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Deterioration of Israel's Caesarea Maritima's ancient harbor linked to repeated tsunami events identified in geophysical mapping of offshore stratigraphy

Beverly N. Goodman-Tchernov [a,*], James A. Austin Jr. [b]

[a] Charney School of Marine Sciences, University of Haifa, Israel
[b] Jackson School of Geosciences, University of Texas, United States

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ABSTRACT

Modern observations have shown that harbors are especially vulnerable to the effects of tsunamis, both due to their position on the coastline and the tendency for tsunamigenic eddy production within enclosed harbor basins. Presumably, this was as much the case in the past as in the present. The Roman-era mega-harbor Caesarea Maritima, which is today submerged in some parts up to 5 m below sea level, is an ideal research site for understanding these impacts. Over the past three decades, archeologists, geologists and historians have searched for the cause of the rapid demise of this harbor, turning to explanations ranging from offshore faults, seismic disturbances, general failure and deterioration, to liquefaction and settling on unconsolidated sands. While tsunamis are recorded repeatedly in the Eastern Mediterranean historical record, it has only been in the past decade that physical evidence directly attributed to tsunamigenic sediments along the Israeli coastline near Caesarea has been documented. To date, deposits from at least three tsunami events that impacted the harbor have been identified in sediment cores, coastal exposures and archeological trenches, but no laterally continuous picture has been produced. In this study, using a dense offshore survey produced by a high-resolution subbottom profiler, shallowly buried sediment horizons offshore of Caesarea produce distinctive reflectors that correlate with the tsunamigenic stratigraphic sequence identified in cores and excavations. These surface structure maps allow for a laterally extensive reconstruction of these distinctive deposits. The results have led to the following conclusions and interpretations: 1) multiple offshore tsunamigenic horizons at Caesarea can be recognized, 2) individual tsunamigenic event horizons result in distinctive and unique surface morphologies that elucidate tsunami-based channeling/backflow processes, and 3) these backwash channels can be used to assess the general physical condition of the harbor at the time of each tsunami occurrence, ultimately revealing major differences between the state of the harbor following earlier events (i.e., 2nd c. CE) vs. later events (6–8th c. CE). We conclude that the combined acoustic-sampling approach is an effective way to document the interaction of tsunamis with harbor complexes/adjacent coastlines over millennia.

1. Introduction and background

1.1. Evidence for tsunami impacts on coastal morphology and associated structures

Coastal morphology, including adjacent landforms, artificial structures, and coastal-fringing natural features (i.e., extensive coral reefs, mangroves, e.g., Baird et al., 2005; Fernando et al., 2005; Kunkel et al., 2006; Giri et al., 2008) can all influence the impact of tsunami wave flow (Hori et al., 2007; Sugawara et al., 2012). As the inundating wave breaches the coastline, natural and man-made obstacles that obstruct or impede the wave's force can lead to channeling and variable flow, both as the wave advances inland and retreats seawards. Such energy redistribution is also evident in affected rivers or artificial channels, in which tsunami flow will continue inland to distances far exceeding that of uninterrupted portions of the coastline (e.g., Crete 1956, Bruins et al., 2008; Okal et al., 2009; northern Japan 2011, Mori et al., 2011; Goto, 2011a; Chile 2010, Fritz et al., 2011). The tsunami return/outflow is even more influenced by the presence of structures, and therefore is typically characterized by channeling (Umitsu et al., 2007; Feldens et al., 2009), which can result in shore-perpendicular bathymetric and topographic features (Atwater et al., 2010). In Sumatra following the 2004 tsunami, evidence of such complex back-flow included filled channels, boulders moved into deeper water, movement of sand into previously silty areas, and man-made rubble immediately seaward of the shoreline (Feldens et al., 2009; Goto, 2011b). Similarly, in northern Japan following the Tohoku-Oki earthquake in 2011, canals and road

* Corresponding author.
E-mail address: bgoodman@univ.haifa.ac.il (B.N. Goodman-Tchernov).

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features often corresponded with variations in tsunami inundation heights along the Sendai Plain.

Amongst the range of coastal structures that interact with tsunamis, harbors have been identified as locations of acute magnification and flow intensification in both simulations and field studies (Raichlen, 1966; Synolakis and Okal, 2005; Lynett et al., 2012). For example, during the 2004 tsunami, at the Port of Salalah, Oman, strong currents produced inside the harbor caused a 285 m ship to break away from its moorings and beach on a nearby sandbar after spinning and drifting for hours (Okal et al., 2006). At Port Blair, India, harbor structure damage included movement or complete collapse of the jetties (Kaushik and Jain, 2007). Examples are also available for the far-field effects of tsunamis, where harbors have been damaged while adjacent coastlines experience little inundation. One such harbor is located in Crescent City, CA; this site was damaged repeatedly following both near-field events, such as Alaska 1964, as well as far-field tsunamis, such as those generated from seismic events in 2006 (Kuril Islands) and in 2011 (Tohoku-Oki) (Griffin, 1984; Horrillo et al., 2008; Kowalik et al., 2008; Wilson et al., 2013). Widespread documentation of ships originally moored in harbors that have been displaced inland and/or damaged along the adjacent coastline during tsunamis are common; this phenomenon includes relatively small events, such as the tsunami following the 1999 Izmit earthquake in Turkey, with varying reports of wave heights, but with possible localized heights of ~6 m (Rothaus et al., 2004).

Following a tsunami, a variety of characteristic markers can be left behind, both on the shallow sea bottom and on shore, including massive debris fields, sheets of sand, muddy film, and/or eroded surfaces, amongst a list of over thirty-two published indicators (e.g., Goff et al., 2012). Depending on the specific surface conditions of the impacted coastline, e.g., surficial sediment types, strandline morphology and available unconsolidated debris, coastal zone bathymetry can be altered as contents carried within the tsunami flow drop out as the wave energy dissipates (Jaffe et al., 2012). Inland, tsunami-based deposits are generally characterized by landward thinning (Morton et al., 2007), unless interrupted by some limiting structure or topography.

The patterns of tsunami deposits and bathymetric forms created by these waves can be informative regarding the character of the affected coastline and adjacent offshore areas (Richmond et al., 2012). In northern Japan, for example, artificial channels and a highway constructed on the Sendai Plain before the 2011 Tohoku-Oki earthquake influenced the distribution of tsunami-deposited sediments and wave run-up heights (Sugawara et al., 2012), relative to the distribution of known preexisting tsunami deposits. Recognizing and mapping tsunami-related features from historical events should inform us as to the state of both natural and artificial structures on a coastline which were affected by these tsunamis, including the influences of the back-wash phase of sedimentation. In this study, the ancient harbor of Caesarea Maritima, on the eastern Mediterranean coast of Israel (Fig. 1), is presented as an ideal site to consider this tsunami-impact phenomenon, and how and whether the physical evidence for such recurring impacts might be preserved over two millennia.

1.2. Caesarea Maritima: the ancient harbor, its deterioration and demise, and recent tsunami research

When King Herod had the city of Caesarea built on the coastline of what is now Israel between 25 BCE and 9/10 BCE, he applied Roman city planning, organization and building techniques, including the costly installation of a state-of-the-art, artificial mega-harbor (Holum et al., 1988; Hohlfelder, 1988, 1996; Raban, 2009; Votruba, 2007; Raban, 2008; Fig. 1). The natural environment afforded little protection or anchorage, with the exception of periodic, remnant, exposed ridges of eoleonite sandstone (locally referred to as 'kurkar') roughly paralleling the coastline immediately offshore. These bedrock structures are exposed and eroded lithified dunes 135,000–45,000 year old (Sivan and Porat, 2004). The harbor was constructed on portions of this bedrock and extended seaward onto unconsolidated Nile River-derived sands (Goldsmith and Golik, 1980; Neev et al., 1987; Stanley, 1989; Zviely et al., 2007), with the use of man-made foundations. Roman engineers succeeded in this task by building wooden frameworks ('caissons') on land, then towing them into position where they were submerged, filling them with hydraulic cement, and ultimately finishing them with above-water superstructures. Fields of large cobbles (<20 cm diameter) were emplaced beneath the caissons (Raban, 2008), presumably to give them added stability against erosion and undermining, suggesting that the engineers of the time were aware of the inherent risks for constructing directly on unconsolidated sandy sediments. These caissons were arranged in rows to produce the spinal walls of the harbor, completing the entire project in <15 years (Brandon, 1996). This efficient approach to harbor construction continues to be used today. For example, 'Mulberry I' and "Mulberry II", created by the allies during WWII in preparation for the D-Day landings, were also artificial islands constructed in a similar manner for the purpose of providing supplies and reinforcements until an established harbor could be secured (Stanford, 1951; Ryan, 1959; Bettwy, 2015).

Descriptions made ~70 CE by historian Flavius Josephus describe a fully functional imperial mega-harbor, exceeding the size of most contemporaneous Mediterranean harbors (Raban, 2008). Josephus explicitly describes the expense of and investment made in the harbor's construction. Excavations have since supported these grandiose statements, revealing bulk raw building materials that traveled long journeys before arriving in Caesarea (Votruba, 2007). For example, chemical analysis of the volcanic ash ('pozzolana') used for producing the fast-drying hydraulic cement shows that the ash was brought from Vesuvius (Brandon, 1996; Hohlfelder et al., 2007), while the underlying cobble and rubble beds beneath the cement-filled caissons show non-local mineralogies common to Turkey, Cyprus, and parts of Greece. The wood used for the caisson frames, as was common practice in shipbuilding practices of the time, came from the cedar forests of Lebanon (Votruba, 2007).

However, despite the significant investment and durability of the cement used in the construction process (Jackson et al., 2012), the overall state of the harbor had significantly deteriorated by the end of the 2nd century CE, and probably even earlier, according to radiocarbon-dated sedimentological evidence showing a shift from a low-energy, harbor environment to an open-water exposed, unprotected environment during that period (Reinhardt and Raban, 1999; Reinhardt et al., 1994). Throughout the 1990s, the generally accepted presumption arising from these studies was that the harbor experienced its demise due to some combination of earthquake-related liquefaction, with some credence also given to the possibility of related tsunami, though without clear markers then to support such a hypothesis.

Caesarea harbor phases, from initial construction to the present, have been reconstructed using sedimentological, geophysical (i.e., magnetometry), and archeological surveys (Reinhardt et al., 1994; Reinhardt and Raban, 1999, 2008; Boyce et al., 2009). The most recent summary (Reinhardt and Raban, 2008) suggests six such phases, summarized as follows: 1) initial construction, 1st century CE, 2) 1–2nd century CE destruction, 3) 3–4th century CE, unprotected (meaning exposed to the open sea and therefore without intact harbor features), 4) 4–6th century CE, natural/unimproved harbor, 5) 6th century CE, sand infilling, and 6) 6–11th century CE, renovation/destruction. Unfortunately, the foregoing summary remains vague regarding causation, as it predates later findings (Goodman-Tchernov et al., 2009) that bring to light evidence for tsunami events in both the Byzantine (4–6th c. CE) and Early Islamic (7th–8th c. CE) periods, as well as confirming an earlier suggestion of another 2nd century CE wave-based event (Reinhardt et al., 2006).

Previous geophysical research on the Caesarea Maritima harbor has included both seismic and magnetic surveys (Mart and Perecman, 1996; Boyce et al., 2004, 2009). Boyce et al. (2004) conducted a magnetic survey with the aim of determining the feasibility of using magnetic signatures to map and define the concrete installations of the harbor, as the pozzolana cement used by the Romans was iron-rich. Although the high resistivity of the kurkar bedrock proved to be challenging, the overall form of the foundations of the harbor, particularly the individual