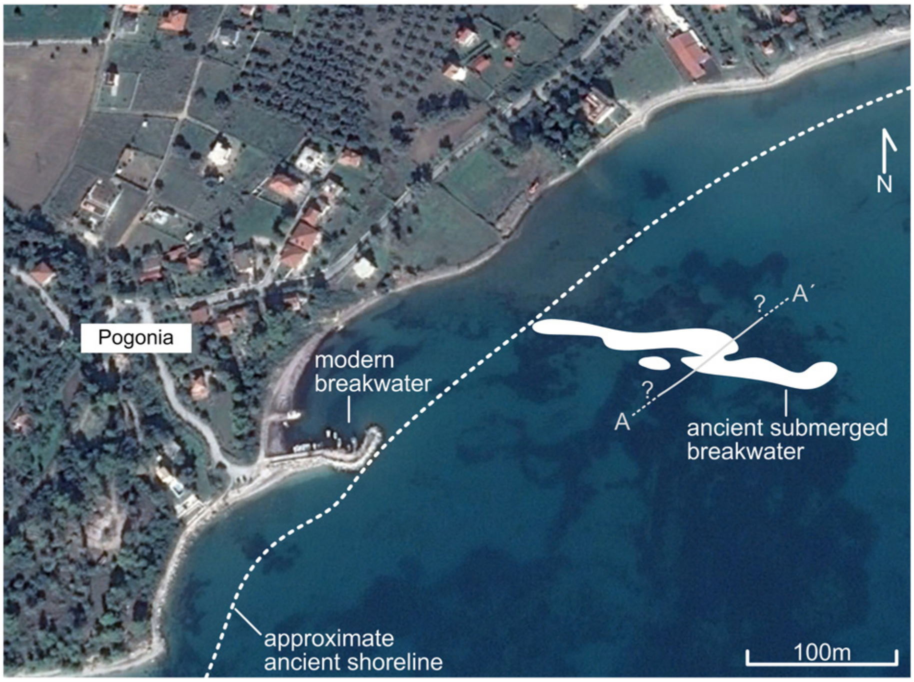

Fig. 2. Location map for the Palairos mole (based on data of Murray (1982, 1985), superimposed on Google Map imagery, for location see Fig. 1. Mark the unusual shape of the ancient submerged mole, consisting of two segments. Line AA′ indicates approximate sense of lateral offset, which needs to follow only roughly the fault because of secondary dislocation (liquefaction). A dashed line indicates the approximate shoreline during the period of use of the mole (see text for details). The Palairos fault zone covers a zone roughly striking along the coastline.

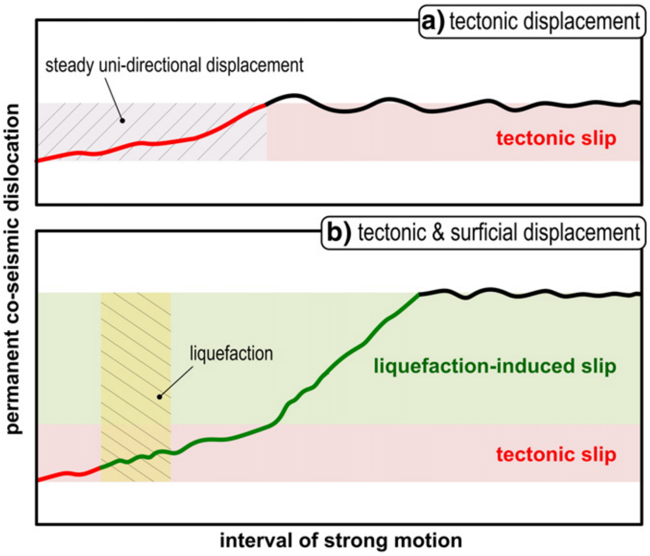

Fig. 3. Typical records of dynamic displacement along or in the near field of a reactivated fault during the strong motion of an earthquake. (a) Displacements induced by tectonic motion. A red zone indicates the width of permanent seismic dislocation ("fling step"). A red line indicates a very long-period steady, nearly uni-directional dynamic displacement (based on Saltogianni et al., 2016 and references therein). (b) Conceptual model for the dislocation of the Palairos mole. Displacements induced by a combination of tectonic motion and of liquefaction (green line). Due to the viscous behavior of the foundations, the liquefaction-induced slip is expected to be several times larger than a typical tectonic movement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The observed west edge of the breakwater is about 50 m from the modern coast, but sea-level rise in the last millennia (Pirazzoli and Pluet, 1991) is expected to have produced marine transgression and landward shifting of the shoreline (see Fig. 2), while the westernmost part of the mole to be covered by silt.

Murray (1982) surveyed in details this structure offshore, which in some points slightly only protrudes from the present-day sea bottom due to silting, and his plans are summarized in Fig. 4a. His data and analysis indicate that although the surviving structure is not characterized by any paved surface, an original upper layer at least 0.5 m thick is missing due to wave action and that the uppermost surface of the mole has a consistent pattern. A sigmoidal pattern is also obvious (Fig. 4a). In addition, based on dating of ancient pottery fragments and historical data Murray (1985) concluded that the ancient harbor was most probably constructed between 380 and 330BC, and served to protect the harbor of the nearby small town of Palairos which lasted for a few centuries.

3. Scenarios for the pattern of the ancient mole

Murray (1982) noticed the unusual shape of the remains of the ancient mole and in lack of any other explanation he discussed the possibility to originate from a platform-type structure which was eroded by waves in its NE and SW parts, so that only the central part, 30 m wide describes the original structure. This scenario is not easy to accept for two reasons. (1) There was no reason for such an unusually wide and expensive platform-type mole in a small and short-lived town like Palairos; indeed, the width of ancient moles or breakwaters constructed in antiquity in shallow waters was limited to approximately 10 m maximum, a width necessary to provide structural stability and functionality in shipping usually light cargo. Breakwaters much wider and made of hewn blocks were very rare in antiquity, and certainly limited to major harbors and deep waters. (2) The proposed pattern of erosion which produced the sigmoidal shape of Figs. 2 and 4 (linear erosion to the NE and SW, near the coast) cannot be justified; erosion is associated with vortices and is unlikely to end at quasi-linear fronts. In addition, the mole is silted along its northern edge, and this is indicative of deposition, not of erosion. In fact silting prevented the use of the ancient structure as foundations for the modern mole, which was shifted southwards (Fig. 2). A second possible scenario is that the sigmoidal shape of the mole reflected an original structure adapted to the local micro-topography, i.e. built between certain shoals or reefs, as was the case in antiquity (for a parallel, the Alexandria, Egypt, harbor; Marriner and Morhange, 2007). According to this scenario, the western part of the mole (BB′ in Fig. 4) was built between the shore and the northern part of a central shoal (or micro-reef), explaining the increased width of the mole at its central part, while its eastern part was built between the southern part of this shoal and of another one farther east. Still, there is no evidence of such shoals and the overall morphology and geology of the area (Fig. 4) do not favor this explanation.

A third possible scenario is that the observed structure indicates an originally linear breakwater offset by a gravity-driven slide, not unusual in the area (Hasiotis et al., 2002). This last possibility can be rejected, however, because in the case of gravity-sliding, the direction of transport should be towards the deeper parts of the gulf, i.e. towards SE, not SW, while more important vertical dislocations than those deriving from Fig. 4b would be expected.

A fourth possibility is the offset of the breakwater by strike-slip faulting. Clearly, strike-slip faulting is not unusual in the geological

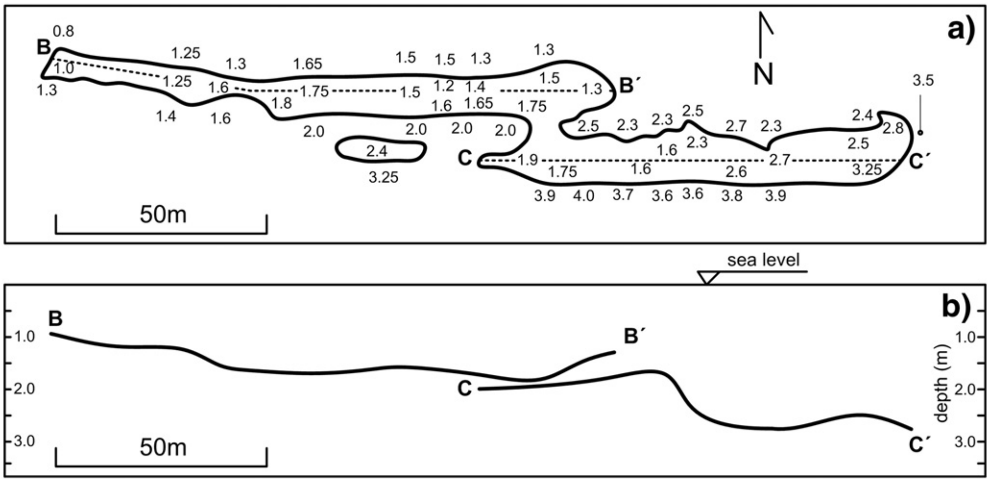

Fig. 4. (a) Details of the bathymetric survey of the mole at Palairos. Numbers indicate depth below mean sea-level. Redrafted after Murray (1982, 1985). (b) Plot of depths of the axes of the two segments of the mole (doted lines in (a)). Based on data in (a).

record of the wider area (BP Co. Ltd., 1971) which is tectonically active, while in various cases offsets of ancient constructions along strike-slip faults exceeding 10 m in 2000 years are known (Meghraoui et al., 2003). However, we were so far reluctant to propose this explanation for two basic reasons. Till recently, there was no evidence of significant Holocene and recent strike-slip faults in the broader area, while the inferred amount of slip, is of the order of several meters (Fig. 4), too large for a small strike-slip fault in a period of 2500 years.

A fifth scenario, combining strike-slip faulting and liquefaction-induced slip during the strong motion is proposed below.

4. Geological and seismological background

The Palairos Gulf and plain represent a tectonic depression between two structural highs of a highly faulted carbonate Mesozoic platform. The western coast of the Gulf is marked by a zone of parallel, narrow-spaced, subvertical faults with evaporitic diapirs, offset by faults of various orientations (Fig. 5; Manakos et al., 1996), thereafter named the Palairos fault-zone (Fig. 1). This fault-zone controls the morphology of the west coast of the Palairos Gulf, is likely to extend offshore and has been interpreted as a strike-slip fault (BP Co. Ltd., 1971) and may explain diapirism as a positive flower structure in a complex fault pattern.

Sedimentological studies based on vibracoring indicate that the Palairos plain is covered by a layer of coarse to fine littoral and lagoonal Holocene unconsolidated sediments, about ten meters thick close to the seafront (Fig. 5c; Vött et al., 2006). It is reasonable hence to accept that this layer extends offshore and its thickness increases towards the depocenter (i.e. towards the mole). On this background, susceptible to liquefaction and faulting, the ancient breakwater was built.

The only significant late Holocene paleoenvironmental change observed in the Palairos area is a relative sea-level rise first documented by Murray (1985) and confirmed also by Vött (2007). In particular, it was documented a >2 m relative sea-level rise since the function period of the harbor (4th c. BC) resulting to marine transgression which separated the ancient mole from the present-day coast.

No clear signs of tectonic activity in the Palairos area have been found (Pérouse et al., 2016) but in the nearby Myticas area (Fig. 1) another submerged harbor provides evidence of episodic subsidence in antiquity (see Pirazzoli and Pluet, 1991). In particular, in the mole of the Myticas harbor, a paved layer was added on top of the original paved surface. The only reason for this raising of the mole surface was to counteract an increase of the relative sea level (Murray, 1985) after a seismic subsidence, in analogy to what has been observed in the Rhodes harbor (Stiros and Blackman, 2014).

Evidence of Late Holocene tectonic activity is consistent with intense seismicity, especially in the Leucas Island (Fig. 1), the constructions on which have been destroyed in past by numerous earthquakes. As a consequence, Leucas was the first area in Greece and probably in the world in which a strict antiseismic construction code, structures with specific timber bracing was introduced (Stiros, 1995). In their majority, earthquakes in the wider Leucas area were probably not of high magnitude, but are associated with locally high accelerations. Two examples are the recent 2003, M6.2, and the 2015, M6.6, Leucas strike-slip earthquakes (faults shown in Fig. 1). The 2003 earthquake was associated with peak near-field accelerations ~0.5 g. Liquefaction seems to accompany earthquakes in the wider area (Gazetas et al., 2006; Papathanassiou et al., 2016) and especially damage harbor constructions at distances of several kilometers from the seismic fault. For example liquefaction and associated displacements of >20 cm were observed in harbor construction of Leucas town (Gazetas et al., 2006; Fig. 1). Accelerations (peak values >0.3 g), velocities and displacements during the 2015 earthquake from the accelerometer station VAS2 in SW Leucas (for location see Fig. 1) are shown in Fig. 6.

Apart from this earthquake associated with strike-slip faulting offshore, there is evidence of a major 2008, Mw6.8, strike-slip earthquake SW of Patras (Feng et al., 2010), of a strike-slip fault east of Palairos (Pérouse et al., 2016) and of small strike-slip earthquakes with limited surface rupture, mostly en echelon ruptures NW of Palairos (Koukis et al., 1990). Some evidence of strike-slip faulting from shearing deformation of ancient box-type graves (cf. Stiros, 1988) exists in the Kariotes area in Leucas as well (unpublished data; for location see Fig. 1). All these data indicate that Holocene strike-slip motions in the wider Palairos area are likely, and that the possibility of reactivation of the Palairos fault zone in the last 2000 years is high.

On this background, reactivation of the NE-SW trending Palairos Fault zone, crossing the Pogonia area (Fig. 1) is possible and may explain

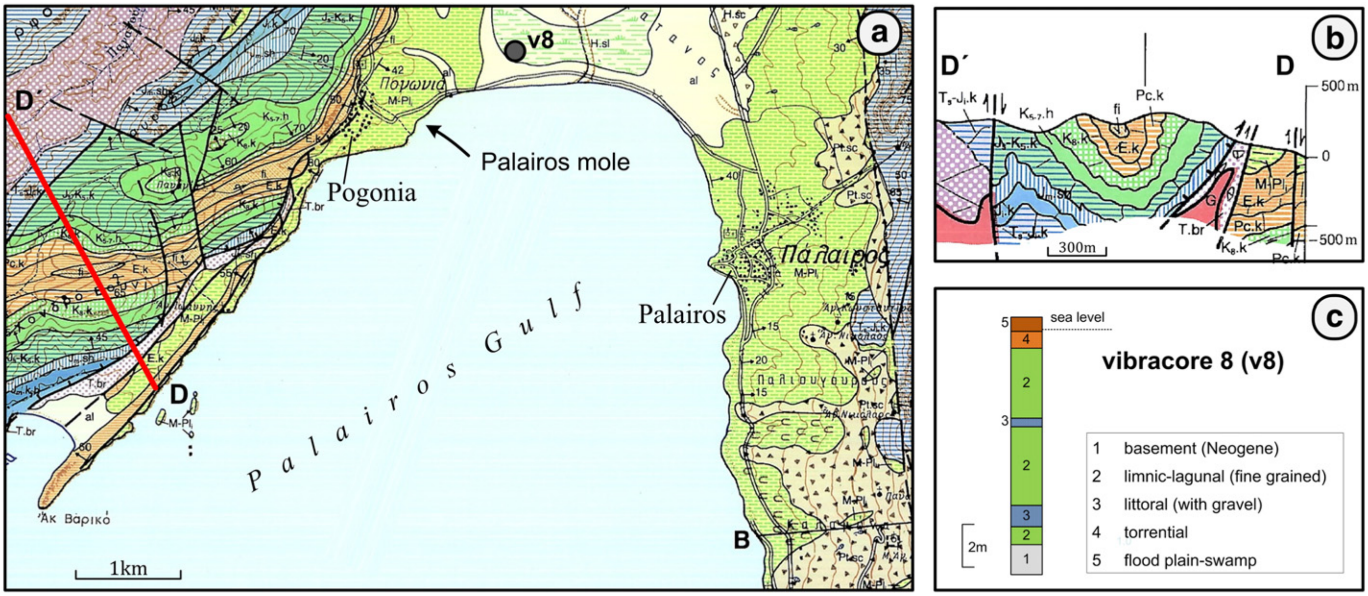

Fig. 5. Geology in the study area. (a) Geological map of the Palairos-Pogonia area, modified after Manakos et al. (1996). The Palairos-Pogonia plain is built of Miocene (M) to Pliocene (Pl) consolidated sediments covered by Holocene (H) aluvia (al), and locally swamp sediments (sl) and scree (sc). (b) Geology along section D-D′ in (a). (c) Stratigraphic column from vibracore 8 (v8) of Vött et al. (2006) in the Palairos plain, proximal to the coast and the ancient harbor (location marked in a). An about 10 m thick layer of lagoonal, limnic and littoral sediments susceptible to liquefaction is observed above the Miocene basement. The west coast of the Gulf of Palairos is marked by the Palairos strike-slip zone (for location see Fig. 1), appearing as subvertical faults in (b).

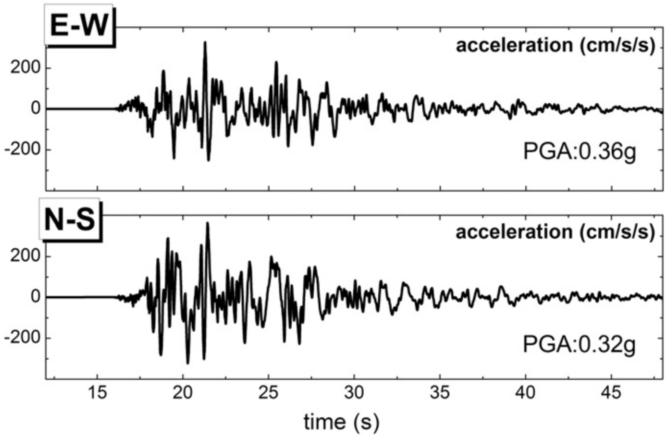

Fig. 6. Acceleration records in E-W and N-S component derived from the recordings of the 17 November 2015, Mw 6.6 strike-slip earthquake in Leucas in VAS2 station (after ITSAK, 2015; for location see Fig. 1). This pattern seems typical for the area. Long-period oscillations are evident in the first seconds of the strong motion, and relatively high amplitude oscillations continue for several seconds. This pattern of strong motion is consistent with the proposed scenario for the Palairos mole. Important to notice that this high acceleration level was observed ~5 km kilometers away from the causative fault, and along the causative fault (shown in Fig. 1) much higher acceleration is expected.

an earthquake producing high accelerations and small amplitude (fraction of a meter) tectonic strike-slip offsets. Also, due to the significant thickness of coarse-to-fine littoral and lagoonal Holocene unconsolidated sediments (Fig. 5), extensive liquefaction is expected in the Pogonia area, as is the case with the Leucas Town (see above). Liquefaction in the Pogonia area may be combined and enhanced by mobilization of evaporites outcropping in the area (T-br in Fig. 5); this is because due to high strain rates during earthquakes evaporites (salt, gypsum and breccia, conglomerates with a matrix of salt and gypsum) are mobilized and temporarily transformed into high-viscous fluids (Jackson and Talbot, 1986; Stiros et al., 1994; Davison, 2009). A question of course is whether such mobilization of evaporites (and of its effects) can occur during the strong motion or much later.

5. A case of liquefaction-induced large-scale offsets in marine structures

Liquefaction is produced in unconsolidated fine sediments usually by earthquakes (dynamic or seismic liquefaction) and occasionally without earthquakes (static liquefaction). Because of pressure saturated or nearly saturated soils lose their strength and behave like a liquid. During liquefaction soil foundations of structures in particular, behave like high viscous fluids on which structures tend to float. Because of the strong motion liquefaction is known to have produced lateral displacements, but their amplitude is certainly small, typically a fraction of a meter (Ye and Wang, 2015; see also Gazetas et al., 2006). Still, in these cases liquefaction is not observed along a seismic surface fault.

However, in the last years, liquefaction producing extreme displacement has been observed in the Barcelona harbor. An about 1.6 km long quay was constructed using concrete caissons approximately 18 m high and wide and 40 m long. This line of caissons was founded on an artificial foundation bed, after the removal of the uppermost levels of a sequence of Holocene fine-grained deltaic deposits with a maximum thickness of approximately 60 m. During the backfilling of the quay area, an about 600 m long part of the caisson line failed due to static liquefaction and its fragments were shifted several tens of meters, in one case up to 90 m towards the sea (Fig. 7; Alonso et al., 2009; Del Campo and Negro, 2010; Gens, 2015).

The case of Barcelona implies that displacements/offsets of extreme amplitude are possible due to liquefaction effects, especially in harbor structures. Such displacements could be up to several or several tens of meters in amplitude, i.e. much larger (one order of magnitude larger) than the corresponding tectonic slip.

6. A scenario for the deformation of the Palairos breakwater

An implication of the impressive failure of the Barcelona harbor is that large-scale, offsets and quasi-horizontal "sliding" of marine or coastal structures is possible for structures on sediments prone to liquefaction, especially during earthquakes. Such slip in surficial sediments can be combined with, or can be triggered or amplified by seismic slip in the near-field of activated surface faults (Fig. 3).

Recently it was recognized that in the near-field of faults the earthquake strong motion is characterized not only by short period (<1 Hz) effects, but also by a long-period pulse (with a period of several seconds) in acceleration and velocity (Fig. 6; Makris and Black, 2004; Mavroeidis et al., 2004).

Recent evidence from high-rate (1 Hz or higher) GPS data indicates that the seismic displacement in the near-field of faults, especially of strike-slip faults, does not correspond to a short-period oscillatory movement, but to a very long period, essentially *steady, nearly unidirectional movement* in the sense of the movement described by the focal mechanism ("first motion"). In simple words this means that during the strong motion near a strike-slip fault the land is continuously "pushed" towards a specific direction for a period of approximately 10–20 s, and this interval tends to increase closer to the fault (Fig. 3a; Saltogianni et al., 2016 and references therein). In the case of liquefaction occurring at an early stage of the strong motion, the long-period tectonic dislocation is expected to amplify the non-tectonic displacement imposed by liquefaction and hence lead to a locally amplified and modified seismic dislocation (Fig. 3b).

In our study area all the above effects can concur because, *first*, reactivation of the strike-slip fault (zone) at Pogonia is possible, and the associated earthquake is expected to have been characterized by the pattern of dynamic displacement described by Fig. 3a. And *second*, the foundations of the Palairos mole are prone to liquefaction (Fig. 5), while relatively strong earthquakes producing liquefaction are rather frequent in the broader area (Gazetas et al., 2006; Papathanassiou et al., 2016).

Based on the above, we propose the following scenario to explain the deformation of the Palairos mole

i. An earthquake with magnitude around 6.0–6.5, typical for the area, associated with shallow strike-slip faulting occurred along the Pogonia fault crossing the breakwater. This earthquake produced high accelerations, much higher than those shown in Fig. 5, because these were measured several kilometers away from the fault and the strong motion was somewhat attenuated.
ii. The early part of the strong motion initiated tectonic surface rupture process (tectonic slip). In addition, it produced typical liquefaction of the breakwater foundations (Fig. 3b). This liquefaction of unconsolidated fine sediments was possibly combined and enhanced by mobilization of evaporites outcropping in the Pogonia area (see above). The last part of the long-period tectonic dislocation occurred while the breakwater was practically above a liquefied (viscous, nearly frictionless) layer and hence the combination of high acceleration and of nearly uni-directional tectonic slip led to excessive local dislocation. The latter was a combination of the tectonic strike-slip and of secondary, local, surficial slip (Fig. 3b).
iii. The overall horizontal motion was likely combined with limited settlement, tilting and/or thrusting leading to the small relative vertical offset of the two segments of the mole (Fig. 4) and does not strictly follow the direction of the tectonic slip. The main impact of the combination of the tectonic and of the surficial, liquefaction-induced movement was that the two segments of the mole slipped laterally a considerable distance, giving the impression of a sigmoidal structure.

Fig. 7. Failure of the Prat Quay, Barcelona harbor in 2007 due to static liquefaction, which produced lateral offsets of the order of 90 m (after Gens, 2015). Such static offsets highlight the potential of dynamic liquefaction to excessively amplify seismic strike-slip motions.

iv. Further failure of upper parts of the mole possibly occurred during subsequent strong motion events, while wave action led to dismantling of the uppermost layer of the mole, with the boulders fallen sideways giving the impression of a much wider structure. The area around the mole, especially along its northern flank, was subsequently silted. This may have contributed in the preservation of the remains of the ancient structure.

7. Discussion

A basic limitation is that the survey of the submerged mole was based on traditional, though reliable, underwater surveying techniques. A new, more detailed survey based on echo-sounder instruments, when/if it will be possible due to administrative limitations, may permit a more detailed mapping of the ancient structure, especially along the silted northern flank of the ancient breakwater. However, such a new survey is not expected to provide a pattern of ancient mole different from that shown in Fig. 4. The reason is that its sigmoidal pattern of the mole is unambiguous, and any refinement of its plan by a few tens of centimeters is not expected to change its overall pattern testifying to its unusual, if not enigmatic shape.

Several scenarios to explain the unusual shape of the Palairos harbor can be proposed, but they do not seem satisfactory (see Section 3). The alternative scenario discussed here implies an unusual interaction between soil and structure and became possible only after the documentation of large-scale slip of parts of the Barcelona harbor due to (static) liquefaction (Fig. 7; Gens, 2015), and of the pattern of dynamic displacements in the near-field of strike-slip faults (Fig. 3a; Saltogianni et al., 2016).

In particular, the pattern of dynamic displacements offers a new view of the type of destruction expected during an earthquake. Hinzen (2009) for instance modeled the effect of seismic oscillations leading to chaotic structural failure. Such modeling is fine in the far field of faults, but in the near-field, and especially along the faults, the strong motion has some particular characteristics: acceleration and velocity are dominated by a long-period pulse (Makris and Black, 2004; Mavroeidis et al., 2004) while the dynamic displacement by very long period nearly uni-directional motion, as is schematically shown in Fig. 3a. These characteristics, which fade away from the fault, may explain various unexplained so-far effects of earthquakes, including the offset of the Palairos mole, far exceeding the modest tectonic displacement expected in a typical strike-slip earthquake in the area (Saltogianni and Stiros, 2015).

The new scenario, however, requires reactivation of a strike-slip faulting crossing the ancient harbor and liquefaction of its foundations. While there is widespread evidence for recent strike-slip faulting and liquefaction in the broader region (see Section 4), and there is potential for both of them in the Pogonia area, there is no precise palaeoseismic evidence for both of them in the specific site since the construction of the breakwater. This is a clearly a limitation of the proposed scenario. On the other hand, this is the only scenario at present which offers a satisfactory explanation for the shape of the ancient breakwater or mole. A further study of the Palairos harbor is expected to shed more light to this problem.

8. Implications

Our study focuses on horizontal displacements, but seismic dislocation and liquefaction may produce vertical dislocations as well. This is a factor to be taken into consideration because various markers of sea-level change are located on unconsolidated sediments, especially river deltas, which may have been deformed by various geotechnical effects, including static and dynamic liquefaction, compaction and creep, and hence a correction to the estimation of the amount of sea level change is necessary. For example, subsidence of more than one meter in about 50 years has occurred in the vicinity of ancient constructions in the Thessaloniki Plain, Greece, due to a combination of consolidation and flow of recent deltaic sediments (Psimoulis et al., 2007; Ghilardi et al., 2008). Another implication is that seismic offset measured along faults should be checked for possible contribution of liquefaction.

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