



PALAEOTSUNAMI SIGNATURES IN HOLOCENE COASTAL GEO-ARCHIVES OF THE EASTERN IONIAN SEA REGION, GREECE

A. Vött, G. Bareth (1), H. Brückner (2), I. Fountoulis (3), F. Lang (4), D. Kelletat (5), D. Sakellariou (6), A. Scheffers (7) and S. Scheffers (7)

- (1) Institute for Geography, Universität zu Köln, Albertus-Magnus-Platz, 50923 Köln (Cologne), GERMANY. andreas.voett@uni-koeln.de
- (2) Faculty of Geography, Philipps-Universität Marburg, 35032 Marburg, GERMANY.
- (3) Department of Dynamic, Tectonic, Applied Geology, National and Kapodistrian University of Athens, 15784 Athens, GREECE.
- (4) Department of Classical Archaeology, Technische Universität Darmstadt, El-Lissitzky-Str. 1, 64287 Darmstadt, GERMANY.
- (5) Institute for Geography, Universität zu Köln, Albertus-Magnus-Platz, 50923 Köln (Cologne), GERMANY.
- (6) Hellenic Centre for Marine Research, 19013 Anavissos, GREECE.
- (7) School of Environmental Science and Management, Southern Cross University, PO Box 157, Lismore NSW 2480. AUSTRALIA.

Abstract: This paper gives an overview of four different groups of tsunami signatures encountered in near-coast geological archives along the shores of the eastern Ionian Sea, Greece. As the study sites are exposed towards the seismically highly active Hellenic Arc, the palaeotsunami events are suggested to have been triggered by seismic events or related landslides over or underwater. The group of sedimentary tsunami signatures comprises (i) dislocated blocks and boulders, (ii) allochthonous marine sediments deposited in littoral or near-shore environments and often mixed with terrigenous material and cultural debris, (iii) allochthonous fine-grained marine deposits intersecting in-situ sediments of near-shore swamps, quiescent freshwater lakes or lagoonal environments, and (iv) beachrock-type calcarenitic tsunamites. Results from case studies are presented for each group of tsunami signatures.

Key words: Palaeotsunami, dislocated boulders, sandwich layers, beachrock

INTRODUCTION

Tsunami hazard in the eastern Mediterranean belongs to the highest worldwide. This is mostly due to the high seismic activity along the Hellenic Arc where the African Plate is being subducted under the Eurasian Plate inducing numerous strong tsunamigenic earthquakes. Also, the Arabian Plate, moving northward by high rates, is a serious source of seismically related hazards. Further potential tsunami triggers in the Mediterranean are submarine slides, meteorite impacts, and explosional volcanic activity, for instance around Sicily or in the Aegean Sea. The eastern Mediterranean is characterized by comparatively short shore-to-shore distances, a highly variable underwater topography and thousands of kilometers of coastline with numerous indentations. In terms of tsunami hazard, this constellation implicates short time intervals for advance warning of local populations, strong refraction effects difficult to predict and a variety of secondary, mostly earthquake-related hazards such as rockfall, liquefaction and subaerial and underwater landslides.

Palaeotsunami research in the eastern Mediterranean has been strongly intensified during the past decades, in order to improve our understanding of the dimension and the dynamic of tsunami landfalls and to gain reliable background information for future risk assessment. Besides archival studies based on ancient accounts and historical data related to extreme wave events in the Mediterranean, an increasing number of geo-scientific field studies have been carried out to detect palaeotsunami deposits. These tsunami deposits can be classified into four main groups.

DISLOCATED BOULDERS – THE CAPE SKALA CASE STUDY

The first group comprises dislocated boulders, originating from bedrock units within the littoral zone, that were torn out, uplifted, turned over and/or transported dozens of meters inland by tsunamigenic wave action. Such deposits are reported from southern Italy (Puglia), Greece (Ionian Islands, Peloponnese, Crete), southern Turkey, Cyprus and from the Levant. In the western Mediterranean, tsunamigenically dislocated boulders were recently described from the Algerian and Tunisian coasts.



Fig. 1: Dislocated boulders near Cape Skala, southern Peloponnese with imbrications structure. Person as scale measures approx. 1.65 m.

Within the framework of our studies, tsunamigenically dislocated boulders were encountered west of Cape Skala at the Lakonian Gulf, southern Peloponnese. Large boulders were found more than 150 m inland and up to

+14 m above sea level (m a.s.l.). Some boulders show clear imbrication (Fig. 1), some are balancing on sharp rock needles which formed between rock pools in the supratidal area. Many boulders, lying fairly well above present sea level, are characterized by rock pools. In most cases, these rock pools are strongly inclined or even upside down. Such geomorphological features are usually formed by bio-erosional processes in the littoral zone and their original position is horizontal. This clearly documents that the blocks were dislocated from their original position. In case the blocks were not transported beyond the spray zone itself, fresh smaller pools with a horizontal bottom have been formed within the older inclined ones. In some cases, the blocks were re-deposited within the littoral zone so that vermetid rims could form after the dislocation. The results from dating these vermetid rims attached to dislocated boulders let us conclude that a tsunami hit the coastline around 1300 cal AD may be related to the catastrophic earthquake which affected large parts of the eastern Mediterranean in 1303 AD (Scheffers et al. 2008). Local bathymetric conditions are shallow (maximum depth < 3 m for hundreds of meters offshore) and therefore prevent larger storm waves from reaching the coast without losing energy. As a wave will break when water depth is less than 1.28 times its height, storm waves cannot have been higher than about 3 m, much too less to overturn or transport the large boulders onshore. Wave transport of the boulders is therefore suggested to be the result of tsunami landfall.

LITTORAL OR NEAR-SHORE GEOARCHAEOLOGICAL LAYERS – THE POGONIA CASE STUDY

In some cases, allochthonous marine sediments, mostly sand and/or gravel, were found in littoral or near-shore geological archives, often associated to terrigenous material and cultural debris. Examples are known from Italy, mainland Greece, the Aegean Islands, Israel and from Egypt (see e.g. Vött et al. 2008, Bruins et al. 2008).



Fig. 2: Tsunamigenic layer at the cliff near Pogonia (Akarnania) including allochthonous marine shell debris, foraminifers, sand, gravel and ceramic fragments mixed up with terrigenous deposits and covered by a palaeosol

In Akarnania (NW Greece), the cliff near Pogonia, almost 100 m long and up to 2 m high, reveals a homogeneous colluvisol including isolated ceramic fragments predominantly dating to the Byzantine epoch (Figs. 2 and 3). The colluvisol covers an up to 2 m-thick stratum with plenty of diagnostic ceramic fragments, well adjusted,

partly imbricated, and mixed up with beach gravel and sand as well as with numerous remains of marine macrofossils. Due to its texture and contents, this mixed geoarchaeological layer may neither be interpreted as (i) colluvial deposit, nor as (ii) landslide deposit, nor as (iii) usual (supra-)littoral deposit. In its upper part, it shows a well developed palaeosol. Supplementary vibracoring revealed that the layer overlies, on top of an unconformity, fine-grained foreshore sand deposits. Within the mixed layer, we encountered rip-up clasts out of underlying marly bedrock. Microscopic analyses revealed that the matrix of the ceramic-rich stratum contains weathered and reworked bedrock material as indicated by mostly angularly shaped mineral grains but also marine indicators such as shell debris of marine macro- and microfauna and marine foraminifers.

Based on these distinct sedimentological and palaeontological features, we conclude that the mixed geoarchaeological layer is of tsunamigenic origin. The chaotic and wide-spread spatial distribution of archaeological remains of a nearby ancient mole, today submerged, may also be caused by destructive tsunami landfall in conjunction with co-seismic subsidence. Diagnostic ceramic fragments from the destructive layer are up to 20 cm large. We found both rounded and angular fragments. Preliminary archaeological studies show that they all date to Classical/Hellenistic to (early) Roman times. This is consistent findings of a homogeneous group of pottery wedged in the submerged mole dating to the late 4th to 2nd centuries BC. Former palaeogeographical studies in the Palairos coastal plain already suggested that the area was subject to considerable tsunami impact possibly contemporaneous to the strong tsunami which hit the nearby Lefkada coastal zone between 395 and 247 cal BC (Vött et al. 2008).

INTERSECTING MARINE DEPOSITS IN QUIESCENT NEAR-SHORE ENVIRONMENTS – THE LAKE VOULKARIA CASE STUDY

Another type of tsunami signatures is characterised by allochthonous fine-grained marine deposits intersecting homogeneous autochthonous sediments of near-shore swamps, quiescent freshwater lakes or lagoonal environments. Recent studies have shown that this constellation offers best premises for sandwich radiocarbon dating of event deposits. This is due to weaker erosional dynamics and the large availability of datable in-situ organic material not affected by marine reservoir effects.

We found evidence of multiple tsunami impact on the near-coast freshwater lake environment of the Lake Voulkaria (Akarnania, NW Greece). Sedimentological, macro- and micropalaeontological, micromorphological, geochemical and geophysical methods were used to differentiate between autochthonous quiescent water mud and intersecting layers of allochthonous material out of sand, gravel, marine shell and foraminifer debris, organic matter and/or ceramic fragments (Fig. 3).

Analysing the Lake Voulkaria sediment trap and its environs revealed a sequence of four tsunami generations (Vött et al. 2009a). Geochronostratigraphic

interpretations are based on relative palynological age determination, radiocarbon dating and geoarchaeological findings. Tsunami generation I did probably not affect the lake itself but connected the adjacent former Lake of Cheladivaron to the open Ionian Sea; this event already took place in the 6th millennium BC or shortly afterwards. The subsequent tsunami generation II is dated to around 1000 cal BC; the following generation III hit the lake most probably during Classical-Hellenistic to maximum Roman times.

Thick deposits of tsunami generation IV from the 4th century AD were encountered all around the lake, probably representing traces of the 365 AD earthquake and tsunami catastrophe that destroyed large parts of the eastern coastal Mediterranean. We found generally good accordance between number and age of tsunami sediments found in the Lake Voulkaria and tsunami traces from adjacent coastal sites described in previous papers. Our studies revealed the Lake Voulkaria to be an outstanding tsunami sediment trap highly valuable to establish a local geochronology for large extreme events in the northwestern Ionian Sea.

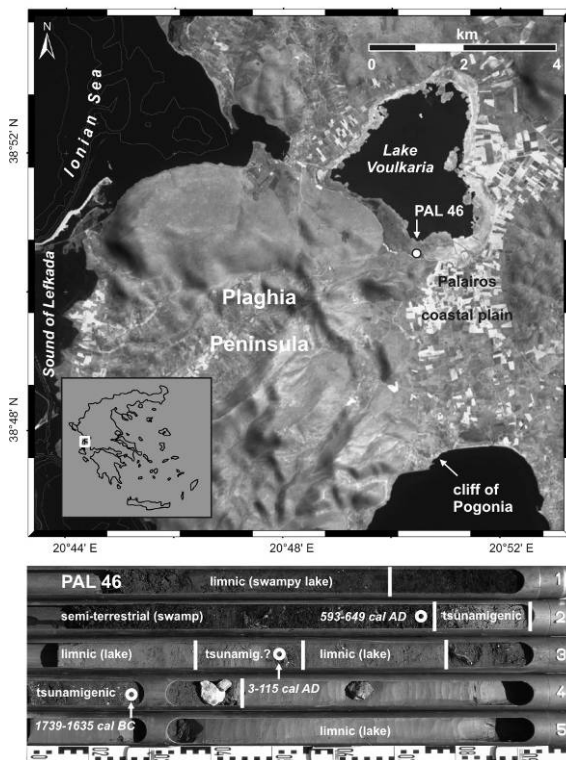


Fig. 3: The Lake Voulkaria tsunami sediment trap in northwestern Greece. The freshwater lake environment is separated from the Ionian Sea by a bedrock sill with elevations between 5-18 m a.s.l. Vibracore PAL 46 was drilled at its southwestern shore and revealed several tsunamigenic layers out of allochthonous material intersecting in-situ limnic mud or peat. Core PAL 46 thus documents multiple tsunami impact (after Vött et al. 2009a)

BEACHROCK-TYPE CALCARENITIC TSUNAMITES – THE PHEIA CASE STUDY

The fourth group of tsunami deposits – beachrock-type calcarenitic tsunamites – has been recently described, for the first time, based on three case studies from western Greece (Vött et al. 2009b). Here, we present details of the

Pheia case study and describe the sedimentary characteristics of the calcarenites which help to better understand the tsunami-related sedimentation and post-event processes.

Ancient Pheia is located in the Bay of Aghios Andreas in the western Peloponnese. In antiquity, it was used as a sea harbor for Olympia which is situated some 28 km further east. The archaeological remains of Pheia are almost completely submerged and lie in water depths down to 5 m below present sea level. The harbor is said to have been destroyed by earthquakes in the 6th century AD, most probably in 521 AD and/or 551 AD. The modern beach of Aghios Andreas is characterized by thick beachrock layers. Within former studies, this beachrock was used as sea level indicator thus explaining the submergence of ancient Pheia by a complex sequence of gradual subsidence (6.5 m) and following minor uplift (1.5 m).

We carried out geomorphological, sedimentological and geoarchaeological studies and found that the beachrock, up to 3 m thick, is clearly laminated and consists of several fining upward sequences out of fine sand from the littoral zone. We also encountered coarse-grained layers including marine shell debris and ceramic fragments, partly rounded, partly angular, at the base of the fining-upward sequences. Further sedimentary structures such as convolute bedding and load casting are untypical of littoral environments (beaches) and rather indicate gravity-induced flow dynamics in a water-saturated suspension-like matrix; convolute bedding structures are thus assumed to reflect intermittent backflow shortly after high-energy deposition of thick allochthonous sand deposits onshore. The basal section of the beachrock is lying on top of an erosional discordance and consists of abundant gravel also inferring high-energy influence. In some areas, large ashlar were found incorporated into the calcarenite (Fig. 4). These man-made blocks, still angular, do not show any signs of being moved in the littoral zone; one block is even coated with original white plaster. Intra-beachrock ceramic fragments and ashlar pre-date the end of the 6th century AD; this date, marking the end of the continuous colonization of the site since the Bronze Age, is suggested a *terminus ad quem* for the event. Vibracoring revealed clear thinning land- and sideward of the beachrock, and the beachrock was discovered up to 40 m distant from the coast and up to 2.60 m a.s.l. It is, however, known from previous studies that during the Holocene the relative sea level has never been higher than at present (Kraft et al. 2005, Vött 2007, Engel et al. 2009).

Based on our results, the beachrock sequence at Aghios Andreas does not show at all sedimentary characteristics typical of a (lithified) beach but rather represents a high-energy event deposit. We therefore suggest that Olympia's ancient harbor at Pheia was hit by a strong tsunami associated to one of the strong earthquakes reported for the 6th century AD. Submergence seems to be of co-seismic nature such as observed during the southeast Asia tsunami in 2004.



Fig. 4: Beachrock-type calcarenitic tsunamite at Aghios Andreas (Peloponnese), up to 3 m thick and reaching from present sea level up to 2.60 m a.s.l. Note incorporated non-rounded ashlar with original white plaster. Likewise untypical of usual beach deposits are convolute bedding structures (inlay photo); circle symbolizes a 2 Euro coin

Associated to the beachrock, an adjacent cliff profile reveals a mixed geoarchaeological layer out of sand, gravel, ceramic fragments, and marine shell debris. The upper part of this layer subsequently weathered and formed a palaeosol. Geomorphological studies at the nearby Cape Katakolo and Tigani Island further revealed numerous dislocated blocks lying up to 40 m distant from the present shore which seem to be associated with both beachrock-type tsunamite and geoarchaeological tsunami layer.

CONCLUSIONS

By our case studies, it was possible to show that tsunami signatures in coastal sedimentary environments are highly variable. Many controlling factors have to be taken into consideration for a better understanding of the spatial distribution of tsunami deposits and the question of how, when and why tsunamigenic erosion prevails over depositional processes. Such controlling factors are, for example: (i) the availability and nature of potentially dislocatable material in foreshore, littoral and near-shore areas, (ii) the pre-existing topography and its channelling and diverging effects concerning tsunami wave dynamics, and (iii) the existence of appropriate tsunami sediment traps. Simple lists of geomorphological and sedimentological arguments currently used for identifying tsunami deposits more and more turn out to be inapt instruments for tracing tsunamis and explain major difference to storm events. Therefore, major significance has to be attributed to the geographical dimensions and variabilities of tsunamigenic processes and sedimentary

signatures which will then help to better understand the overall nature of tsunami impact on coastal environments all over the world.

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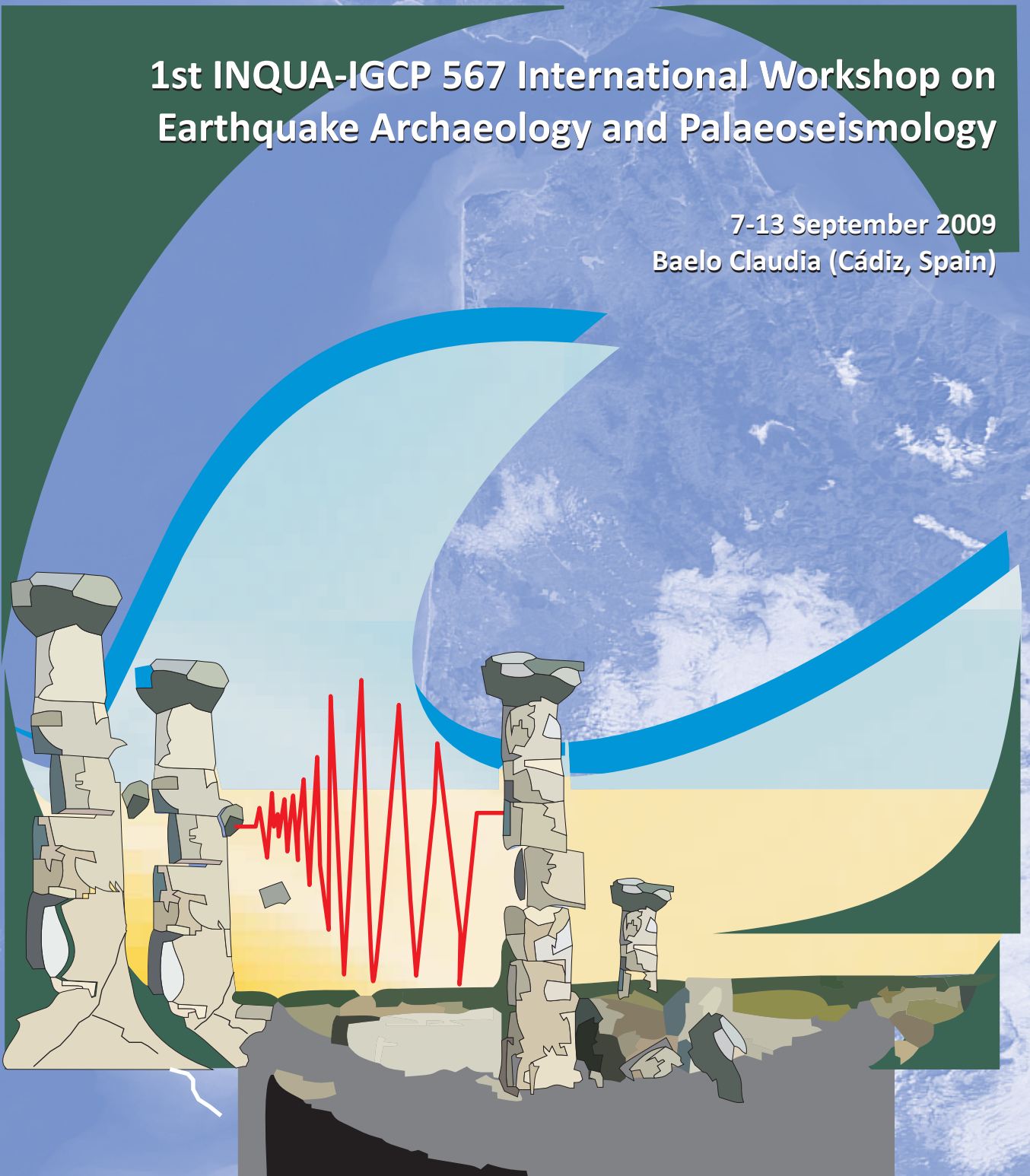
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