Integrated methods for understanding and monitoring the loss of coastal archaeological sites: the case of Tochni-Lakkia, south-central Cyprus

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Abstract: Previous research on the environment of island and coastal areas has demonstrated that erosion substantially affects coastal archaeological site preservation and can lead to the loss of important information regarding past trade and maritime activities. These same at risk coastal archaeological loci are central to much current archaeological focus on networks and connectivity. In practical and theoretical terms, this places significant stresses on local governments and archaeologists, who are trying to monitor rapidly deteriorating cultural heritage and rescue information vital to future research. Beyond *ad hoc* observations, rigorous methods to quantify such issues have rarely been developed in the archaeology of the Eastern Mediterranean, including the island of Cyprus. In this paper we demonstrate an integrative method, which employs historic aerial photographs and laser scanning to illustrate, quantify and monitor coastline change and its impact on cultural heritage since the industrialisation of the south-central coast of the island in the mid-20th century CE.

Keywords:

Erosion monitoring, Eastern Mediterranean, coastal archaeology, aerial photography, laser scanning, Cyprus

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1. Introduction – Archaeology and the problem of coastal erosion

The coast, as the natural interface between land and sea, provides unique opportunities to explore past socioeconomic processes and human-environment interactions, as well as significant challenges to archaeologists in terms of preservation and methods of investigation (Ford, 2014; Tartaron, 2014: 188-190 on “coastscape”). Coastal areas are places of high connectivity and intensified interaction, and the character of their archaeology often reflects this centrality. While these coastal zones shed light on a distinct set of activities in the past, our ability to interpret them can be severely hampered by the impact of coastal erosion – a problem that is affecting archaeological and historic contexts in the Mediterranean (e.g. Little and Yorke, 1975; Paskoff et al., 1985; Raban, 1992; Nieto and Raurich, 1998) and beyond (Black Sea: Stanchev et al., 2013; Red Sea: Bailey et al., 2007; North Sea and Atlantic Europe: Dawson, 2005; Bates et al., 2013; Daire et al., 2014; Caribbean: Fitzpatrick et al., 2006; Fitzpatrick, 2012; Persian Gulf: Khakzad et al., 2015b; Pacific: Carson and Athens, 2007; North America: Rick et al., 2009; Reeder-Myers, 2015).

The loss of coastal land to erosion presents a serious obstacle to our still emerging – let alone efficacious – understanding of the archaeology of these liminal areas, as it engenders the deterioration of coastal archaeological features at an unpredictable rate. This results in the exposure and subsequent disappearance of material culture often without systematic archaeological recording – a phenomenon that Erlandson (2008) summarised as the “erosion of human history”. As a result, a wide range of past human activities associated with the coast remain unrecorded, their context poorly understood and our understanding of past human interaction at local, regional and interregional scales impaired. Coastal erosion is, thus, both a predicament of cultural heritage preservation and an epistemological problem.

In this framework, the Mediterranean Sea, a region defined by its coasts (Horden and Purcell, 2000), a protagonist in archaeological and historical scholarship on liminality (Monroe, 2011), networking (Knappett, 2011), and connectivity (Braudel, 1972; Broodbank, 2013), and a place with a long history of maritime archaeology (summary in Marriner and Morhange, 2007: 137-144) is particularly vulnerable and relevant (fig.1). Erosion linked to rapid coastal development has greatly affected Mediterranean archaeology over the past century. Yet, while widely recognised as a problem, efforts to systematically quantify coastal erosion at archaeological sites remain limited. In addition, although valuable information has been obtained by integrating archaeological, historical, geological, sedimentological and geomorphological studies (papers in Pye and Allen, 2000; Marriner et al., 2000; Marriner and

Morhange, 2008a; 2008b; Anthony et al., 2014: 336; Tartaron, 2014: 162-171; Devillers et al., 2014), coastal erosion is a destructive process that does not allow the reconstruction of lost material.

The unpredictable and geodynamic nature of the coastline complicates the identification of material evidence that holds important information regarding past human interactions on the coast (Davis and Barnard, 2000; Erlandson, 2012; Rick and Fitzpatrick, 2012; Mourtzas, 2012; Mourtzas and Kolaiti, 2013: 411). In addition, it tends to defocus quantifying and interpreting the reality of progressively lost archaeological record. In several Mediterranean contexts, researchers linked coastal erosion with changes in the sediment supplies (e.g. Anthony et al., 2014: 340; Anthony, 1994), particularly from rivers that are the most important sources of sediment (Tartaron, 2014: 145). In this context, extensive reservoir construction, dredging and fluvial regulation, resulted in delta and coastal erosion (Anthony et al., 2014: 351, tbl.2), which was in turn “controlled” with coastal defences. These features in association with dredging and the construction of artificial beaches and marinas have impacted sediment movement through longshore drift and altered the coastal topography.

Alterations to the sediment supply of the coast have progressively affected the geomorphological stability of Mediterranean coasts, and geomorphologists have argued that coastal destabilisation over the past two centuries, and especially over the past 50 years, appears more aggressive. Many also argued that accelerated erosion – erosion exceeding 0.5m/year – is largely a 20th century phenomenon (Anthony, 1994; Hooke, 2006; El Banna and Frihy, 2009; Anfuso et al., 2011; Anthony and Sabatier, 2012, 2013; Anthony et al., 2014: 336; 347-352; El Mrini et al., 2012; Halouani et al., 2013) and linked, among other factors, to the modernisation of earlier traditional land-use practices. This does not suggest that pre-modern coastal alteration was less dramatic (e.g. Ford, 2014: 775-776). It suggests, though, that modern alterations appear more consistently aggravated and extensive. As such, they provide an excellent opportunity, and archaeologically critical necessity, to study the relation between erosion and cultural heritage preservation, quantify erosion and enable action to restrain this recent, rapid degradation of vanishing archaeological resources.

Heritage management strategies to date have focused on environmental monitoring, and the implementation of integrated coastal zone management plans (Micaleff, 2003; Khakzad, 2014a, 2014b; Khakzad et al., 2015a; 2015b). To this end, researchers and heritage managers have employed large-scale monitoring of coastal recession and advancement to reconstruct erosion patterns and investigate their relationship with the relative preservation of

archaeological materials *in situ*. Some of these approaches include: (1) production and comparison of coastline maps via *in situ* recording with total station (digital topographical survey) and interpolation through aerial photography and satellite image analysis (e.g. Vasseur and Hequette, 2000; Vrieling, 2006; Zhang et al., 2007; Ghanavati et al., 2008; Sesli et al., 2008; Kuleli, 2010: 388; Bell, 2012: 470-471; Brunning, 2012: 455; Fitzpatrick, 2012); (2) examination of the extent of material evidence suggestive of ancient shorelines via terrestrial and underwater survey (e.g. Sewell, 2013; Andreou and Sewell, 2015); (3) production of a visual record of newly exposed features with comparative section photography (e.g. Fitzpatrick et al., 2012; Andreou and Sewell, 2015); (4) statistical analyses with the use of Digital Shoreline Analysis Software (e.g. Kuleli, 2010); (5) production of quantifiable 3D models via aerial laser scanning (e.g. Risbol et al., 2015; Doneus et al., 2015) and terrestrial laser scanning (TLS) (e.g. Rosser et al., 2005; Infante et al., 2012); (6) production of smaller-scale, less detailed, yet quantifiable 3D models of eroding features with aerial photogrammetry (e.g. Yilma et al., 2007; Magnami and Schroder, 2015); and (7) production of vulnerability models of exposed archaeological heritage (e.g. Dawson, 2005; Daire et al., 2014; Reeder-Myers, 2015).

In seeking a high-resolution but rapid and cost-effective approach to the topic, we selected to combine aerial photographs (APs) and terrestrial laser scanning (TLS). We use these as the primary tools to provide standardised observations in order to monitor and study coastal erosion and assess its impact on the cultural heritage along the south-central coast of Cyprus since its industrialisation in the mid-20th century. We use APs as a basemap to digitise the diachronic coastline and quantify the amount of land lost since the 1960s. This will provide an indication of the rate in which archaeological features have been deteriorating in the modern era and highlight vulnerable areas that require more diligent recording. We then employ a TLS survey as a time-effective means of detailed recording of the archaeological components of coastal sections on an annual basis. With this integrated approach, we develop a valuable methodology, which can be applied on similar cases in rapidly vanishing archaeological contexts.

Before presenting an analysis of these methodologies and their application, it is necessary to contextualise coastal erosion in the archaeology of Cyprus.

2. The eroding history of the island of Cyprus

Archaeological and textual evidence as early as the Late Bronze Age (LBA; 1680/1650-1100 BCE) suggests that Cyprus was a key participant in the international economic spheres of the Eastern Mediterranean, particularly through export of its copper resources (Knapp, 2013: 416-427). Despite the abundance of material evidence of engagement with the sea, we know surprisingly little regarding the locations of anchorages and harbours on the island (Sauvage, 2012) and less on their role in local and regional-scale dynamics. This is hardly surprising, given drastic topographic alterations on the coastline and the river mouths that are considered desirable locations for ancient anchorages (e.g. Raban, 1991; Blue, 1997; Tartaron, 2014: 151). Some of these historical changes, especially the alluvial coverage of harbours, have been documented in Cyprus via geomorphological studies, whilst the impact of environmental change, increased sedimentation and tectonic uplift has been examined in association with changes in settlement patterns (e.g. Dalongeville et al., 2000; Morhange et al., 2000; Devillers, 2008; Brown, 2013; Devillers et al., 2014; Ghilardi et al., 2015).

Geomorphological studies demonstrate that the sediment supply to the Cypriot coasts has been highly varied since the Bronze Age (Deckers, 2002; Devillers, 2008). However, the rivers of the area under investigation (Fig.2) lack permanent streams, suitable for reconstructing the palaeo-environment (Ghilardi et al. 2015: 184). Amongst those rivers, the Vasilikos was the subject of one of the earliest fluvial geomorphological studies on the island (Gomez 1987). However, this study did not focus on the evolution of the alluvial system. The Tremithos river, in contrast, has received more detailed examination, but little is known about its sedimentation rates (Ghilardi et al., 2015: 187). Some information can be derived from geomorphological studies of other valleys on the island (Devillers 2008: 141-168; Deckers 2002; Morhange et al., 2000). For example, recent publications discuss the dynamic coast of LBA Hala Sultan Tekke (fig.3), the anchorage of which silted up due to tectonic uplift during the periods under discussion (Dalongeville, 2000: 16-17, 19; Devillers et al. 2014: 76), and can provide useful regional paradigms for the evolution of the Cypriot coastline (e.g. Ghilardi et al., 2015: 197). These studies also discuss the role of coastal progradation on the eastern coast of Cyprus, related to a decrease in sea-level (Dalongeville et al., 2000 contra Gifford, 1978).

In addition to the low archaeological visibility of anchorages and harbours, coastal erosion is another significant factor in the poor preservation and problematic identification of coastal archaeological features, particularly on the south-central coast of the island. This

region(Fig.2), has been described as an area with accelerated erosion (Delft Hydraulics, 1993; Triton Consultants, 2002) and has been observed to have the highest rates of coastal erosion on the island (Thomas, 1981; EUROSION, 2004). However, although general knowledge of eroding sites exists in Cypriot archaeological scholarship as early as the 1960s (Catling, 1962; Manning et al., 1994, 2000; Leonard, 2005), only in the past five years has this problem begun to be investigated systematically (Andreou, 2014; Andreou and Sewell, 2015; 2016).

Since 2011the *Tochni-Lakkia Project* and the *Cyprus Ancient Shorelines Project* implemented a series of lab- and field-based studies to map eroding archaeological sites from the south-central coast of the island (Fig. 3). These studies included *insitu* visits, archaeological illustration,topographical, pedestrian, geophysical and underwater survey, photography and photogrammetry, comparisons of aerial photographs and a historical study of Medieval and Ottoman charts.Our aim was to: (1)produce a high-resolution, quantifiablerecord of actively disappearing coastal archaeological features; (2) contextualise these assemblages in their natural and anthropogenic environment; and (3)shed light on factors that have accelerated erosion since the industrialisation of the south-central coast in the mid-20th century.

Although we recorded coastal sites that contain archaeological remains (Fig. 3), in most occasions we were unable to associate theseassemblages with harbours or anchorages. It is unclear whether the nearby river mouths were used asanchorages, althoughthis is likely,given the location patterns of Bronze Age anchorages in the Eastern Mediterranean (e.g. Raban, 1991; Tartaron, 2014: 151). Given the lack of geomorphological studies for the majority of rivers in south-central Cyprus, if one relies on information from theTremithos River (Ghilardi et al., 2015), or the most extensively studied Gialias (Devillers, 2008), it could be argued that the LBA was a period with increased sedimentation, coastalprogradation and tectonic uplift that potentially contributed to the alluvial coverage of ancient anchorages located in the mouths of these rivers.Based on the same information, it also becomes obvious that there is insufficient evidence to estimate how much land has been lost to erosion since antiquity. However, since accelerated erosion is a phenomenon of the recent century(section 1), the quantification of modern coastal alteration and its impact on cultural heritageis a useful research direction. To highlight the impact of coastal erosion on cultural heritage and demonstrate methods for its quantification andsustainable recording, we use as a case study LBA Tochni-Lakkia, one of the sites we recorded more extensively.

3. The case of Tochni-Lakkia

Amongst the coastal sites shown in Fig. 2, Tochni-Lakkia (Todd, 2004: 133-134), Maroni-Tsaroukkas (Manning et al. 1994) and Zygi-Petrini (Manning et al., 2000) are the most severely eroding coastal sites of the island, and the most intensively explored with respect to coastal erosion. Between 2011 and 2016 were recorded various archaeological features (Fig.4), many of which have since eroded away.

Pedestrian survey (2012) recorded LBA and Cypro-Geometric (1050-750 BCE) material culture spread over an area of 750 m (E-W) x 250 m (N-S). Although the survey was limited to outside the former Relay Station (Fig.5), this fenced area was examined with trial trenches (2014) that verified the continuation of the site to the west (Andreou and Sewell, 2016). Moreover, the exposed coastal sections have been recorded intensively, and the remains indicate that the site extended further off the coast during its active life.

Underwater surveyors investigated the extent of the LBA coastline and record material remains that might indicate maritime activities (Sewell, 2013). The current state of the seabed including stone debris, sediment, and algal and plant growth obscured archaeological visibility and decreased artefact preservation. While the survey did not locate structures or anchors, it identified fragments of utilitarian wares and storage jars (likely recently eroded from the coastal scarp).

Additional insights into the preserved extent of Tochni-Lakkia were provided by geophysical surveys, which have been used effectively at nearby archaeological sites (Manning et al., 2000, 2014; Urban et al., 2014a). Surveys carried out at the site (2014), parallel to the bank and starting 2m from the edge, used fluxgate magnetometry, electromagnetic induction (EM), and ground-penetrating radar (GPR) and suggested that archaeological features continue inland from the eroding bank (Fig. 5).

The area of study, dominated by limestone derived substrate, is generally described as a region of calcaric lithosols (Soteriades and Grivas, 1970), characterised by high calcium carbonate content and high soil pH. High soil pH was confirmed on site at 3 augur positions where soil pH, moisture, and texture were examined. The soil texture was found to be dominated by a high clay fraction, with numerous embedded cobbles that made auguring below 0.25m impossible. The shallow substrate examined was found, with a dielectric probe, to retain < 20% volumetric water content. This type of substrate results in high ionic activity that limits GPR performance due to electromagnetic attenuation (Urban et al., 2014 a.; 2014b). The rocky surface also made deployment of GPR difficult, so the technique was

limited to a single cross-section where a clear path was possible. A broader survey sample was obtained with magnetic and EM methods, as these were easily deployed at the site. Based on examination of the exposed coastal scarp and TX-RX (transmitter, receiver) offset of the EM system, it was determined that EM sampling would likely be limited to the vadose zone.

The EM quadrature response indicated high electrical conductivity closest to the bank, likely associated with increased salt content from wave action (Fig.5a). The quadrature component also indicated geometric patterns consistent with cultural features. The magnetic survey indicated several large dipole responses possibly related to heat intensive archaeological features, such as kilns (Fig.5b). We should note that igneous boulders could yield a similar magnetic response, but are not known to be present in this area. The EM in phase response also indicated geometric patterns consistent with cultural features (Fig.5c), while GPR data collected close to the bank indicated walls continuing inland, including one that corresponded with a wall visible in the eroding scarp(Fig.5d).

Overall, despite the vulnerable nature of *Tochni-Lakkia*, the archaeological surveys have provided unprecedented information both regarding the site and the settlement patterns of the Vasilikos valley. The available evidencesuggests an important coastal site, likely including specialised productionandstorage. Moreover, the location of the site within 4km of an important LBA centre at *Kalavastos-Ayios Dhimitrios*, down the Vasilikos drainage on the coast, suggests the likelihood that *Tochni-Lakkia* served as the port and entrepôt locus for *Ayios Dhimitrios* and the putative political entity it controlled (or was part of). As this spatial pattern differs from most regions on the island, where the primary LBA urban centre is a coastal site (Knapp, 2013: 354-359), *Tochni-Lakkia* is significant to our evolving understanding of the economic organisation of LBA settlements on the island.

Given the importance of *Tochni-Lakkia*, it is necessary to quantify our empirical observations regarding its erosion,estimate how much information has been lost through time, and find ways to record accurately and rapidly the eroding features.In the following sections, we demonstrate and integrate the results of two methods of coastal erosion quantification. At a larger scale, we first compare historical APs between 1963, 1993 and 2008 that are widely available and relevant to much of the Eastern Mediterranean. At a smaller scale we compare data we acquired via TLS to attempt a finer-grained analysis throughout the exposed coastal section and showcase a time-effective and accurate method of producing a digital record of rapidly vanishing archaeological features.

4. Aerial photographic analysis: methodology and results

In analysing APs to quantify erosion and study erosional processes, inaccuracies are introduced in various ways including photography rectification, geo-referencing errors, coastline mapping errors, poor photography resolution and errors made while taking measurements within a geographic information systems (GIS) environment (Sear et al., 2011:118-120). While sub-meter quantification and comparison of coastline locations is neither accurate nor reliable based solely on the AP evidence, the comparison of APs is a very useful tool when aiming to understand larger-scale and longer-term landscape changes. For the purpose of this research, the AP comparison was carried out as follows:

- (1) Collection of georeferenced APs taken in 1963, 1993 and 2008. The APs were georeferenced by the Department of Lands and Surveys of the Republic of Cyprus (DLS).
- (2) Coastline mapping following the location of the visible coastline on the APs and on additional data provided by the DLS (Figs.6a-c).
- (3) Superimposition and comparison of APs from different dates and respective coastlines with discreet colours in order to visualise potential coastal recession and advancement (ArcMap) (Fig.6d).
- (4) Rough quantification of land-loss based on comparative coastlines using the “measure” tool in ArcMap (Fig.6d).

Through this process, we produced a series of two-layer maps (1963-1993 and 1993-2008) to illustrate loss of land in the area of interest. In the first example, we superimposed the 1993 black coastline on the 1963 aerial photograph with the red coastline, to note a land loss between 10m and 12m close to the main Tochni-Lakkia field, and directly adjacent the industrial zone to the west (Fig.7). This roughly corresponds to an annual land loss of 0.3m – 0.4m. One can also observe that the mouth of the Vasilikos River, prior to the construction of a new port in the 1980s, can be measured as approximately 65m; a length that could accommodate the arrival of small vessels, assuming that the unknown bathymetry of the river’s mouth would permit it.

To illustrate the alterations of the coastline between 1993 and 2008, we used the 2008 aerial photograph with the pink coastline as a background and superimposed it with the 1993 black coastline (Fig.8). The results of this superimposition seem to corroborate the land-loss

rate estimated over the 1963-1993 period. With a total loss of approximately 6m in 15 years, the average annual loss of land at Tochni-*Lakkia* ranges between 0.3m and 0.4m. Similar rates of erosion were observed in the nearby Late Roman Zygi-*Petrini* (Manning et al., 2000).

The comparison of APs suggests a much higher rate of coastal erosion than anticipated based on empirical observations on the site since 2011 (Andreou and Sewell, 2015). Moreover, when one considers that LBA Tochni-*Lakkia* was exposed to coastal erosion for over three millennia, the amount of lost land estimated through the comparison of APs, appears excessive, if not unrealistic, if consistently projected back to the LBA. It seems rather unlikely that over 1000m of land have been lost since the abandonment of the site early in the first millennium BCE, especially considering existing evidence for increased sedimentation during the abandonment of contemporaneous sites (Devillers et al., 2014: 75-76). If we assume that dramatically increased rates of erosion have occurred since the mid-20th century (section 1), we can estimate a loss of at least 25m of land since the 1950s. The archaeological significance of this land depends on the spatial proximity of the features to the LBA coastline. As discussed in section 3, these distances have changed with the increased sedimentation noted in the LBA, when the coast of the Tremithos river and Hala Sultan Tekke protruded following tectonic uplift (Dalongeville et al., 2000). If we assume that Vasilikos has experienced a similar rate of sedimentation due to tectonic uplift, then the extent of land loss, including archaeological features since the site's abandonment, is probably not in the range of several hundreds of meters, but likely of several tens of meters (and mainly recent).

Overall, although we cannot estimate nor reconstruct what we have lost prior to 2011, we can predict that this consistent rate of erosion is largely a 20th century phenomenon that will continue into the future. Finally, although the APs provided a clear indication of the vulnerability of the coast, they only provide a top down view that does not enable detailed measurements. For that reason, we employed more accurate methodologies to record and diachronically compare the threatened exposed archaeological sections.

5. Multi-year terrestrial laserscanning campaign: methodology and results

Laserscanning and photogrammetry have become standard techniques for coastal monitoring and assessments of landscape change at the local and micro-regional scale.

Studies applied in cultural heritage and environmental monitoring have variously employed airborne laserscanning (Risbol et al., 2015; Doneus et al., 2015), terrestrial laserscanning (Rosser et al., 2005; Infante et al., 2012), and airborne and terrestrial photogrammetry (Mancini et al., 2013; Ružić et al., 2014) to create high spatial resolution, diachronic, 3D models of the coast. Some studies combine techniques to extend the temporal reach of their analysis, for instance using historic air photos to create a digital surface model at a slightly coarser spatial resolution, adding greater time depth to a change detection analysis (Gracia et al., 2005). Overall, the method is widely accepted, and now in use by commercial archaeological and charitable organisations (e.g. SCAPE; <http://www.scapetrust.org/>).

At Tochni-*Lakkia* we carried out TLS surveys in 2011, 2012, and 2015 using a Leica C10 instrument. The scanner was set up at low tide, in shallow water. Data were collected at a nominal 0.5cm resolution each year to produce a detailed model of the coastal morphology. Large radio masts from the neighbouring relay station were captured in the annual scans, providing stable control points with which the survey datasets could be aligned. Basic processing of each year's scan data was carried out in Leica *Cyclone*. The point clouds resulting from each set of scan data were imported into *CloudCompare* (open source software; <http://www.danielgm.net/cc/>). The data were then subsampled to a uniform 5cm grid spacing to facilitate processing and to remove noise from vegetation and spurious returns. All datasets were aligned roughly, using points on the radio masts as control points. Each dataset was then segmented to separate the sections with towers from the area of interest, the eroding coastline. The tower segments were then aligned finely, and the resulting transformation matrices were applied to the coastline sections to complete the referencing of the scan datasets for each year. Data were cleaned further to remove any remaining areas of vegetation and points from shallow water areas, which are not spatially reliable. The local cloud-to-cloud distance was calculated for each pair, using a 15cm radius kernel to define the local area over which the distance measurement is averaged. The point clouds have been colourised based on these distances (Figs.10-11; http://ropitz.github.io/tochni/tochni_lakkia_TLS.html).

As expected, the results of the comparison of this series of scans illustrate that coastal erosion is occurring along the coastal strip of Tochni-*Lakkia*. Interestingly, the results indicate that the pace of erosion varies, both spatially and diachronically. Within the surveyed coastal strip, we see a broadly consistent rate of erosion in the western two-thirds of the area between

2012 and 2015, and between 2011 and 2012. Between 2011 and 2012 the pace of erosion is between 0.3m and 1m of coastline retreat in the western part of the coastal strip, with the majority of erosion occurring at a rate between 0.2 and 0.4m. In the three-year period between 2012 and 2015 we see a broader distribution of rates of coastline retreat, with the majority between 0.4m and 2m, approximately an annual rate of 0.1m to 0.6m. In the case of the 2012-2015 scans there is a substantial amount of vegetation covering the upper part of the section. Based on a visual assessment of these data we would suggest that a 0.4-0.6m rate is most representative of the situation (Fig. 9). In the eastern part of the coastal strip we find a small inlet (Figure 10, right side profile), which seems to provide some protection and reduce the overall rate of erosion. Here, between 2011 and 2012 the predominant rates of erosion range between 0.1m and 0.4m. Moreover, between 2012 and 2015, we only recorded an erosion range between 0.1 and 0.2m. This rate is notably lower than the generally estimated annual rate of <0.7m and typically ca. 0.4-0.6m.

The resulting datasets and visualisations highlight two methodological points. First, while the rates of coastal retreat due to erosion as calculated based on the scan data generally agree with those as calculated based on the historical AP data (see section 4), the TLS survey has highlighted and provided detail on the variations that exist in the rates of erosion even within a relatively small area. This local variability is likely due to a combination of tidal patterns, local differences in sediment and geology, the local morphology of the coastline, and the presence and different types of archaeological materials and features. Following these observations, it becomes clear that high resolution spatial data are necessary for a valid assessment of the degree of erosion, and a deeper understanding of the environmental dynamics of these coastal zones. On the contrary, more generalised and larger-scale measures potentially overlook localised areas of extreme erosion or preservation within the coastal interface of a site. At *Tochni-Lakkia* we can provide some explanation for the presence of two areas with distinct erosion dynamics based on the local coastal morphology. A small promontory divides the western and eastern areas we have defined. While the western coastal strip presents a more or less linear face to the sea, the eastern area is both slightly protected by this promontory and characterised by a small cove or inlet. This cove is likely slowing the pace of erosion, as during the process of its formation (getting deeper) it affords increasing protection to that segment of coast.

A second methodological point is the use of the radio towers as control points to reference the datasets relative to one another. In many projects alignment between scans from multiple dates is achieved with the use of a Differential Global Positioning System (DGPS). However, many local efforts at coastal monitoring are now attempting a lower cost, more flexible approach, relying on photogrammetry as their tool for 3D documentation. In these situations, one may use instead fixed off-coast control features (e.g. buildings, permanent fence lines, etc.) to provide accurate relative referencing. Our method (Fig.11) provides an approach that can be implemented without access to DGPS, thereby expanding the potential for community groups or organisations with fewer technological resources to participate in these monitoring efforts.

6. Conclusions

The dynamic coastal environment is an integral part of archaeological interpretations, especially those focusing on human interactions at multiple scales. Several studies have provided unprecedented insight into our understanding of past coastscapes by reconstructing the alluvial sequences of rivers and the palaeoenvironment of ports and harbours. They also highlighted the problem of archaeological visibility in coastal environments, particularly the alluvial coverage of features and sites. In this context, our paper addressed a similar problem, by focusing on coastal archaeological sites that are actively deteriorating due to a consistently low sedimentary supply that led to accelerated erosion for, at least, the past 50 years.

In this study we combined archaeological evidence with GIS to suggest a refocused investigation of past coastal landscapes in a way that incorporates their modern, natural and anthropogenic contexts. We consider that this juxtaposition addresses more productively the dialectical relation between humans and the environment, particularly the profound and often not easily quantified ways in which river and coastal landscapes have altered in the more recent years. We finally proposed a more holistic study of coastal archaeology through an integrated methodology that combines: (1) comparison of historical aerial photographs in order to quantify land loss and identify areas that experience higher rates of erosion and potentially contain highly vulnerable archaeological sites that require more diligent recording; and (2) TLS survey as a highly accurate and time-effective recording method

that produces a visual record of rapidly vanishing archaeological features and identifies local patterns of erosion.

This integrative method can be used to identify areas experiencing higher rates of erosion, map vulnerable archaeological sites, quantify their erosion for the past 50 years, predict their future erosion rate, and implement frequent monitoring surveys. Moreover, these surveys can produce an accurate, quantifiable visual record of rapidly disappearing features, which will facilitate their incorporation into larger-scale archaeological interpretations, especially those focusing on human interaction at local and regional levels. Finally, these methodological approaches can set the basis for the development of policies focusing on rapidly-eroding archaeological features and the production of vulnerability models that will assist in their management and long-term preservation by government bodies and heritage consultants.

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Figure 1. Coastal erosion in Europe (adopted from EUROSION, 2004, using ESRI base map) – COLOURED IMAGE

Figure 2 The south-central coast of Cyprus (Base map from DLS and data from Andreou and Sewell, 2016) – COLOURED IMAGE

Figure 3. Map of coastal archaeological sites and known ancient harbours (Base-map from DLS and data from Andreou and Sewell, 2016) – COLOURED IMAGE

Figure 4. Archaeological features recorded at Tochni-*Lakkia*. Top: stone-lined feature containing clay-like substance; bottom: wall with LBA and Cypro-Geometric pottery.

Figure 5. Maps showing Tochni-Lakkia survey areas. Geophysical survey results elucidate the extent of the site and suggest the presence of structural remains running inland from those identified in the eroding coastal bank. The GPR cross-section was collected with a 0.05 m sample interval, and processing included dewow, SEC-2 gain, migration, envelope, and background subtraction. – COLOURED IMAGE

Figure 6a. 1963 photograph and coastline; 6b.1993 photograph and coastline; c.2008 photograph and coastline; 6d. 1963 photograph and 1963-1993-2008 coastlines (Aerial Photographs by the DLS) – COLOURED IMAGE

Figure 7. Land loss at Tochni-Lakkia between 1963 and 1993; aerial photograph from 1963, 1963 red coastline, 1993 black coastline (Aerial photograph by the DLS) – COLOURED IMAGE

Figure 8. Land loss at Tochni-Lakkia between 1993 and 2008; aerial photograph from 2008, 1993 black coastline, 2008 pink coastline (Aerial photograph by the DLS) – COLOURED IMAGE

Figure 9. The amount of coastal retreat in meters (red = maximum observed range to blue = smallest observed range as quantified by scales to right of each plot), as measured through the TLS survey. Top: Comparison of the 2011-2012 coastal scarp. Note the greatest changes are on the eastern end (right) of the coastal strip. Bottom: Comparison of the 2011-2015 coastal scarp. Note the greatest changes are on the western end (lower left) of the coastal strip. – COLOURED IMAGE

Figure 10. Top: The locations of two 1 m profile slices through scan data from 2011, 2012 and 2015, shown against the scan data from 2011. Left: The western (left) profile shows minimal coastal retreat between 2011 and 2012 but significant change between 2012 and 2015. Right: The eastern (right) profile shows a greater rate of change between 2011 and 2012 than between

2012 and 2015.– COLOURED IMAGE.

Figure 11. Processing workflow outline for TLS data.