IGCP Project 639
“Sea Level Change from Minutes to Millennia”

Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
IGCP Project 639 - Sea Level Change from Minutes to Millennia
Crossing Southern Italy...a travelling meeting from Taranto to Siracusa

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First and Fourth of Cover: Raised tidal notch and present bioerosive platform, Fanò (Othonoi, Οθωνoi), Ionian Islands, Greece (Photo by Giuseppe Mastronuzzi)

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A special thank to Prof. Gilberto Pambianchi, President of AIGeo – Associazione Italiana di Geografia Fisica e Geomorfologia and to Prof. Mauro Soldati, President of IAG – International Association of Geomorphology.
This book is dedicated to the memory of Paolo Antonio Pirazzoli, one of the most important coastal geomorphology scientist, Honorary Member of the International Association of Geomorphologists (IAG).
About a year ago, in September 2017 Paolo Pirazzoli left us. Today, he is around somewhere, in a better world, to measure ... the “water level”; one of his latest editorial efforts presents just this name “La misura dell’Acqua” (2011, Corte del Fontego Editore, Venezia, 36pp).

Born in Venice in 1939, Paolo Antonio Pirazzoli started his research activity after obtaining a degree in Civil Engineering. Naturalized French in 1978 for the love of his Michèle, author of fundamental studies on Chinese art and civilization, he has carried out its brilliant and captivating career as researcher and research director at the CNRS (Centre National de la Recherche Scientifique) in Paris.

In a location far from the sea, Paolo has built the field research “tout cour” on the sea level changes. He left with his Citroen 2CV and his boat for coastal explorations, sometimes accompanied by local experts and he stopped to photograph, measure and reason the sites he thought interesting for the reconstruction of sea level changes. Paolo saw the evidence of sea level variations with a sure eye; he dated and interpreted them in a complex context, on a local scale without underestimating their possible global significance.

I don’t think that anyone could deny that we owe the modern approach to the sea level dynamics study to the researches performed by Paolo. He showed that morphological, stratigraphic, biological and geoarchaeological evidence, if wisely correlated to the local geodynamics and other geological behaviour, allows us to understand where the sea level was in the past and to construct future scenarios.

Paolo has managed important international projects with an attentive eye on young researchers and particularly on the young researchers of emerging countries: he was leader of the IGCP Project n. 200 “Correlations of sea level and applications” (1983-1987) and a relevant member of many other IGCP projects; he was a promoter of the DISCOBOLE project on sea level and coastal developments during the Quaternary and their forecasts.

He has published more than 250 scientific articles and five volumes of great international diffusion, including “Sea level changes, the last 20,000 years” (Wiley), and the “World Atlas of Holocene Sea level changes” (Elsevier). Paolo directed the journal Global and Planetary Change (Elsevier) since its foundation in 1988.

Many awards and prizes were significant, such as: “Best Paper Award 1989” of the International Society for Reef Studies; geography award “Konstantin Ktena 1995” of the Academy of Athens; “Best Paper Award 1995” of the International Society for Reef Studies; “Rhodes Fairbridge 1999” award from the Union Internationale pour l’Étude du Quaternaire.

I met Paolo first time in 1994 at the conference GEOSUB 94 organized in Palinuro (Italy) by ENEA and the University Federico II of Naples; since then Paolo has been a reference for the development of my research in the field of geomorphology and coastal morphodynamics. Like me, many other “ex-young people” Italians, Europeans and from the whole world owe him the enthusiasm and curiosity that he has always transmitted, up to his last days. With Paolo I was lucky to work quasi all around the coasts of the world; but, mainly, from Paolo, I had the spur that allowed me to enter into a stimulating and intriguing scientific context such as that of IGCP projects. It is surely thanks to him that, with Paolo Sansò, we had the opportunity to organize Puglia 2003 in Italy, the meeting that closed the IGCP 437 project; the first IGCP project in which I was officially involved with the Italian delegation.

I hope that thanks to the presence of Paolo’s energy, even the young people present at this conference breathe that sparkling sea breeze that pushes to brave all difficulties in order to obtain knowledge regarding the “things of the sea”.

Grazie Paolo

Giuseppe
Foreword

We would like to extend a warm welcome to all the participants in the third international annual meeting “on Sea Level Change from Minutes to Millennia” IGCP Project 639.

This is not the first time that an official meeting of an IGCP Project related to sea level change is to be held in Southern Italy. This time it will interest the study of sea level changes crossing the chain-foredeep and foreland dominion, interested in the last years by numerous papers produced by scientists from the entire world focusing their interest on a large variety of geological aspects.

The coastal landscape of the Southern Italy has attracted the attention of the international scientific community involved in IGCP projects on various occasions over the course of the last 30 years; during the final meeting of IGCP 437 in 2003, participants viewed around the more significant sites for reconstructing the evolution of the coastal landscape in Puglia during the late Quaternary; in 2008 in the framework of the IGCP Project 495, the 2nd International Tsunami Field Symposium permitted to visit the most important areas hit by historical tsunami in Apulia and Ionian Greece.

The present book collects the scientific abstracts, which we believe will improve our overall knowledge on coastal environment modifications in response to sea level change and we hope also the book may provide useful indications for the management of future coastal changes.

The foremost scientific task of an international meeting must of necessity be the world itself, but any global reconstruction needs to make a start from local and regional analysis.

We are of the opinion that researchers must always be prepared to compare their own ideas with ideas of other; and it is for this reason that we are happy to show you around sites the significance of which remains a matter debate, and this occasion is one also for improving the techniques and the scientific approach in general.

The science is never absolute; it is forever changing...sometimes slowly, sometimes swiftly and there are no investigative methods which should be considered, a priori, as either completely valid or absolutely fallacious. We are far from know all details about the dynamics of the sea level during the Quaternary. Moreover, we are only able to built possible scenario for the future; no one still can know what, where, when, and in which measure will occur ... may be only why.

Of necessity each one of us always hopes to be able to provide more new data; and if some may tend to contradict those data discussed and outlined in these pages, we will be more than willing to address and discuss another time.

We would like to take this occasion to thank the AIGeo – Italian Association of Physical Geography and Geomorphology, the IAG – International Association of Geomorphology who scientifically support the activity of this meeting and the INQUA - International Union for Quaternary Research.

We are pleased to gratefully acknowledge the financial support afforded us by the Central Administration of University of Bari, the Department of Earth and Geo-environmental Sciences, the PhD School of Geosciences of University of Bari “Aldo Moro”.

Finally, our thanks must also be extended to UNESCO and IUGS for any efforts done to improve the knowledge of Earth Sciences in the young scientists coming from the entire scientific community.

The organizers of the Conference

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IGCP 639 Italian delegation
Introduction

Welcome to the Third Annual Meeting of
IGCP 639 project “Sea Level Change from Minutes to Millennia”

Project 639 is the natural evolution of the many previous IGCP sea-level programmes that commenced with Project 61 “Sea-level change during the last deglacial hemicycle” directed by A.L. Bloom (1974-1982), and continued through Project 200 “Sea-level correlation and application” directed by Paolo Antonio Pirazzoli (1983–1987), Project 274 “Coastal evolution in the Late Quaternary” directed by Orson van de Plassche (1988-1993), Project 437 “Coastal environmental change during sea-level highstands” directed by C.V. Murray-Wallace (1999-2003), Project 495 “Quaternary land-ocean interactions: driving mechanisms and coastal responses” directed by Antony J. Long and Shahidul Islam (2004-2009) and Project 588 “Preparing for Coastal Change” directed by Craig Sloss, Benjamin Horton and Yongqiang Zong (2010-2015). Forty years on from the first IGCP coastal project, the global sea-level community is now well equipped to develop local, regional and global records of relative sea-level (RSL) change. It is also increasingly able to describe linkages between terrestrial, coastal and marine environments through the application of new techniques of sediment fingerprinting, dating, as well as the implementation of quantitative models of coastal mobile systems and rocky coast dynamics, wave impacts, and sediment flux in relation to the local and global sea-level changes.

IGCP Project 639 is focused on the central theme of all IGCP sea-level related science with the aim to provide a platform for the development of integrated records of sea-level change and coastal hazards obtained from instrumental, historical, archaeological, and geological records. This project expands upon the research theme of project 588 that focused on the impacts of humans on coastal landscape dynamic, highlighting its results in a coastal hazard toolkit that can be applied by those who are at major risk from future coastal inundation over varying timescales.

As in previous projects, IGCP 639 has strong links with other international research programmes; an optional two day workshop developed in collaboration with the INQUA projects MOPP-Medflood, HolSea and CMP1701P is planned for after the meeting. This workshop will be focused on the standardization of RSL data with a particular focus on examples from the Mediterranean that also have applications globally, including field trips to see examples.

Since the inception of IGCP 639, there have been two international meetings of the project:

The first meeting (2016) was held in Muscat, Oman. The trip provided a wonderful start to the project with a focus on tectonic-driven sea-level changes along the coast of Oman.

The second meeting in 2017 was in Durban and St Lucia, east coast of South Africa: the meeting was held jointly with the INQUA project CMP1701P “Late Quaternary records of coastal inundation due to earth surface deformation, tsunami and storms” and CMP1601P “HOLSEA”.

We wish all those attending the Third Annual Meeting an enjoyable and stimulating conference.

Finally, we would like to take this opportunity to thank those researchers from all around the world whose contributions focused on Southern Italy have allowed the preparation of four days of field trip that will follow the completion of the scientific sessions.

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COASTAL GEOMORPHOLOGY
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The raised wave cut platform of southern Kerkira Island, Greece

Chairs

Fabrizio Antonioli, Helmut Brückner
Relative sea level rise projections and flooding hazard by 2100 along the main coastal plains of the Mediterranean: insights from the SAVEMEDCOASTS project

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Keywords: Sea level rise, Mediterranean, coastal plains, Civil Protection.

Sea level rise (SLR) is one of the main global threats caused by climate change. When in combination with vertical land movements (VLM) for natural or anthropogenic causes, changes in relative sea levels are particularly crucial in subsiding coasts, accelerating land flooding.

In this study we focus on the main coastal plains of the Mediterranean region, located at less than 2 m above sea level, which are more prone to be flooded by sea level rise in the next decades.

For the analysis, we used high resolution Digital Terrain Models (SRTM, ASTER EUDEM, DLR, ALOS and UAV data for topography and EMODnet and local multibeam surveys for bathymetry), rates of land subsidence (based on geodetic and geological data) and IPCC projections, to realize relative sea level rise and marine flooding scenarios expected for 2100 AD along targeted areas of the investigated region.

We focus on the UNESCO sites of the Venice lagoon, Lipari Island and Cinque Terre (Monterosso and Vernazza) and the Island of Lefkada (Greece), besides other densely inhabited coastal areas. In particular, the Venice lagoon and the volcanic island of Lipari are highly exposed to relative sea level rise being both subsiding at rates of up to several mm/yr.

Figure 1. Map of the coastal plains of the Mediterranean region with elevation <2 m above sea level, prone to marine flooding (www.savemedcoasts.eu).
Here we show and discuss the first results arising from the SAVEMEDCOASTS Project (Sea Level Rise Scenarios along the Mediterranean Coasts, co-funded by the European Commission ECHO A.5, www.savemedcoasts.eu), which aims to respond to the need for people and assets prevention from natural disasters in Mediterranean coastal zones placed at less than 2 m above sea level, which are vulnerable to increasing sea level rise under the climate change impacts.

The hazard implications for the population living along the shore are considered to push land planners and decision makers to take into account scenarios similar to that reported in this study for cognizant coastal management. Despite SAVEMEDCOAST is still ongoing, it is improving governance and raising community awareness towards the impacts of coastal hazard, fostering the cooperation amongst science, affected communities and civil protection organizations for these high economic and environmental value zones of the Mediterranean coasts.

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Raised MIS 5a paleoshorelines in the northwestern coast of Calabria (southern Apennines, Italy)

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Keywords: Raised paleoshorelines; MIS 5a; U/Th dating; geomorphology; southern Italy.

The Tyrrhenian coastal landscape of southern Italy, from Campania to Calabria, exhibits impressive flights of marine terraces that represent the result of the interaction between long-term tectonic uplift and Quaternary sealevel changes (Ascione and Romano, 1999; Bianca et alii, 2011; Carobene and Dai Pra, 1990; Carobene and Ferrini, 1993; Dumas et alii, 2000; Filocamo et alii, 2009; Miyauchi et alii, 1994; Monaco et alii, 2017; Westaway, 1993). The age and vertical distribution of the marine terraces suggest that the Tyrrhenian margin of the southern Apennines has been differentially uplifting during Quaternary times, with the southernmost segment (southern Calabria) recording higher uplift rates (Ascione and Romano, 1999; Ferranti et alii, 2006; Miyauchi et alii, 1994; Westaway, 1993). The overall deformation pattern is related to a local tectonic component, i.e., Middle-Late Quaternary activity of the normal fault segments bounding the Tyrrhenian coastal area, which is superimposed to regional uplift that is attributed to deep-seated processes in the slab underlying the Calabrian arc (Bianca et alii, 2011; Bordoni and Valensise, 1998; Catalano et alii, 2008; Chiarabba et alii, 2008; Cosentino and Gliozi, 1988; Minelli and Faccenna, 2010; Miyauchi et alii, 1994; Tortorici et alii, 2003; Westaway, 1993).

Faster uplift of southern segment of the southern Apennines has been maintained in late Quaternary times. Indeed, average elevation of raised marine shorelines associated with MIS 5 highstand increases from North (e.g., Esposito et alii, 2003; Filocamo et alii, 2009) to South (Cosentino and Gliozi, 1988; Bordoni and Valensise, 1998; Dumas et alii, 2000; Ferranti et alii, 2006; Monaco et alii, 2017), where uplift rates are locally higher than 1 mm/yr, and Holocene markers of sea-level stand indicate an increase of uplift rates up to 2.2 mm/yr (Ferranti et alii, 2008, 2007; Scicchitano et alii, 2011). The northward transition of the fast uplifting sector is not well identified (Ferranti et alii., 2006), and a number of evidences can be traced in discontinuous remnants towards the North suggesting the presence of different uplifting areas (Carobene and Dai Pra, 1990; Carobene and Ferrini, 1993; Sorrison Vallo and Sylvester, 1993; Robustelli et alii, 2005; Filocamo et alii, 2009).

Within such a framework, we have focused our study on the marine terraces preserved along the Basilicata to northern Calabria sector of the Tyrrhenian coast, in the area spanning from Scalea, in the South, to the Noce River mouth in the North (Fig.1). A first attempt to characterize the marine terraces in the northern sector of Calabria was made by Cortese (1895). Subsequently, few direct geo-chronological constraints (Carobene et alii, 1986; Filocamo et alii, 2009) were pivotal in order to assess the very low uplift rates affecting the study area since the late Middle Pleistocene (Carobene and Dai Prà, 1990, 1991; Filocamo et alii, 2009).

Our work combines geomorphological and stratigraphical approaches, which are integrated by mineralogical and geochronological (U-series dating) analyses, and is aimed at getting new constraints on the late Pleistocene sea-level markers from this key area. In particular, we focus on (i) unravelling the recent tectonic behaviour of the coast of Basilicata and northwestern Calabria, (ii) assessing the Late Pleistocene uplift rates, and (iii) evaluating possible temporally and spatially uneven uplift.

The study area is characterized by an alternation of bays, such as the Noce River plain, and promontories made up of Triassic to Miocene carbonate rocks tectonically overlain by ophiolitic rocks (Fig.1). The geomorphological study, integrated with Quaternary stratigraphy analyses, X-ray powder diffraction (XRD) and geochronological (uranium-thorium dating) analyses, has been carried out on detail-topographic data e.g. 1:5.000 scale map (Regione Calabria, LiDAR data) and field surveys. The latters were aimed at the characterization of sea-level markers and of the shallow marine and continental deposits associated to the marine terraces. Much attention was devoted to the analysis of paleoshorelines located up to few tens of metres a.s.l.
The precise elevation of paleo-sea levels markers has been measured on the field with the aim of a laser distance meter and a handheld GPS. 

*Cladocora caespitosa* bioconstructions and speleothems have been sampled for U-series dating, in order to constrain the marine terraces. For radiometric dating, ~3g of *Cladocora caespitosa* and ~40 g of speleothems, which predate or postdate sea-levels indicator, were used. Therefore, to verify the aragonitic nature of the corals and avoid possibly opening of the chemical system, XRD analysis, using a GE-Seifert MZVI automated diffractometer, has been carried out on the internal part of the corals. The coral samples containing more than 5% of calcite amount were discarded because the abundant presence of calcite indicates weathering processes, which could interfere with the age determinations.

The combination of field data, geomorphological and geochronological analyses provide new data on late Quaternary paleoshorelines along the northern Tyrrhenian coast of Calabria spanning from the Noce River mouth, in the north, to Scalea in the south. The field surveys have evidenced different types of sea-levels markers such as wave-cut platforms, tidal notches and bands of lithophaga holes. Among the analysed shoreline remnants, those located around 20 m a.s.l., e.g. the Grotta del Prete key outcrop that is described herein, are widespread and show interesting geomorphological stratigraphical evidences.

In particular, in the Grotta del Prete site (Fig. 1) a wide abrasion platform cut in the carbonate bedrock crops out. Its inner edge is located at an elevation of ~20 m a.s.l. The outcrop (Fig. 2) shows, above the wave-cut terrace, few metre thick shallow-water deposits formed by a beach conglomerate that passes upward to a bioconstruction with *Cladocora caespitosa* specimens. The bioconstruction is eroded by potholes, which are covered by shoreface arenites. The presence of potholes could indicate a sea-level fall, while the arenite may be related with a sea-level rise postdating the *Cladocora* bearing deposits. The succession is closed by a reddish paleosoil.
The radiometric analysis of a *Cladocora caespitosa* sample from the Grotta del Prete site has provided an age of 83.8±3.6 ka, which points to correlation of the bioconstruction of the Grotta del Prete site with MIS 5a. Based on such a correlation, sea-level oscillations observed in the field may be framed within MIS 5a. Such an interpretation is consistent with similar evidence reported by Dumas et alii (2005) by analyses of MIS 5a marine terraces from southernmost Calabria.

Dating of the Grotta del Prete marine terrace indicates recent uplift of the study area. In fact, comparison of the MIS 5a shoreline position in the study area with elevation of MIS 5a sea-level markers from both stable areas in the western Mediterranean (which occur ~1.3÷1.9 m a.s.l. in the Mallorca island; Tuccimei et alii, 2006; Dorale et alii, 2010), and the Campania coast of southern Italy (which occur in the +1.5÷2 m elevation range both in the Sorrento Peninsula and northern Cilento; Iannace et alii, 2001, 2003; Riccio et alii, 2001), points to uplift of the studied coastal sector postdating MIS 5a of ~18÷20 m.

The first results of our study, and in particular the identification of recent vertical motions in the study area, provide new constraints to the reconstruction of the Quaternary behaviour of Calabria and suggest active motions in the study region.

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Variation of coastal geomorphology at Unawatuna bay beach during last four decades

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Keywords: Coastal geomorphology, erosion, coastline.

Unawatuna bay beach belongs to a dynamic coastal region in Sri Lanka giving stunning aesthetic and socio-economic advantages for a long period. This area was selected to study the annual and long term variation of the coastal geomorphology, to verify the reasons for such changes and to examine how geomorphological changes have influenced the natural environment and socio-economic status of the area. Firstly, the digital thematic maps of the study area were prepared for the period of 1974 to 2016 using sequential aerial photographs and satellite images. Coastline changes were identified using these maps. Then the relationship between identified changes and variables which are effect on coastal geomorphology were examined using tidal, wind and data relevant to coast oriented activities of the area. After the analysis of thematic layers, it was found that the coastline changes from 1974 up to sand nourishment which was established in 2015 shows a continuous pattern of degradation and also wide sandy beach has been washed away. The trend in degradation of the coastline in Unawatuna central GN division is more than that of Welle devalaya site during 1974 to 1994. It is due to concentration of more tourism related activities within that coast. Analysis of thematic layers show a significant change in coastline at Welle devalaya site from 1994 to 2002. A catastrophic coral depletion occur after the El Nino event in 1998 can be surmised as the main reason for such observation. Breakwater and sand nourishment which were established in the area also have been caused to change the nature of bay and beach. Annual variation of the bay beach are occur due to wind and wave actions which accelerates during Southwest monsoonal period while the rest of the period have been influenced by spring tides. It can conclude that, distinctive geomorphological changes occur due to human interventions while annual variation pattern has been controlled by the monsoonal activities and spring tides.

Introduction

Changing nature of the geomorphic features may occur by degrading, prograding and as newly emerging or even by eliminating from the system. It is common for coastal systems and also changes may occur not only over centuries or decades, but it can occur within a day, hour, minute or even in second. This study was attempt to make sense about significant changes of coastal geomorphic features in different time scales. Erosion and deposition are the two major driving forces for changes of those features interacting magnitude of several other physical and anthropogenic conditions which operate within coastal systems. Hydrodynamic and aerodynamic processes are responsible for geographical variations in coastal geomorphology. Main hydrodynamics are the oceanographic forces such as waves, tides and currents. Atmospheric conditions are also important aspects to decide the significance of geomorphic changes. According to the Davies (1980) classification of coastal types based on wave height and tidal range, coastline around country is belongs to ‘West coast swell’ wave environment and ‘micro tide range’ environment. Those are the dominant sources of nearshore energy and interact with the coastline to generate nearshore currents and sediment transport. According to the Coast Conservation Department reports, geology of the coastal zone, hydrology, wave climate and littoral drift, and the world trend of rise in ocean water levels play a significant role in the characteristics and behaviours of the coastline of Sri Lanka (Swan, 1982). Morphodynamic processes are strongly influence for the variation of the coastline and beaches. Cooray and Katupotha (1991) have been identified entire South-West coastal zone as a retreating zone. Unawatuna is a very famous beach among local and foreign people. However, it belongs to dynamic coastal region which has been subjected to serious coastal erosion within last fifty years. Main costal geomorphic features in Unawatuna bay area are bay, wide sandy beach and headland at one end of the bay.
The Study area
The Unawatuna beach is located in the Galle suburb within Habaraduwa Divisional Secretariat Division. Coral reefs at Unawatuna helped to minimize wave action and to support swimming and scuba diving recreational activities. Many tourists visit famous Rumassala hill rock which is adjacent to Unawatuna bay to discover its mysteries. There are interesting mythological stories relate to Unawatuma area. According to Ramayana, this area was a part of Himalaya. Unawatuna has become a famous tourist attractive site in Sri Lanka and many economic activities established within the area. Unawatuna bay beach area is shown in Fig. 1. This beach considered as one of the serious erosive beach in Sri Lanka (Dayananda, 1992). It had been established sand nourishments at Unawatuna beach at several occasions to protect the beach from erosion.

Materials and method
Sequential recent Google Earth images were used to demarcate and compare the recent beach area at Unawatuna. Using these images and GPS survey, digital thematic maps were produced to represent recent beach area at Unawatuna. Archives topographical maps, ancient aerial photographs and satellite images were used to prepare digital thematic maps of the old Unawatuna beach. Arc GIS (version 10.3) software has used to compare the variation of coastal geomorphology of the beach in different periods from 1974 to 2016 by applying the overlay analysis technique.

Results and Discussion
Coastal erosion trend of the study area from 1974 to 2016 is the indication of annual changes of the coastline in different time intervals. There is a pattern of coastline change can be identified in two sides of the bay during the study period. The entire coastline change during the 1970’s and 1980’s were protrude towards sea approximately 30 m comparing to present coastline in the area. However, entire coastline is not indicated obvious change from 1974 to 1983. This status exist until significant change occurred during 1983 to 1994 at the Eastern part of the bay. Figure 2 shows that the distinct coastline movement at the area which belongs to Unawatuna central GND.

Spatial variation of erosion at either sides of the bay can be identified by overlaying available coastline layers from 1974 to 2016. Accordingly, some outstanding variation can be identified at different locations of the bay (Fig 2). According to this figure, highest coastal erosion rate recorded close to ‘Unawatuna Beach Resort’ site (UBR) for the entire time period i.e. from 1974 to 2016.

It has been shifting approximately 49 m towards inland. Another significant factor is that, the lowest erosion also recorded at the Eastern part of the bay area. It was noted that coastline has changed at the boat landing site near Sun & Sea hotel only 3 m from 1974 to 2016. Other two locations of highest and lowest erosion rates recorded at the Western part of the bay. At ‘Happy Banana’ hotel site coastline has shifted approximately about 41 m while at the ‘Samaya Tranz’ hotel site coastline has shifted about 11 m. Due to variation of erosion at different locations, the entire bay area can be divided into for parts based on the loss of land area as shown in the Graph 1. The classification of these coastline areas are shown in Fig 2.

When analyzing the coastline evolution since 1974 to present, the highest land area lost has been occurred during 1983 to 1994. It is approximately 14, 984 m$^2$ of the net area lost as shown in Graph 1. Eastern part of the bay has been recorded a significant amount of land lost and the highest is recorded along the coastal stretch from ‘Banana Garden to Unawatuna Beach Resort (UBR)’ site. It is approximately about 5755 m$^2$ of land area. The coastline from ‘UBR to the Villa’ hotel site shows an area lost in Western part of the bay during 1974 to 1994. However, erosion has been not recorded at Welle devalaya site. The erosional trend has been shifted towards Western part of the bay and severe erosion has been occurred at the Welle devalaya site. It has been calculated that the net area lost from 1994 to 2002 at Welle devalaya site is approximately 5000 m$^2$.

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But, there were no considerable erosion occur at Eastern part of the bay during this period. Erosion trend at the Western side of the bay has been continued until 2013. After 2013, erosion at the Western part of the bay has been completely stopped and exist at present coastline position. However, erosion has been continued from ‘Banana Garden stretch to UBR’ hotel site. It is very clear that, there is no further erosion or coastline changes occur after 2015 at either sides of the bay.

**Conclusion**

Although the coasts are continuously evolve, morphodynamics of the coasts are vary in different areas in different levels respect to magnitude of coastal dynamic forces and other physical processes. As indicated in the above, entire Unawatuna bay beach area has been shown periodic fluctuations of coastline and extent of beach. Although coastline indicated only landward retreat during the study period, beach has been subjected to both erosion and accretion at either side of the bay. These changes are continuously happen as coastal areas experience in different oceanographic and meteorological conditions. Particularly tides and wind are caused to these changes while other distinctive spatial and temporal variations has occurred through the combination of both physical and anthropogenic factors. During the late 20th century, morphological changes have been distinctively caused by physical factors specially increase the sea water level. Although coastal zone protection strategies have been taken to minimize the coastal erosion, obvious changes of shoreline retreat and extent of beach during 21st century can clearly identified as a result of these strategies. Beach at the Eastern part of the bay undergone devastation due to construction of breakwater in 2013 and it was minimize by offshore sand pumping and expansion of wide sandy beach. Basically the coastal erosion have been threaten to tourism oriented socio economic environment in the study area. However, creation of artificial beach have been adjust previous socio economic damages by providing favourable conditions to development of the tourism industry. Also it is further indicated that there is a threat on physical environment in the area. According to the results of this study it can be concluded that the short term variation of the beach is mainly due to climatic conditions while the long term variation of the coastal geomorphology of the area is an effect of rise in sea water level.

**References**


Geomorphological numerical model of an uplifting coastal area: the case study of Taranto, Italy

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Keywords: Marine terraces, coastal evolution, sea-level change, landscape evolution model.

Marine terraces are usually indicated as subhorizontal surfaces cut by the action of the sea. Old marine terraces, standing above or below present sea level, can be covered (depositional terraces) by coeval sediments or not (abrasive terraces). The formation of marine terraces is controlled by the interplay between the vertical motion of the land and the sea-level oscillations. The correlation between sea-level curves and the current elevation of Quaternary marine terraces allows us to define the local history of the uplift; this approach is frequently not accurate due to the subaerial erosion events experienced by raised marine terrace since the time of their formation (Pirazzoli, 1996).

A 1-D numerical model was developed to help the interpretation and analysis of the evolution of a flight of Quaternary marine terraces in southern Italy during the last 430 ky. We used SIGNUM (Simple Integrated Geomorphological NUmerical Model) landscape evolution model (Refice et alii, 2012) to simulate the 3D evolution of a topographic surface and to predict the geomorphic response of a coastal landscape to the reconstructed sea-level history, uplift rate and erosion processes. We applied the model in a coastal area of south-eastern Italy, near the city of Taranto; in this area one of the most studied successions of Pleistocene marine terraces of the Mediterranean area is located (Fig. 1); here the most reliable data set of marine deposits is available, whose age was attributed to the MIS 5.e. (eg. Antonioli et alii, 2009, Amorosi et alii, 2014). The modeling results were used to infer new hypotheses for the uplift and erosion history of the real landscape and as a basis for the development of general models of coastal landscape evolution under the forcing of sea level oscillations. We show that using the parameters that describe the different processes it was possible to reconstruct the sequence of marine terraces and to identify hypothetic polyphasic erosional surfaces (Fig. 2).

Figure 1. The Taranto flight of marine terraces looking seaward.
Figure 2. Result of SIGNUM model applied to the Taranto area for the last 430ka. Eleven different wave cut platforms are recognizable but some of them are poliphasic.

References


Impact of Sea Level Rise on Heritage Resources of the Delaware Estuary

Sea level rise (SLR) poses a major threat to natural environments and archeological sites present in the low-lying coastal areas. Global sea levels could rise one meter or more throughout the 21st century, presenting major challenges to coastal environments including salt marshes (Stammer et alii, 2018). With an estimated 13,000 plus archaeological sites predicted to be submerged by 2100 in the southeastern United States (Anderson et alii, 2017), alone, it is evident that priorities must be developed for addressing such large-scale loss. We documented archaeological resources and estimated that ~5% of Delaware’s archaeological and historic resources will be inundated or surrounded by salt marsh in the nearest future under the current rate of SLR (Fig. 1a-b).

Using geoarchaeological approach we conducted paleo-landscape reconstructions at selected sites with documented coastal archeological resources in order to reveal connections between human settlement and coastal environments. We also conducted archaeological survey on Shepard’s Island, Delaware producing non-diagnostic archaeological evidence for human occupancy. Using stratigraphy of coastal sediments and the Holocene sea-level database for Delaware estuary, we reconstructed the coastal landscape during the time of human occupation. We use salt-marsh sediments as proxies for paleo-environmental and sea level history reconstructions at archeological sites and used them to predict future changes. These data will allow to refine predictive models for the impacts of SLR on natural and cultural coastal resources of Delaware. The paleo-reconstructions will contribute to a model for human settlements.
We are applying the knowledge of wetland evolution driven by SLR from site specific to estuarine scale in order to assess the vulnerability of existing cultural resources along the coast of the Delaware Bay. Our multi-disciplinary approach will contribute to the development of a multi-scalar “Landscape Archaeology of Wetlands” methodology for contextualizing the archaeological record of wetland landscapes (Gearey et alii, 2018). The results will help to prioritize protection of Mid-Atlantic heritage resources and promote the development of stakeholder partnerships for future resources conservation and/or management.

References


Morphometry and elevation of the last interglacial tidal notches in tectonically stable coasts of the Mediterranean Sea

Keywords: Tidal notch, sea level change, LIT, Mediterranean Sea.

We report detailed morphometric observations on several MIS 5.5 and a few older (MIS 11, 21, 25) fossil tidal notches shaped along carbonate coasts at 80 sites in the central Mediterranean Sea and at an additional six sites in the eastern and western Mediterranean. At each site, we performed precise measurements of the fossil tidal notch (FTN) width and depth, and of the elevation of its base relative to the base of the present tidal notch (PTN). The age of the fossil notches is obtained by correlation with biologic material associated with the notches at or very close to the site. This material was previously dated either through radiometric analysis or by its fossiliferous content.

The width (i.e. the difference in elevation between base and top) of the notches ranges from 1.20 to 0.38 m, with a mean of 0.74 m. Although the FTN is always a few centimetres wider than the PTN, probably because of the lack of the biological reef coupled with a small erosional enlargement in the FTN, the broadly comparable width suggests that tide amplitude has not changed since MIS 5.5 times. This result can be extended to the MIS 11 times because of a comparable notch width, but not to the MIS 21 and 25 epochs. Although observational control of these older notches is limited, we regard this result as suggesting that changes in tide amplitude broadly occurred at the Early-Middle Pleistocene transition.
The investigated MIS 5.5 notches are located in tectonically stable coasts, compared to other sectors of the central Mediterranean Sea where they are uplifted or subsided to ~100 m and over. In these stable areas, the elevation of the base of the MIS 5.5 notch ranges from 2.09 to 12.48 m, with a mean of 5.7 m. Such variability, although limited, indicates that small land movements, deriving from slow crustal processes, may have occurred in stable areas. We defined a few sectors characterized by different geologic histories, where a careful evaluation of local vertical land motion allowed the selection of the best representative elevation of the MIS 5.5 peak highstand for each sector. This elevation has been compared against glacial isostatic adjustment (GIA) predictions drawn from a suite of ice-sheet models (ICE-G5, ICE-G6 and ANICE-SELEN) that are used in combination with the same solid Earth model and mantle viscosity parameters. Results indicate that the GIA signal is not the main cause of the observed highstand variability and that other mechanisms are needed. The GIA simulations show that, even within the Mediterranean Basin, the maximum highstand is reached at different times according to the geographical location. Our work shows that, besides GIA, even in areas considered tectonically stable, additional vertical tectonic movements may occur with a magnitude that is significantly larger than the GIA.


References


Coastal Tectonics and Relative Sea Level History of Cebu Island (Philippines) Inferred from Emergent Marine Terraces and Coastal Notches

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Keywords: Marine terrace, coastal notch, coastal tectonics, relative sea level changes.

Flights of well-preserved marine terraces along the coasts of Cebu Island are studied to understand relative sea level changes and tectonic processes in this highly vulnerable region of the archipelago. From IFSAR-derived DEMs, two to four steps of marine terraces were interpreted and mapped in northern Cebu (Tabuelan, San Remigio, Bogo City, Tabogon) while four steps were recognized in the southern region (Santander, Oslob). Field surveys along headlands further reveal lower (1 to 3 m above mean sea level) and narrower steps of emergent coral reef platforms, which consist of cemented coral rubble, coral heads, and shell fragments. The ages of the upper terrace surfaces (with elevation up to more than 70 m amsl) were inferred to be Late Pleistocene based on a previous dating of a 5-m-high terrace in the nearby Mactan Island. Modern tidal notches were also observed and show varying morphology at each site. Although differences in coastal notch profiles are generally attributed to wave exposure and preservation, profile asymmetry or indentations could also imply tilting or land level changes in the past. The variable distribution and elevation of coastal geomorphic features in northern (from west coast to east coast) and southern Cebu Island offer insights on regional sea level fall or local tectonic processes in the Late Quaternary.

Figure 1. (A) Location of the Philippines in the west Pacific region. Red box highlights the study area in central Philippines. (B) Emergent marine terraces are extensive in Cebu Island. Red boxes indicate the sites where emergent marine terraces and coastal notches were observed. Red solid squares indicate locations of sea level indicators studied in the past.

References

Historical morphoevolution of the high rocky coast in the southwestern sector of Procida island

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Keywords: Sea cliff evolution, marine erosion, photointerpretation analysis.

The Italian coasts are characterized for about 60% by sea cliffs (plunging cliff or cliff with abrasion platform, Sunamura, 1992). These kind of coasts typically suffer a slope instability due to several factors, among them, the wave action at the base of the scarp (particularly effective during the storm events) is the main and faster morphogenetic process triggering sea cliff erosion and parallel retreat (e.g. De Pippo et alii, 2009; Pennetta and Lo Russo, 2011, 2013). Mass wasting processes contribute significantly to cliff evolution anyway other minor processes such as those related to runoff and wind action have to be considered. In this paper, the morphoevolutive trend of a sea cliff located in the southwestern sector of Procida Island is investigated as a typical example of high coast evolution due to wave action. Procida belongs to the island part of the Campi Flegrei volcanic area a poly-calderic morpho-structure whose activity date back to more than 60 ky BP (Aucelli et alii, 2017a and references therein). Still active today it represents one of the two main hazardous volcanic area in the Gulf of Naples (Southern Italy, Aucelli et alii, 2017b and references therein). The island of Procida together with Vivara islet, have been formed by several eruptions through monogenetic vents, during the explosive volcanic activity of Campi Flegrei. The oldest tuff deposits are related to the activity of Vivara, Pozzo Vecchio, Terra Murata centres and are dated at about 70 ky BP (De Astis et alii, 2004; Putignano et alii, 2014). One of these (Pozzo Vecchio) is characterized by a succession of volcanic products including also a lava flow (the lava dome of Punta Ottimo), which is the only effusive episode on the island (Morra et alii, 2012).

The remains of twelve monogenic volcanoes, whose construction is associated with the proximal deposition of phreatomagmatic products, are still visible. The volcanoes are very similar to each other, being formed by deposits with a cinder matrix, sometimes interposed with lapilli layers. These deposits are often separated by unconformities related to periods of repose of volcanic activity and exogenous erosion. In term of vertical ground movements, Procida has suffered at least three distinct uplift phases in the time interval between 40 and 4 ky BP (De Astis et alii, 2004) anyway the island is mostly flat, with maximum altitude at Terra Murata (91 meters asl, NE sector) and on the ancient volcano of Vivara islet (109 meters asl). These phases of uplift have however influenced coastal morphology that is characterized by high rocky coasts in volcanic deposits alternating with low sandy coast for about 16 Km. The numerous cliffs that border the island are continuously exposed to the erosion due to exogenous forcing. Considering statistical analysis of offshore wave climate from the Ponza buoy, which can be considered representative of the offshore wave conditions in the study area, shows that the dominant directional sector is SW–WNW while the maximum and medium Hs values are 6.90 m and 4.31 m, respectively. The coastal sector here studied (Figure 1) is located between Punta Serra (NE) and Chiaiolella (SW) and it is characterized by a sea cliff mainly cut in pyroclastic deposits. The physiographic unit includes the beaches of Chiaiolella (length of about 600 meters) and Ciraccio (length of about 800 meters) and develops for about 1500 meters. The aforementioned coastal stretch is characterized by a vertical cliff, about 20/30 m high, facing on a narrow sandy beach (no more than 20 m) with a slope of about 10%. The sea cliff is modeled in gray tuff of Solchiaro (22 Ky BP, Morra et alii, 2012), consisting of three distinct units: the lowest is made up of stratified and lithified yellow tuff with scoriaceous bombs; the intermediate is characterized by a dense alternation of ash, scoriaceous lapilli and scoriaceous bombs levels; the upper unit is composed of shoshonitic basalt and shoshonite lavas. The study coast can be divided in three sectors Ciraccio, Chiaiolella and the central headland portion so called Belvedere - north-western portion of the Vivara volcano - where two sea stacks are present. In each sector, a morpho-evolutive analysis was carried out by means of direct surveys, and
photo interpretation. Furthermore, along the whole coastal stretch, a bathymetric survey was carried out, allowing a reconstruction of the submerged beach geomorphology.

As result of the bathymetric data elaborations, a succession of bars (200 m wide) and rip current channels was precisely detected as well as the marine abrasion platform gently descending (type A: sloping shore platform - Sunamura, 1992) in the central sector. In recent years, the coast has been affected by repeated rock fall events in particular where the base of the cliff is less protected by sea action. As regard of Ciraccio coast sector, a photo of 2005 testifies a landslide that involved a wide part of the cliff exposing a house foundations built very close to the edge of the cliff (Fig. 2A, B, C).

In April 2008, a landslide occurred and affected the cliff in S. Margherita area, causing the collapse of 500 cubic meters of rock: as consequence, a cliff retreat of eight meters caused the exposure of another house. Another important retreat of the cliff has been registered 1987 in Belvedere area where the cliff recession give rise to a new sea stack. By analysing historical photos, in figure 2D it is possible to observe the coast in the 80’s when only one sea stack was present and the Chiaiolella and Ciraccio beaches were separated by an headland already affected by an abrasion cave. This cave is still recognizable in some photos of the 80’s. In the year 1987, the arc collapse led to the formation of a second sea stack (Fig. 2E, G). This event induced a cliff retreat of about 20 metres. Today, the older sea stack is characterised by a notch evolving into another abrasion cave (Fig. 2F). The analysis of all data highlight that among all the factors causing retreat process, the cliff lithology plays an important rule.

The investigated cliff is in fact characterized by in grey tuff of Solchiaro mainly composed by coarse unwelded volcanic ashes. Furthermore, the study shows that during intense storm events, due to offshore waves with Hs values up to 6.90 m, waves can reach the footslope. On the other hand, during the periods of low energy waves, the wave run-up cannot reach the footslope due to the presence of the beach that acts as protection. In the last years, in order to limit the cliff retreat and to protect the narrow beach, several protection systems have been realized. Three interventions have been built to protect the cliff in the Santa Margherita area: a longitudinal rock barrier in front of the debris deposit, a barrier in grazing rocks at the footslope and a containment bolted grid on the whole cliff. At the base of the cliff in the Belvedere area and continuing northwards in the Ciraccio area, a retaining wall was built at the footslope and concrete blocks between the sea-stacks were placed. The effectiveness of the defences structures has reduced the waves impact at the base of the cliff determining sediment accumulation around the protected area. On the other hand, in Ciraccio area the cliff does not have any protection to the wave action and continues to be eroded. In this case, the presence of sediment accumulation at the footslope can represent a temporary cliff protection.

In conclusion, the investigated area presents a high coastal risk due to the parallel retreat that characterized the unprotected areas of the cliff as consequence of marine abrasion process acting at the mean sea level and predisposing cliff collapse and therefore an increase in hazard degree. It would be advisable to prevent, through the installation of defence systems, the erosive processes that naturally shape the morphology of the cliff. Furthermore, the hazard highlighted in the study could become even worse if the effect of rising sea level due to climate change is taken into account.
The last assessment report of the Intergovernmental Panel on Climate Change (IPCC AR5, 2014) provides new sea level rise projections, with mean values that range between 0.44 m (scenario RCP 2.6) and 0.74 m (scenario RCP 8.5) by the end of the XXI century. These values should be introduced when risk assessment and risk management plans are proposed, in order to providing a more detailed mapping of the future impacts of storm surges scenarios in terms of both erosion and flooding processes.

References


Geomorphological coastal response to sea level rise during the Holocene: the knowledge of the past as key for the prediction of future inundation scenarios

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Keywords: Relative sea level change, Holocene sea level, marine coastal inundation.

Several recent studies (Lambeck et alii, 2011; Antonioli et alii, 2017) underline that wide coastal areas along the Italian peninsula are considered particularly prone to be affected by shoreline retreat and submersion processes by the end of the 21st century as consequence of relative sea level rise (RSLR). Risk analysis scenarios suggest that in the near future natural areas, beaches, human infrastructures, and wide portions of agricultural areas located along the coastal sector could be impacted by potential marine erosion and inundation.

Future scenarios of sea level rise proposed by the Intergovernmental Panel on Climate Change (IPCC) in the last assessment report range between 0.44 m and 0.74 m by 2100, but these values can be locally higher if the analysis of tide gauge data, coupled with the local vertical movement rates, are taken into account. Nevertheless, not necessarily a rise in sea level can result in shoreline retreat and/or coastal flooding, depending on the rates of sea level rising, coastal geomorphological setting and sediment balance. The rates can locally vary as consequence of local vertical ground movements that can amplify or reduce the effect of eustatic rise. In addition, the sediment supply provided by the main rivers from the upstream catchment areas play a very important role in the local coastal adaptation to sea level rise. Therefore, each coastal area could have a typical response to a rising sea with well-identified thresholds of sea rising rates that separate the progradation to submersion stages.

Considering these factors, a key rule for the prediction and the validation of future inundation scenarios due to sea level rise is played by the study of the past geomorphological response to the RSLR. Based on these assumptions, the future scenarios of the coastal evolution can be evaluated by comparing future projections of relative sea level rise with the coastal response to Holocene different sea level rise rates.

In this study, some coastal plains located in Campania Region (southern Italy) (Volturno, Sele and Alento rivers alluvial coastal plains), which result particularly prone to be affected by the negative impacts of the ongoing sea level rise (Amato et alii, 2010; Amorosi et alii, 2012; Pappone et alii, 2012; Amato et alii, 2013; Aucelli et alii, 2017; Di Paola et alii, 2017), have been investigated by taking into account their evolution during the Holocene time.

The present day geomorphological setting of these alluvial coastal plains is the result of their early Holocene evolution, being mainly controlled by a marine transgression caused by post-glacial sea level rise (Cinque et alii, 1995; Amato et alii, 2010; Amorosi et alii, 2012; Amato et alii, 2013). In details, as a consequence a rapid flooding of the plains occurred, also with the formation of wide sandy barrier and lagoonal systems, that migrated landward. At the end of this transgressive phase (mainly about 6.500 year BP), the shorelines and the barrier-lagoon systems prograded several hundred meters mainly for the decrease of sea level rise rates.

As response to this paleogeographical evolution, the Campania alluvial coastal plains host, still today, several low-land areas characterized by an average elevation of approximately 0-1.5 m a.s.l., usually localized at the back of the sandy coastal dunal ridges, where the latter reach an elevation up to 5-6 m a.s.l. Also some sectors of the rivers’ mouths can be considered as low-lands having a very low elevation (ca. 1-2 m a.s.l.). Furthermore, during the last decades the investigated coastal plains were characterized by different vertical ground displacement rates, which have been accurately evaluated by means of the analysis of several DInSAR (Differential Interferometry Synthetic Aperture Radar) datasets (Di Paola et alii, 2017; Matano et alii, 2018). These studies highlight the presence of wide coastal sectors characterized by subsidence and/or uplift trends.
In this work, we propose a first application of a methodological approach, based on the comparison of the data related to the Holocene coastal evolution with the corresponding geomorphological coastal response with the future sea level projections. The Holocene sea level variation rates have been estimated for the last 10,000 years taking into account the sea level curves proposed by Lambeck et alii (2011). Based on stratigraphic and morphological paleo sea level markers (Romano et alii, 1994; Amorosi et alii, 2012; Amato et alii, 2010; Amato et alii, 2013; Sacchi et alii, 2014), two temporal phases have been identified to distinguish the prevalent submersion phase from the progradation phase. These phases are separated by a transition interval that represents the uncertainty on the temporal threshold between the end of the flooding and the beginning of progradation phase.

The future sea level rates have been evaluated taking into account the sea level projections proposed by IPCC (2014): considering the 2100 projections, the projected rates are 4.40 mm/yr (scenario RCP 2.6) and 11.20 mm/yr (scenario RCP 8.5). The different subsidence/uplift rates that affect the investigated coastal areas can locally increase/decrease the sea level rise rates. The vertical displacement (subsidence) rates of the alluvial coastal plains have been estimated for the 1992-2010 period thanks to the DInSAR data analysis. In the coastal low-lands the average subsidence rate is -2.3 mm/yr in the Sele and Volturno plains, while the Alento plain shows almost a stability trend with an average value of -0.1 mm/yr.

The future RSLR rates referred to the studied coastal plains were obtained by summing the eustatic rates and the local ground deformation trends, derived by available DInSAR datasets. In detail, the medium, minimum and maximum values of the subsidence rates obtained for each coastal plain by DIn-SAR data processing have been summed to the eustatic IPCC rates (RCP 2.6 and 8.5). The rates range from 4.8 mm/yr to 15 mm/yr for the Volturno plain, from 5 to 14.7 mm/yr for the Sele plain and from 4.4 to 11.5 mm/yr for the Alento plain.

The analysis of the Holocene geomorphological evolution as response to different rates of sea level rise (Fig. 1) shows that until 6,800-6,500 years BP the investigated plains were subject to submersion and prevailing coastal retreat (Romano et alii, 1994; Cinque et alii, 1997; Amato et alii, 2010; 2013; Amorosi et alii, 2012; Sacchi et alii, 2014). Starting from ca. 4,000 yr BP, the coastal plains started to prograde, allowing the closing of the barrier-lagoon systems and the emersion of large sectors of the coastal areas.

Future sea level rates have been plotted in the graph of Figure 1, where the curves of sea level rates during the Holocene and the coastal geomorphological stages are also represented. In this way, it has been possible to compare the future rates with the ancient coastal behaviors for analogous sea level rise rates.

Figure 1. Holocene sea level trends and 2100 projections of RSLR. The blue line identifies the sea level trends evaluated from the sea level curves proposed in Lambeck et alii (2011). The Holocene sea trends and the geomorphological coastal settings as response to different rates of sea level rise are compared with the future scenarios of RSLR. A) Volturno coastal plain B) Sele coastal plain C) Alento coastal plain. The symbols identify the RCP 2.6 scenarios (dots) and RCP 8.5 scenarios (rhombus), while the colours identify the minimum (green), medium (yellow) and maximum (red) values of relative sea level rates.
The results of our analysis support the assumption that during the Holocene the Volturno, Sele and Alento alluvial coastal plains suffered inundations under rates of relative sea level rise similar to those expected for the end of the 21st century. The historical trend occurred in circumstances of completely natural landscapes, where the river systems were not affected by human regulation. It is remarkable that none of the estimated future trends has been recognized during the progradation phase of the plains. Moreover, the present day situation can be considered even worse due to the high human pressure imposed to the river systems, which affects the present and future river sediment discharges and therefore the natural capacity of the coastal system to cope with the sea level rise. The estimated future trends of relative sea level rates are fully comparable to those that have characterized the first phase of Holocene (up to 6,500 yr BP). Therefore, a submersion of many low-lying coastal sectors should be expected by the end of the century.

In conclusion, the adopted method has resulted useful to validate the inundation hazard assessments proposed for the investigated coastal areas in Campania, where future scenarios of marine inundation and submersion phenomena were already available (Aucelli et alii, 2017; Di Paola et alii, 2017; Matano et alii, 2018).

References


The so called *givoni* in the Taranto Gulf (Apulia region, Italy): key-features in understanding the link between terracing processes and sea-level fluctuations

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**Keywords:** Marine terrace deposits, givoni, marine terracing on soft substrates, MIS 5, MIS 7, Gulf of Taranto.

A detailed geological and geomorphological analysis of a well-exposed series of marine terrace deposits in the northern Gulf of Taranto (Southern Italy) has been carried out. We identified and mapped three terrace deposits (Fig. 1), dating them to MIS 7.3, 7.1 and MIS 5 (De Santis and Caldara, 2018).

![Figure 1. Location of the study area and schematic geomorphological map.](image)

The *givone* (plural: *givoni*), which are a peculiar features of the MIS 7.3 and MIS 5 terraces, is the local term used to indicate low reliefs that are subparallel to the coastline and several kilometres long; they were in past described by some authors (Boenzi *et alii*, 1977; Brückner, 1980; Bentivenga *et alii*, 2004) but never interpreted with certainty. By means of an accurate study of several natural sections of *givoni* (Fig. 2) and a comparison with current similar landforms (Fig. 3) (De Santis and Caldara, submitted), we interpreted them as former beach ridges, swash/drift-aligned barriers or swash/drift-aligned spits (Cope, 2004; Stripling *et alii*, 2008); thus, they can be used as palaeoshoreline indicators, and their origins is related to various sea-level stands.
We develop a complete set of cases that lead to the formation of beach ridges, spits or barriers (BSB) within marine terrace deposits, starting from the evidence that the BSB of our study area are typically located a certain distance from the inner edge of the terrace and from their property to be paleo sea-level indicators.

Figure 2. Comparison between a *givone*, observable in section (a, b), and a current beach ridge present at a beach of the Gulf of Taranto (De Santis and Caldara, submitted).

Figure 3. Shingle barriers of Rakaia River mouth (New Zealand) on the left and Chesil Beach (England) on the right (source Google Earth). According to our reconstruction, the *givoni* of study area were able to form in a context very similar to that represented in these photos.
According to this set of cases, it arises that while the inner edge of the terrace indicate the highstand peak, the BSB within the marine terrace deposits can indicate:

1) a new coastline coeval with the same highstand peak that generated the inner edge of the terrace but placed at a more seaward point due to the accumulation of a coastal sedimentary wedge. This process can generate one (Fig. 4c) or more (Fig. 4d) BSB depending on the coastal progradation rate;

2) a coastline that settled during short sea-level stands within the regressive phase following the highstand peak that created the inner edge of the terrace (Fig. 4e).

3) a new highstands on unconsolidated terraced deposits. In this case, the return of a high-standing sea level on an existing previous sedimentary coastal wedge does not form a classic abrasion platform with an adjoining cliff but rather a beach ridge, a spit or a barrier. Eventually, a narrow abrasion platform and cliff can form, which can subsequently be totally or partially masked by the growth of the BSB (Fig. 4f);

4) a new highstand on pre-existing unconsolidated terraced deposits, where the sea level stops rising at a pre-existing BSB (Fig. 4g), giving rise to a composite form.

The set of cases we developed regarding the formation of givoni, implies new models regarding the formation and evolution of marine terraces on loose or semi-consolidated substrates that overthrows the traditional formation of a platform and a scarp.

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Rapid sea level rise on a low gradient continental shelf: the case of Manfredonia Gulf (Apulia region, Italy)

In the Manfredonia Gulf two seismic surveys were carried out: one in January 2009 and the other between September and December 2017 (Fig. 1). The first survey involved the realization of 14 sub-bottom profiles, 3 parallel and 11 perpendicular to the coast, for a total of about 120 km. The second survey involved the realization of sparker seismic profiles, 10 parallel and 9 perpendicular to the coast, for a total of about 500 km.

The chosen area, characterized by a bottom with very low inclination, less than 0.07° (Fabbri and Gallignani, 1972) towards the open sea, makes it possible to investigate the ways in which such type of continental shelf is drowned. The migration towards the inland of transitional coastal environments in conditions of rapid sea level rise, like the one that occurred during the last termination. This will help to create future predictive models in the event of rapid sea level rise that could affect the Tavoliere plain or other coastal plains with similar physiographic characteristics.

Some seismic profiles have highlighted different situations where it is possible to recognise the backstepping towards the inland of various seismic facies that can be interpreted as representative of different coastal environments and sub-environments. These seismic facies are present at the base of the Transgressive System Tract (TST), deposited during the last sea level rise between about 18-20 ky and about 5,500 y BP (Ridente, 2018). This rapid sea level rise drowned the continental shelf, which were emerged during the previous glacial period (MIS 2). During this process of drowning, the repeated formation of coastal/transitional systems took place: with the continuation of the transgression, a previous coastal/transitional system were drowned by the sea and covered by more distal sediments, while new coastal systems were formed in a more internal position on the shelf.
In particular, the recognized coastal systems consists of:
1) sandy barrier with tidal inlets (Fig. 2); 2) bayhead deltas (Fig. 3a,a’) 3) dune systems, also with retrodunal ponds (Fig. 3b,b’).

The first data allow us to hypothesise that, in situations of rapid sea level rise on substrates with very low inclination, a great variety of coastal environments and sub-environments can arise, in relation to: 1) presence of morphological elements that interrupt the continuity of the substrate that is drowned (e.g.: presence of incised valleys); 2) short stands during the sea level rise; 3) climatic fluctuations (De Santis and Caldara, 2015).

The seismic surveys have also allowed us to highlight a deep difference between the valleys incised in the surface of subaerial exposure dating back to the last glacial maximum (MIS 2) in the Manfredonia Gulf, in particular between the so-called Manfredonia Incised Valley (MIV: Maselli and Trincardi, 2013; Maselli et alii, 2014; De Santis and Caldara, 2016) and the Ofanto valley. The first is deeply incised, with slopes that exceed 40 meters in height, but with a low width, which does not exceed 3 km (Fig. 3a-a’). The second one appears much less deep, with slopes that never exceed 20 meters in height, but much wider: as far as it is recognisable, the width never drops below 4 km (Fig. 3c, c’), but it can exceed 10 km. Although the incision of the two valleys occurred presumably in the same period and in the same climatic conditions, there were one or more factors that have made the Ofanto have incised much less the continental shelf compared to MIV.

Figure 2. Seismic profile (a) and interpretation (b) showing dune-like features and migrating sand barrier within the TST unit filling an incised valley. Depths: metres below sea level. ES1: MIS 2 surface of subaerial exposure; ES2: MIS 6 surface of subaerial exposure; TST: Transgressive System Tract; HST: Highstand System Tract; mfs: maximum flooding surface; a: limit of subunits in the TST unit; in green and cyan the reflectors belonging to the last and MIS 5-3 depositional sequences respectively.
Figure 3. Seismic profile (a,b,c) and interpretation (a’,b’,c’) showing respectively: bayhead deltas in the MIV (a,a’), dune systems with retrodunal ponds (b,b’), and the Ofanto valley in a sector with a small width (c,c’). Depths: metres below sea level. For acronyms see caption of Fig. 2.
In both valleys, however, it is possible to recognize different filling units; in the MIV, in particular, clinoform filling units are present, probably due to situations of bayhead deltas (Fig. 3a-a’). Finally, another important aspect highlighted by the analysis of seismic profiles is the presence of various surfaces of subaerial exposure formed during as many glacial phases, each then covered by seismic facies indicative of the subsequent transgression.

References

De Santis V., Caldara M. (2015). The 5.5-4.5 kyr climatic transition as recorded by the sedimentation pattern of coastal deposits of Apulia region, southern Italy. The Holocene, 25(8): 1313-1329.
The textural and mineralogical features of Riva degli Angeli beach sands (Salento Peninsula, Southern Italy)

Riva degli Angeli beach (literally, Angel’s Shore) is an impressive portion of the coastal littorals characterizing the city of Porto Cesareo: one of the most wonderful landscapes and touristic attractions located in the Apulia Region Ionian side. It extends for 2.2 km between Punta Prosciutto and Punta Grossa headlands. From a naturalistic point of view, Riva degli Angeli covers a significant role, as it is part of the protected marine area (AMP) of Porto Cesareo. It is characterized by fifteen different habitats on the seabed, with a very high degree of representativeness of the Mediterranean submerged populations and a significant percentage of Posidonia Oceanica coverage. By a sedimentological point of view, it is a pocket beach (Milli et alii, 2017) with no significant supply of sediment from adjacent sedimentary systems and therefore, the sands have an almost entire bioclastic origin. In 2016, a naturalistic engineering intervention was carried out in order to protect the dunes and to restore the coastline. While the intent to safeguard the entire beach environment from touristic activities and coastal erosion, a backshore nourishment procedure was conducted with uncertain provenance sands and unknown grain size. Indeed, the sands were compacted with Posidonia Oceanica layers forming a significant sand relief in the supratidal environments. After two years, the dune protections have been destroyed. The current beach profile contains few portions with a perfect flat top and a continuous erosional scarp (1.5m – 2.0m high) that causes the accumulation of Posidonia Oceanica at its base (Fig. 1).

In this study, we show the results of some image analysis carried out on multitemporal orthophotos trying to recognize the beach evolution during the last 10 years. Two detailed sampling campaigns (2016 and 2018) were carried out in the backshore-foreshore-shoreface-offshore transition environments. Textural and mineralogical features of the sands have been analyzed in order to establish their variation within the beach and during the considered period.

References

ARCHAEOLOGICAL DATA AS MARKERS
IN SEA LEVEL STUDIES

Tomb of lycian age submerged by sea level rise and tectonic subsidence (2.3 Ka age BP), Kevova, southwestern Turkey

Chairs
Marco Anzidei, Merle Muru
Coastal seafaring and sea level change in ancient Lipari – Sicily from the Greek period to the Late Roman and Medieval time.

Keywords: Underwater archaeology, coastal seafaring, sea level change, Lipari, Sicily.

Archaeological sites are of extraordinary importance for better understanding past and future environmental and sea level changes (Auriemma and Solinas 2009). Several scholars worldwide demonstrated that an interdisciplinary methodology is the key strategy to investigate ancient palaeoenvironment and past and future sea level change (Lambeck et alii, 2011; Antonioli et alii, 2012; Melis et alii, 2012; Anzidei et alii, 2014; Anzidei et alii, 2012; Rovere et alii, 2012).

Within this framework, this poster focuses on past coastal landscape (Mazza 2016b, 2016a) and human activity scenarios in the island of Lipari, north of Sicily – Italy (Fig. 1). It especially analyses coastal landscape and seafaring practices in ancient Lipari by examining coastal and submerged archaeological sites located between 0 and -45m below the sea level (Bernabò Brea 1985; Tusa 2010).

The sites discussed in this work are dated from the Greek period to the Late Roman and Medieval time. Archaeological data from port infrastructures have been considered as markers for sea level change (Fig. 2) (Anzidei et alii, 2018; Lambeck et alii, 2011; Morhange and Marriner 2015; Ghilardi et alii, 2016; Vacchi et alii, 2016). Furthermore, landing spots and cleaning stations have been included as it can be argued that they are critical markers for coastal landscape changes.

Preliminary results of this study show that by combining local sea level change rate (Anzidei et alii, 2016; Anzidei et alii, 2016), geomorphological and oceanographic data (Bosman et alii, 2015; Casalbore et alii, 2017), archaeological and historical evidence (Bernabò Brea 1985; Mazza 2016b, 2016a) it is now possible to trace with high precision ancient navigation trajectories that were previously only speculated. Therefore, a realistic reconstruction of the coastal palaelandscape of Lipari, and a better understanding of past human activity in the island has become available.
References


Das A.\textsuperscript{1}, Prizomwala S.P.\textsuperscript{1}, Vedpathak C.\textsuperscript{1}, Sodhi A.\textsuperscript{1}, Makwana N.\textsuperscript{1}

5 ka record of sea level and climate change from the Harappan Dockyard ~ Lothal, Gujarat, Western India

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**Keywords:** Harappan civilization, Middle Holocene, OSL, mineral magnetic.

The decay of the ancient Harappan civilization has been credited to unexpected changes in atmosphere during the Mid-Holocene time (Possehl, 2002). Up until now, the reason for demise of the Harappan human advancement is for the most part connected with climatic phenomena i.e. drought events Staubwasser \textit{et alii}, 2003; Gupta \textit{et alii}, 2003; Dixit \textit{et alii}, 2014; Prasad \textit{et alii}, 2014; Raj \textit{et alii}, 2015. Interestingly, the sea level was higher than present during 5000 yr BP to 4000 yr BP, which started to get lowered and led to the coastal dwelling sites to be dysfunctional. This is believed to have affected the maritime trade and lowering of sea from entire Gujarat coastline would have had similar affect in other coastal settlements of Harappan period (i.e. 3000 to 5000 yr BP). Despite the exhaustive attempts, the causal mechanism and human response to persistent landscape changes is still not well understood. The present study site Lothal is one of the intriguing leftovers of the antiquated Harappan (otherwise called ~ Indus Valley) human advancement, which was first exhumed amid 1955-62 (Rao, 1979). Presently above 12m msl and at a distance of 23 km from present day shoreline, Lothal is considered to be one of the ancient dockyards, which had maritime trade links with other civilizations (Rao, 1979; Possehl, 2002). The present study reports a preliminary investigation of the palaeo-environmental conditions during the last 5 ka using sedimentology, geochemistry, and mineral magnetic and optical dating. Based on our multiproxy dataset, we report that the bottom most part of Lothal trench upto 4 ka period was under influence of an estuarine environment, most likely in wake of the Middle Holocene marginal high sea stand. The dockyard at Lothal would have been defunct post 4 ka, owing to lack of water depth and prolonged droughts (aridity). Based on OSL ages and considering maximum high stand of 2m during the Middle Holocene period, the Lothal and surrounding region have experienced an uplift of at least 1.5m since last 4 ka. We have reported 4.1 ka arid periods along with two alternating phases of relatively arid period. The relative sea level change could have remained synchronous causal mechanisms, which led to de-urbanization of port towns of the mighty Harappan civilization.

References


Figure 1. a) Location of study area showing major Harappan sites and b) Geomorphic map of Lothal and surrounding regions.
Roman fishtank and sea level: new results and interpretations

Following the pioneering work of Schmiedt et alii (1972) on establishing the level of the Tyrrhenian Sea in antiquity, a number of studies have examined this evidence from Roman Period fish tanks but with significantly different outcomes due primarily to different interpretations of the functional level of these pools at the time of their construction. As part of a longer-term project to understand the causes of sea level change in the Mediterranean, we have re-examined and resurveyed 12 well-documented fish tanks located along the Tyrrhenian coast of Italy (between Formia and Orbetello). These are all based on the same construction principles, for which it can be established that they were in open contact with the sea at the time of operation. The structural features that tidally control the exchange of water used to define the ancient local sea level are identified as the channel thresholds, the sluice gate and sliding post positions, and the lowest-level crepido. These are consistent for all the tanks examined, permitting the local sea level change over the past 2000±100 years to be established at each location with a precision of ±20 cm or better and against which other coastal archaeological features can be calibrated. We conclude that published local sea levels that are based on the present-day elevations of the foundations of protective walls constructed around the tanks and lie ~50 cm above our inferred levels are inconsistent with the successful functioning of the water exchange and have to be rejected. In one case, for Santa Liberata, we have been able to calibrate our interpretation against sedimentary evidence from the nearby Orbetello Lagoon. This confirms our interpretation of the functional control level of the tanks and we conclude that the accuracy of our local sea levels is ±20 cm. The causes of sea level change along this section of the coast are several, including land motion driven by tectonic and glacio-isostatic processes and any change in ocean volume. The individual estimates for the observed local sea levels range from -0.9 to -1.5m with a mean value of -1.22±0.20m. This indicate that the spatial variability of the local levels is small, consistent with model-inferences of the glacio-isostatic process that indicate near-constant contributions for this section of coast and with tectonic inferences from the elevations of the Last Interglacial shoreline.

Figure 1. Aerial views of two of the best preserved investigated fish tanks along the Tyrrhenian coast of Italy. Top) Punta della Vipera with the submerged pools and the three external vaulted channels. Bottom) the Fosse Guardiole rounded fish tank, with the submerged pools equipped with channel systems and crepido (photo M.Anzidei).
Finally, we summarize previous studies, focus on the material and methods and present an update of relative sea level for the whole Mediterranean basin for 2000 BP, as estimated from a set of the best preserved Roman age fish tanks.

Figure 2. Sketch of a typical channel system for water exchange in Roman fish tank as viewed from within the basins of the best preserved fish tanks. The sluice gate with sliding posts, threshold and lowest level crepido are the main sea level indicators. In particular, the threshold defines the lower limit estimate and a level 20 cm below the lowest footwalk defines the upper limit estimate. The top of the sluice gates coincides with the elevation of the lowest level footwalks and corresponds to a position above the highest tide, as also reported by Latin Authors (modified from Lambeck et alii 2004b).

References


Modelling the Subsidence at Sybaris (Southern Italy): Geological and Geotechnical Problems

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Keywords: Sea level, $^{14}$C age, land subsidence, archaeological site, modelling, PS-INSAR.

An interdisciplinary research has been carried on for several years by CNR IRPI and Politecnico di Bari about the geological, tectonical, morphological and geotechnical aspects connected to the land subsidence of the Sibari alluvial coastal plain. Historical subsidence in this area is made evident by the vertical stacking of three ancient towns along the Crati river. In order to investigate the evolution and the disappearance of the archaeological site, the results of the research defined the causes of the settlements affecting the area since ancient times, while recent studies have focused on a recent component of the subsidence and addressed to the interpretation of the causes of the current subsidence rates logged in the plain by PS-INSAR monitoring (Fig. 1).

Geotechnical modeling has been developed to investigate whether these rates are due to both water withdrawal from deep aquifers, identified in previous studies, and pumping of shallow water through a well-point system still active in a few areas at the archaeological site. The paper is specially addressed to assess the geotechnical modeling that has been developed to interpret the source of the current settlement rates. The model is based on an extensive set of geotechnical profiles and laboratory data. The calculation results are compared to the recent data collected by remote sensing and allow to forecast the possible evolution of the subsidence. In the Sibari plain archaeological excavations brought about the effects of an important subsidence, causing the development of three superimposed levels of continuous habitation since VIII- VII century BC: the hellenistic towns of Sybaris (720-510 BC) and Thurium (444- 285 BC) and the roman Copia (193 BC), currently at -3.5 m to 1.46 m a. s.l. (from 7 to 3.5 m below ground level).

Figure 1. Recent data of subsidence at the archaeological site of Sibari (within the red bounday) by PS-INSAR monitoring and the location of the different excavated areas (Ferretti et alii, 2000).
According to our previous studies the subsidence components are due to: a) tectonic subsidence: the change in elevation caused by Pleistocene activity of the fault systems bordering the graben; b) apparent subsidence: the coastal subsidence relating to the glacioeustatic rising of the sea leve; c) geotechnical subsidence: related to natural: consolidation processes, mainly due to self-weight compaction of the soil layers and the human action: due to consolidation induced by the changes in the hydraulic boundary conditions due to pumping (Cotecchia V. et alii, 1994; Cherubini et alii, 2000; Pagliarulo et alii, 1995; Pagliarulo and Cotecchia F., 2000).

Lithological and chrono stratigraphical studies have been carried out on samples coming from several continuous coring boreholes drilled just for this research across the archeological area and the deep boreholes drilled in the plain during oil-search campaigns in the '50s have been taken into account. The alluvial deposits consist of sands, silty sands, clays, sandy clays and gravels in heteropic facies, also interbedding peat levels at places. Numerous samples were subjected to $^{14}$C dating, allowing the assessment of the deposition environment of the sediments and the reconstruction of the relative sea level rise curve (Lambeck et alii, 2004; Pagliarulo, 2006; Ferranti et alii, 2011).

All the samples taken from the deep boreholes drilled in the archaeological area have been subjected to physical and mechanical testing in the laboratory (Coop and Cotecchia 1997); also, permeability tests and piezometric surveys have been carried out in situ. These data allowed to define the geotechnical characterization.

The 100 m depth soil deposit at Parco del Cavallo has been modeled as a sequence of three strata (model PC; with average $P_I_1 \leq 15\%$, $P_I_2 \approx 20\%-25\%$; $P_I_3 \approx 20\%$) laying above a fourth base stratum of sands and gravels. The data point out that the sediments are normally consolidated.

<table>
<thead>
<tr>
<th>Age, period</th>
<th>Rate of Subsidence</th>
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<tbody>
<tr>
<td>Holocene (10000 yr BP to present)</td>
<td>From 4 mm/yr (average apparent rate)</td>
</tr>
<tr>
<td>Late Holocene (2670 yr BP to present)</td>
<td>1.6 mm/yr (average apparent age)</td>
</tr>
<tr>
<td>1945-1995 IGM – Parco del Cavallo</td>
<td>2.4 mm/yr (average rate /geotechnical)</td>
</tr>
<tr>
<td>2004-2011, PS-INSAR</td>
<td>3.00 ÷ 5.00 mm/yr (current rate/ geotechnical)</td>
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**Figure 2.** Evolution of the subsidence rate for different periods obtained by $^{14}$C dating, measures on IGM benchmark and PS-INSAR monitoring.

**Figure 3.** Geotechnical parameters of the models PC and S1 (Cafaro et alii, 2013).
As recognized by previous work, the clays are of low sensitivity and have compression index close to the index that the same clay exhibits when reconstituted in the laboratory ($C_c^*=C_c$), due to a natural stratified mesofabric. Consequently, it may be inferred that the $C_c$ values of the natural samples are mainly dependent on the plasticity index. A single permeability value, $k = 5 \times 10^{-8}$ m/s, has been found to represent the silty sands with fine matrix, whereas a much lower value, $k = 1.3 \times 10^{-10}$ m/s, has been found to apply to the silty clay strata. One-dimensional strain conditions have been assumed in the modeling of the settlements due to pumping, developed with reference to either model PC, for the central and S-E part of the site, or model S1 (Fig. 3), for the N-W part. The modeling has assumed that sediments deeper than 100 m are not significantly contributing to the recent subsidence. The consolidation settlements have been calculated through FEM analyses (PLAXIS 8.6), implementing the stratigraphic variations in the two areas being considered. For both the models, subsidence resulting from pumping develops in 30 to 40 years and gives rise to total settlements which are consistent with the 12 cm settlement recorded at Parco del Cavallo in about 50 years since 1945. Also the calculated settlement rates are consistent with the rates monitored by means of interferometry. The Sibari case history provides indication of the importance of the modelling of geotechnical processes, both natural and induced by human activities, when designing interventions for the preservation of the historical heritage.

References


IGCP Project 639
“Sea-Level Change from Minutes to Millennia”
Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
Taranto (Puglia) – Siracusa (Sicilia) 16 - 23 September 2018

Curci G.1*, Milella M.2, Pignatelli C.1, De Giosa F.2, Locuratolo G.2, Barracane G.2, Piscitelli A.2

Sea level in the XVI century: geoarcheological analysis through the 3D reconstruction of the Aragonese Castle (Taranto) with LST methodologies
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2Environmental Surveys S.r.l., Taranto, Italy
3Taranto, Italy

Keywords: Sea level, TLS, geoarchaeology, modelling.

A 3D geo-referenced point cloud of the Aragonese Castle of Taranto was acquired by means of a Terrestrial Laser Scanner; the 3D model of the architectonic structure was developed in CAD environment and related to the local basement represented by the Tyrrenian calcarenitic unit. Topographic data have been correlated to the geological survey and implemented by geo-archaeological, geophysical and historical data; as final result cross sections representative of the relation between the geological body and the architectonic structure has been extracted from the point cloud (Fig. 1 A-B). (Mastronuzzi et alii, 2014).

Figure 1. (A) Rendering of the basement morphography; (B) Plan of the Castle: the orange areas represent the Tyrrenian calcarenitic basement (Mastronuzzi et alii, 2014).

The TLS survey was horizontally referred to the WGS84-UTM33N system and vertically referred to the mean sea level in Taranto calculated as the average of the tide series (1998-2016) recorded with the local tide station; it results 0.21 m lower than the Zero Tide Level of the Italian tidal network (https://mareografico.it) (Fig. 2).

In particular, a cross section between San Lorenzo Tower and Annunziata Tower has extracted from the geo-referenced 3D model (Fig. 3): the section relates the internal environments on a single work table, showing the vertical correlations between of some key elements, for example the floor of the casemate (Fig. 4) where the cannons are housed, the fresh water table level, the floor of the present quay (not original) to the historical sea level.

Historical, architectural and hydrogeological evidences related to the operability of the guns during the XV and XVI century (Jachino, 1971; Ulrich, 2000; Santarini, 2011; Ricci, 2012) and compared with the geophysical model by Lambeck et alii (2004; 2011), estimate the sea level 0.30 m below the actual sea level (Mastronuzzi et alii, 2014).
The historical and architectural data of San Cristofaro Tower (Gennarino, 1661, Archivio di Stato di Taranto) indicate the top of the tower at an altitude of 22.11 m above sea level; a technical survey performed during the 1883 (Messina, 1888), when the present quay was built, measured the altitude of the same tower at 21.6 m above sea level. Consequently, a sea level rise of about 0.5 m is estimated between 1661 and 1883.

Applying the sea level rise rate estimated by Anzidei (2011) for the Italian Coast, the sea level rose 0.3 m during the last 500 years and only 0.01 m (one centimeter) during the last 18 years.

According to the IPCC AR5 curve in the Taranto area, the sea level, has risen 0.249 m between 1870 and 2000 with a 1.9 mm/y rate (Antonioli et alii, 2017), while it has risen 0.169 m in the last 18 years with a 9.4 mm/y rate.
Considering the glacio-hydro-isostatic and tectonic contribution, this work calculates a rise of 0.176 m over the last 18 years having a rate of 9.7 mm/y (Tab. 1), matching perfectly with the estimations by Antonioli et alii (2017).

The IPCC AR5 curve gives us information since 1700, between 1500 and 1870 (beginning of the industrial revolution) it is plausible to use the sea level rise estimated by Anzidei (2011); s the different rates of sea level rise during these different periods (Tab. 2), the sea level rise during the last 500 years is equal to about 0.64 m, similar to the historical and architectural data collected between 1661 and 1888 as well as with the functionality of the gunnery in the 16th century.

\[
\text{RSLRT} = (9.4 \text{mm/y} \times 18) + (0.45 \text{mm/y} \times 18) + (-0.14 \text{mm/y} \times 18) = 170 \text{mm} + 8.1 \text{mm} - 2.52 \text{mm} = 175.58 \text{ mm}
\]

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<tr>
<td>Sea level rise rates</td>
<td>0.6 mm/y</td>
<td>1.9 mm/y</td>
<td>9.7 mm/y</td>
<td>(IPCC AR5, Anzidei et alii, 2017)</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>222 mm</td>
<td>249 mm</td>
<td>174.6 mm</td>
<td>645.6 mm</td>
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Table 1. Relative Sea Level Rise in Taranto for the last 18 years (RSLRT).

Table 2. Estimated relative variation in sea level over the past 500 years for Taranto area, resulting from the comparison of the various rise rates.

References


Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
STRATIGRAPHIC RECORDS IN SEA LEVEL STUDY

The stratigraphy of the Upper Pleistocene marine terraced deposit of “Il Fronte”, Taranto, Puglia, Italy

Chairs
Amy Dougherty, Massimo Moretti
Imprints of the Last Glacial Cycle on the Coastal Tract of Eastern India

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Keywords: Last Glacial Cycle, sea level, beach rocks, palaeo-shoreline, teri sands.

Of the four major glaciations in the Quaternary, the Last Glacial Cycle (LGC) has left conspicuous imprints on the sediments and morphology of the continental shelf of eastern India. The late Quaternary glacials and interglacials in the tropical areas are manifested as arid-cold or warm-humid climates and are recorded in the shelf sediments as signatures of regression (during arid-cold) and transgression (warm-humid), dunes and beach-ridge formation, calcareous precipitation binding sediments into beach rocks along palaeo strandlines. It has already been established that during the Last Glacial Maxima (LGM) the sea level was lowered to -122 m relative to the present sea level (psl), and the palaeo strandlines have been mapped as coralline and coarse carbonate sandy ridges with a relief of 5 to 17 m. Subsequent to the setting in of deglaciation the warming led to a transgressive phase and the rise of sea level attained the present sea level around 6000 to 7000 yrs B.P. The entire process of the sea level rise from -122 m below the psl and then to 5-6 m above the psl has left its impression at various still stands. While the low-stands of the LGC are more or less preserved under the sea, the signatures of high stands have been either erased by the natural processes or mutilated by chemical weathering and anthropogenic activity. An attempt has been made in this study to collect evidences of low and high sea level stands related to the Last Glacial Cycle and compile all the available data to create the curve for the high sea level stands along east coast of India (Fig. 1).

The signatures of Last Glacial Cycle have left the following impressions on the shelf and coastal tract of eastern India:
1. Submarine beach-ridges, coralline reef, carbonate ridges, oolitic limestone in the shelf;
2. Teri Sands: Huge dunes were formed during the arid-cold climate of LGM, due to aeolian process;
3. The transgressive sea level reaches the present sea level around 6330 yr BP (interpolated age);
4. Sea level had reached an elevation of around +5 m relative to the present sea level as seen in the beach rocks and beach ridges and linear shaped water bodies parallel to the present shoreline;
5. Wave cut notches on rocky promontories: as high as +1.45 m to +4.70 m above the present sea level have been recorded from several places.

Submarine Palaeo-beach Ridges: The short spells of cool phases during the deglaciation of Last Glacial Cycle gave rise to sea level stands resulting in formation of beach ridges along the palaeo-strandlines, submerged under the transgressive sea. At least 5 ridges were picked up in the echosounder and shallow seismic records along the shore orthogonal cruise transects across the shelf: -122 m, -108 m, -76 m, -63 m and 30 m depths (Faruque, 2014). The shell and coral fragments from these ridges gave the following radiocarbon dates: 21120 and 13820 yr BP (-122 m), 11980 yr BP (-108 m), 9850 yr BP (-76 m) and 8820 yr BP (-63 m) (Faruque, 2014). The peat matter occurring at a depth of 51.5 m (off Gopalpur) has been dated at 10,690±120 yrs BP and the underlying shell from within silty clay sample gave an age of 10,960 ±140 yr BP. The radiocarbon dates of oolites at 100 m depth off Visakhapatnam is placed at 11000 yr BP.

Figure 1. Map of east coast of India and Bay of Bengal.
Teri Sand Dunes: Though not directly controlled by climate, the landward movement of coastal dunes is facilitated by arid and semi-arid conditions. Red sand dunes (locally known as “teri sand” in Tamil) occur in the coastal plains of eastern India between Puducherry and Chilka Lake, are predominantly composed of clay, silt and sand with iron oxide. The teri sands exhibit shades of red with yellow and brown colour and in thickness vary from 1m to greater than 10m. (Jayangondaperumal, 2014). The coastal teri sand deposits occur as vast discontinuous accumulations of medium to fine grained sand in the form of dunes and sheets, roughly parallel to the coast and are ~0.5 to 1 km away from modern shoreline in Puducherry, Tamil Nadu. At Tugidam, Andhra Pradesh the red sediments are located on the beach, however these red sediments are considered genetically different from the teri sands. The red colour originates from heavy minerals when deposited above the water table for easier access to oxygen. During the arid-cold climate of the Last Glacial Maxima, the entire width of the continental shelf was exposed to sub-aerial condition. The sands from the shelf were blown into aeolian deposits as massive dunes, in the form of high mounds or ridges. These red sand sediments have been dated by OSL to be 11.4±0.9ka BP to 5.6±0.4ka BP, depicting a dry period of deposition. Teri sands were syngenetic with the LGM ridges (Jayangondaperumal, 2014).

Shore Parallel Lakes: The transgressive phase continued interrupted by brief spells of cool phases, till it reached the present sea level, however, it did not stop there. Further rise in sea level inundated the near shore coastal tract. The impressions of submergence due to high sea stands are reflected in remnants of series of water bodies at a distance of 1.5km to 2.5km from and parallel to, the shoreline. Samang lake to the north of Puri and Sar Lake to the northeast of Puri, Odisha, Linear shaped Tampara Lake on the west of Rushikulya are the remnants of palaeoshorelines.

Beach Rocks: Abandoned channel of Mahendratanaya river at Baruva: the distributaries of Mahendratanaya river used to debouch into the sea during the high sea stands of Late Holocene period. With the lowering of the sea level due to LIA and weak monsoon the southern distributary went dry while the northern channel became the main channel of Mahendratanaya river and continued to connect with sea (Bay of Bengal) to its present-day position of 1.85m below the abandoned channel. Arca shell from the narrow beach ridge, a trace of the palaeoshoreline, dated 1930 yr BP (Faruque, Cruise ST-135). From the southern tip of the east coast of India, near Vattakattai to Baruva in the Andhra Pradesh coast, proxies of late Holocene high stands are, though few, exposed above the present, sea level intermittently along the east coast of India. (Faruque, 2008). The radiocarbon date derived from onshore carbonate beach rocks from Rameswaram, at 2m above the present msl are 6110 yrs and 5650 yrs BP (GG Vaz et alii, 2008). In Karikovil near the Gulf of Mannar, the drop in sea level due to Little Ice Ages (LIA) has resulted in the exposition of cemented foreshore grainstone, on the beach with intercalations of ilmenite rich laminations dipping seaward, bearing shells of Arca and Astarte etc which analysed a radiocarbon age of 510 yr BP (Banerji, 2000). Wave cut notches and rocky terraces were developed at +1.65m above msl due to high sea stands on Khondalite promontories at Rishikonda (Fig. 2) and Yarada and notches upto +4.70m on the red sediment of different generation at Tugidam in Andhra Pradesh.
The entire process of the sea level rise from -122m below the psl to +5 to +6m above the present sea level, has left its impression at various still stands and almost each still stand has been dated.

But there is no precise date yet for the transgressive phase attaining the present-day sea level, in Indian context. Some researchers place it at around 6000 yrs B.P. The radiocarbon date of carbonate from the seabed sediments, from depths of -17m in the Nizampatnam Bay and -23 m off Visakhapatnam yielded $^{14}$C ages of 8200 yrs BP and 8150yrs BP. The radiocarbon date derived from onshore carbonate beach rocks from Rameswaram, at 2m above the present msl are 6110 yrs and 5650 yrs BP (GG Vaz et alii, 2008). The sea level rise of 19m (-17m to +2m) took 2090 years. It gives a rate of 1m in 110 years. Interpolating with this rate, assuming this to be a uniform rate of sea level rise, the date for sea level attaining the present sea level is pro-rata calculated to be 6330 yrs (8200-1870). Though this is not the scientific technique to calculate the date. It is not possible to date the wave cut notches of Rishikonda and Tugidam in the absence of datable carbonate material.

While the signatures of low-stands of the LGC are more or less preserved under the sea, the signatures of high stands, being sub-aerially exposed, have been either erased by the natural processes or mutilated by chemical weathering and anthropogenic activity.

References


The influence of sediment compaction on Late-Holocene relative sea-level changes along the North-American Atlantic Coast

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Keywords: Sea level, salt marsh, compaction, compression, post-depositional lowering.

Salt-marsh sediments are an important source of relative sea-level (RSL) reconstructions spanning the past 200 to 3000 years (Gehrels, 2000). These reconstructions offer insight into the processes that cause sea-level change across a range of spatial and temporal scales (Gehrels et alii, 2012; Kemp et alii, 2015; Saher et alii, 2015) and constrain the relationship between sea level and climate (Kopp et alii, 2016). High salt-marsh environments that maintained their tidal elevation in response to RSL rise by primary productivity of in situ plant material and by trapping clastic sediment delivered by tides (Craft et alii, 1993; Morris et alii, 2002) are targeted to produce RSL reconstructions using stratigraphically ordered samples from a single core. On the Atlantic coast of North America, high salt-marsh peat is waterlogged, highly organic and has low initial bulk densities, which render it prone to mechanical compression and mass loss and/or weakening by biodegradation (Bloom, 1964; Lillebø et alii, 1999; van Asselen et alii, 2009). These compaction processes can reduce the vertical thickness of a stratigraphic column through time and cause post-depositional lowering (PDL) of core samples (Brain et alii, 2017). PDL results in an overestimate of the magnitude and rate of reconstructed RSL rise (Brain, 2015; Brain et alii, 2015; Horton and Shennan, 2009).

Salt-marsh reconstructions of RSL along a ~3000 km latitudinal gradient on the North-American Atlantic Coast have revealed spatial variations in the timing, magnitude and rate of RSL change which have, in turn, been attributed to specific climatic/cryospheric, oceanographic and glacio-isostatic adjustment (GIA) forcing mechanisms (Kemp et alii, 2015).

Figure 1. An example core of intertidal sediment obtained from Cape May Courthouse, New Jersey, United States.
However, the observed patterns and variability of late Holocene RSL between sites could also be partly attributed to differential sediment compaction (Brain et alii, 2017; Brain et alii, 2015; Brain et alii, 2012). In turn, this may affect our interpretation of forcing mechanisms. This is currently poorly constrained.

We consider the processes of compaction and how these vary in response to local to regional geomorphic, climatic and ecological conditions that vary along the same latitudinal gradient as climatic/cryospheric, oceanographic and GIA processes. We ‘decompact’ key RSL records and consider the influence, if any, of compaction on existing interpretations of the causes of late Holocene RSL along the North-American Atlantic Coast.

References


Organic sediments from a submerged river valley in coastal zone of the Pärnu Bay, Baltic Sea record low relative sea levels in Holocene

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Keywords: Sea level, Baltic Sea, buried organic matter, Litorina Sea, Ancylus Lake.

Understanding the sea-level change and its local, regional and global effects to human populations over the Holocene period requires improved methodologies for high-resolution sea-level reconstructions and detailed data on palaeo-sea-level variation. The Baltic Sea basin, one of the largest brackish-water basins, is one of the best places in the world to study interactions between sea-level change, postglacial land uplift and prehistoric human adaptations. Prehistoric people had to adapt to the conditions of significant marine/lake transgressions and regressions due to the melting of the continental ice sheet, the up-damming and drainage of the basins and glacial isostatic land uplift. Holocene sea-level rise has left the prehistoric coastal landscapes and settlement sites in the southern Baltic Sea submerged, while in the northern Baltic area they have been uplifted and are located successively at different altitudes as a result of glacial rebound. In the peripheral area of the Fennoscandian uplift prehistoric people experienced transgressions and regressions of the shifting coastline owing to competition between glacial isostatic land uplift and eustatic sea level rise. Here the terrestrial landscapes and associated coastal settlements have been inundated in connection of the Ancylus Lake (ca 11–10.2 calii ka BP) or Litorina Sea (ca 9–7.5 calii ka BP) transgressions and occur below or above preset-day sea-level. Recently compiled Holocene sea-level database and its comparison with major GIA models (ICE 5G, ICE 6G) have recorded large differences between models and available sea-level records in the periphery of the Fennoscandian uplift region. These differences are due to the scarcity of high resolution sea-level data in areas of complex rising and falling relative sea levels during the early-to-mid Holocene.

New Holocene RSL data has been discovered in Pärnu Bay area (SW Estonia), eastern coast of Baltic Sea, in the periphery of the uplift (Fig. 1). Due to its gently undulating low topography the Pärnu area has been periodically submerged by the waters of the Baltic Sea and emerged on other times as terrestrial land. Therefore, transgressive deposition of water-laid sediments of the Ancylus Lake and the Litorina Sea have led to repeated burial of organic matter (BOM) layers and associated Mesolithic settlement layers (Veski et alii, 2005; Rosentau et alii, 2011; Habicht et alii 2017).

Figure 1. A. Location of the study area. B. Topography of the Pärnu area and its surroundings with the locations of the Stone Age settlement sites (Kriiska et alii 2011; Rosentau et alii 2011) and sites with buried organic matter (Veski et alii 2005; Rosentau et alii 2011; Habicht et alii 2017). C. Study site with coring and transect locations.
Ca 120 m-wide buried river channel with organic-rich infill associated with the RSL fluctuations was discovered at elevation down to 5.9 m below present water level in the coast of Pärnu Bay (Fig. 2). The channel runs into the bay, where the remains of submerged sediments with abundant wood remains extend ~2 km from the modern coast to depths of ca 4 m below the present sea level.

According to diatom analyses the channel infill developed in a varying environment conditions that were affected by the low brackish conditions of the early Litorina Sea as well as running water from the Pärnu River.

Preliminary results suggest that the channel developed already before Ancylus Lake transgression, but filling with organic matter took place later, before Litorina transgression.

This discovery with multi-proxy approach by combining sediment stratigraphy, AMS radiocarbon dating, pollen- and diatom analyses, GPR and GIS based palaeoshoreline reconstructions provides new data about low water-level phases before Ancylus Lake and Litorina transgressions and about palaeogeography of the Pärnu area which is important to understand Mesolithic habitation of this area. At the same time this new data helps to clarify the development of River Pärnu during early Holocene including its possible reach in the bottom of the Pärnu Bay.

Figure 2. A. Geological cross-section of the study area (Fig. 1C). B. Sediment sequence in the master core RB15-05, with stratigraphical position of radiocarbon dates, LOI results and age-depth model based on radiocarbon dates obtained from organic infill (the lowermost date was excluded because it reflects the age of sediments below organic infill).

References


An overwash sediment record from southern Narragansett Bay, Rhode Island, USA

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Keywords: Paleotempestology, storm surge, relative sea level, coastal evolution.

Coastal inundation events, such as storm surges, can severely impact coastal environments and communities. Storm surges can overtop beach-barrier dunes; removing sediments from nearshore environments and deposit sediments in overwash fans across protected back-barrier systems (e.g., coastal marshes, ponds, and lagoons). Analyses of overwash records improve our understanding of coastal hazard processes and provide valuable insight that can inform coastal communities planning for future environmental and human risk. This sedimentological, stratigraphic, and geomorphic investigation examines the spatial and temporal characteristics of an overwash record archived in southern Rhode Island, USA.

At Fox Hill marsh (Fig. 1), on Conanicut Island in southern Narragansett Bay, eleven clastic sediment deposits abruptly interrupt a ~2.5 m deep continuous peat section located behind a beach-barrier dune (elevation range of 1.5-3 m).

Historical records indicate that eight high-energy wave events, potentially capable of producing an overwash deposit at Fox Hill marsh, have been observed in southern Rhode Island: AD 1991, 1960, 1954, 1938, 1869, 1815, 1638 and 1635.
Chronologic constraints of overwash deposition are provided by accelerated mass spectrometry radiocarbon ages of plant macrofossils, peak $^{137}$Cs from aboveground nuclear weapons testing, and recognition of historical heavy metal pollution horizons, e.g., copper, lead, mercury, vanadium, and ratios of lead isotopes ($^{206}$Pb; $^{207}$Pb) (Fig. 2). For time intervals greater than ~350 years ago, maximum and minimum radiocarbon ages taken from above and below sediment deposits provide age estimates for the timing of intercalated deposition; the oldest deposit occurred AD 1025-1154. At Succotash marsh, 17 km southwest of Fox Hill marsh, which is protected by a beach-barrier dune with a height ≥3m, a reported six overwash deposits (range in age from AD 1411-1446 to AD 1954) are representative of category ≥3 hurricane storm surges over the past 700 yrs (Donnelly et alii, 2001). The Fox Hill overwash record not only corroborates the Succotash overwash record but also archives an older overwash record and serves as a more sensitive overwash recorder because it is susceptible to smaller storm surge magnitudes. We examine the morphology of the coastal system and overwash processes by developing a high-resolution digital elevation model using RTK GPS and connecting observed tidal records to sedimentological signatures of overwash deposits. We also consider the changing sensitivity of the salt-marsh recorder of storm surges over time by incorporating a new high-resolution reconstruction of relative sea-level rise at Fox Hill marsh for the past 3,300 years. Our results highlight overwash characteristics associated with a transgressive barrier dune sequence.

Figure 2. Simplified stratigraphy at FHM.17.800 paired with downcore profiles of $^{137}$Cs activity and also trace metal and isotopic concentrations used to identify regional pollution markers. The lead isotope profile is shown twice with different scales for clarity. Pink shading represents the vertical uncertainty given to each chronohorizon with the associated age (year CE) and age uncertainty of each chronohorizon included next to the shaded area. Chronohorizons are distinguished from one another using horizontal dashed lines where necessary. Analytical uncertainties are smaller than the symbols used.

References

IGCP Project 639

“Sea-Level Change from Minutes to Millennia”

Crossing Southern Italy: a travelling meeting from Taranto to Siracusa

Taranto (Puglia) – Siracusa (Sicilia) 16 - 23 September 2018

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Utilizing GPR, OSL, and LiDAR (GOaL) to document sea level, storms, and coastal evolution recorded in Holocene and Pleistocene prograded barriers

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Keywords: Ground Penetrating Radar (GPR), Optically Stimulated Luminescence (OSL), Light Detection and Ranging (LiDAR), paleo-beachfaces.

Global warming is causing seas to rise and is forecasted to intensify storms, but the degree of these increases as well as their impacts on vulnerable sandy coastlines is uncertain. Paleo-environmental records of sea level and storms as well as their impacts on shoreline evolution can provide insight in forecasting future changes resulting from anthropogenic global warming. Coastlines that have positive sediment budget, and space available to accommodate the sand, have built seaward through time forming strandplains comprising a series of foredune/beach ridges. These accreted coastal sands preserve a history of sea level change, storm impacts and sediment supply within their stratigraphy. The resulting coastal systems, called prograded barriers, have been studied for over a half century to decipher their evolution and extract paleo-environmental records. Over the past few decades, more traditional methods have been augmented by state-of-the-art remote sensing, geophysical and geochronological techniques (Dougherty et alii, 2016; Dougherty et alii, open review). For instance, two-dimensional topographic surveys of dune ridges were expanded laterally by 3D digital terrain models produced using Light Detection and Ranging (LiDAR). Generalized stratigraphic cross-sections interpolated between cores have been filled in with detailed dune, beach, and nearshore structures from high-resolution Ground Penetrating Radar (GPR). Finally, Optically Stimulated Luminescence (OSL) directly dates when beach and dune sand was deposited, which eliminated extrapolation of radiocarbon dates using isochrons.

Studies have shown that utilizing GPR, OSL, and LiDAR on prograded barriers, independently or in various combinations, can: (1) quantify frequency-intensity of storm records, (2) construct sea-level curves, (3) quantify sediment budgets, and (4) decipher coastal evolution. Here we propose that combining GPR, OSL, and LiDAR (GOaL) on one prograded barrier offers the possibility of determining a history of storms, sea level, sediment supply, and their impact on shoreline evolution (Dougherty et alii, open review). The electromagnetic properties of sandy barriers are ideal for GPR and paleo-beachfaces have been mapped with decimetre resolution over kilometers of stratigraphy (Fig. 1). The resulting record of paleo-beachface profiles spanning from the present-day beach through Holocene and Pleistocene barriers, enables our in-depth understanding of morphodynamics to interpret paleoenvironmental histories. Mapping paleo-beachface elevation (which is intrinsically linked to sea level) and morphology (which is inherently affected by storms) across prograded barriers can therefore document sea level and storms over hundreds and thousands of years. In order to perform this analysis, individual beachfaces are digitized to assign elevations and slopes. Using GPR and LiDAR data, certain stratigraphic layers or perimeters are digitized to calculate areas of accommodation space and sediment volumes (Dougherty et alii, 2016). Augmenting this data with an OSL chronology can resolve ages of certain features adding the temporal component necessary decipher barrier evolution and construct paleo-environmental records. Ultimately, a systematic application of GOaL on some of the 300+ prograded barriers around the world has the potential to disentangle local patterns of sediment supply from regional effects of storms or global changes in sea level, allowing direct comparison to climate proxy records (Dougherty et alii, open review).

This presentation uses over a decade of data from prograded systems in the United States, New Zealand and Australia to demonstrate the potential of GOaL to document sea level change over the Holocene in Australia, yet the resolution necessary to contextualize the predicted ~1m sea level rise is lacking. Particular focus has been on ‘far-field’ sites to identify the relationship of global ice-equivalent and global sea level changes in order to model their response to future climate change.
Despite extensive research in Australia, debate remains as to whether there was a ~2 m mid Holocene highstand and if so what was the nature of the subsequent sea level fall. Resolving these smaller scale fluctuations is made difficult as most sea level curves combine a wide variety of biological indicators and other intertidal material, with varying error bars, which obscure any recorded minor elevation changes (Fig.2). Dune-beach or beach-nearshore facies boundary imaged using GPR provide a well-constrained sea level marker which when combined with radiocarbon or OSL ages can accurately produce sea-level curves during interglacial periods (Fig. 1). Research mapping paleo beachface height over time from New Zealand sites capture Eemian and mid Holocene highstands with a subsequent fall indicating a non-linear nature (Dougherty et alii, 2016; Dougherty, 2018a). The distinct decrease in elevation has resulted in a forced progradation along these New Zealand sites. Prograded barriers in Australia show a similar increase in progradation rate at a similar time in the Holocene as New Zealand, indicating a potential regional scale sea level highstand (Dougherty et alii, 2016; Dougherty, 2018b).

Much less is known about paleo-storms than sea level and even less about accommodation space versus sediment supply. This research demonstrated how comparing paleo beachfaces recorded in the GPR data to beach profiles of known high-energy events can extend our storm record beyond historical times. Some examples presented show storm records where the results yielded recurrence intervals with differing coastal impacts that provided information on intensity and frequency of older erosional events (Dougherty et alii, 2016). The least is known about sediment supply and accommodation space over time. Recent studies demonstrate that accommodation space is an important factor to consider when determining barrier evolution. Current research quantifying volumes of the barrier limestones show that sand supply increased drastically starting in the mid-19th century altering foredune formation from previous millennia (Dougherty et alii, 2016; Dougherty, 2018b). Determining what caused this recent shift in barrier evolution as well as any changes in storms, sea level, sediment supply, and accommodation space prior to and since the onset of the global warming is crucial to tease out future responses to climate change.
Figure 2. (a) The left panel show the sea level curve constructed for the east coast of Australia (top) followed by progradation plots constructed from OSL dates collected from three barriers in southeast Australia. The right panel displays Lidar (above) and a topographic profile over the center of each barrier (below). Note the rapid increase in the rate of progradation at all three sites around 3,500 years ago, which coincides with a possible fall from the debated mid-Holocene highstand in this region (left). Forced progradation from a falling sea level could explain this uniform shift as Seven Mile and Wonboyn have no active sediment source, while Boydtown does. In addition, accommodation space varies through time at Boydtown (white dashed line) while abruptly increasing at Seven Mile and Wonboyn (LiDAR on the right), yet all show similar rapid progradation. If sea level was stable, then an increase in embayment width should cause progradation to slow. Whereas, as drop in sea level could not only force progradation but also mine the offshore sand source causing all three barriers to experience a uniform increase in progradation along shore. Another shared feature between these three sites is the existence of a large foredune anomalous from the older series of ridges (topographic profiles on the right). This is a common feature on prograded barriers in Australia, New Zealand and the North America. Over the past decade studies using OSL have dated their formation to within the last 200 years. Appropriately applying GOaL to these sites offers the opportunity to extract a sea level and storm record as well as detail the barrier evolution, determining the exact timing and driver of this recent shift. Figure modified from Dougherty, 2018b.

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Beach Rock as Sea-Level Indicator: solving a common problem by sedimentological facies analysis

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Keywords: Beach Rock, sea level changes, marine terraces, Quaternary, sedimentology, facies analysis, coastal geomorphology

Introduction
Future sea level changes threaten coastal communities worldwide. Therefore, reliable methods for the reconstruction of past relative sea level variations are essential as they allow predictions about upcoming developments. Hereby, the establishment of sea level index points is crucial. A number of sea level indicators are used to accomplish this (e.g. Shennan et alii, 2015). One of these indicators are beach rocks.

Beach rock is defined as cemented beach sediment. They occur presumably along the tropical coastlines of the far field and are best known from the Quaternary timeframe. While beach rocks are a sure indicator of paleo coastlines, their use in the establishment of sea level index points has been criticised due to often meter-scale insecurities regarding the vertical range of their formation (e.g. Kelletat, 2006). Sedimentological facies analysis poses a solution to this problem, as it allows to narrow down the original position of deposition and cement precipitation, as shown by Mauz et alii (2015) and Kelly et alii (2014). Overall goal of our research is thereby to study the variety of beach rock lithofacies and their use in sea level reconstructions. To achieve that a number of key areas worldwide need to be investigated. The beginning made the northeastern coastline of Oman, where a high amount of well-preserved beach rock outcrops is encountered.

The Study Area in Oman
The coastline of Oman, bordered by the Arabian Sea as part of the northern Indian Ocean, constitutes a steep, passive continental margin with no shelf. The Arabian plate is currently drifting northwards, where it is subducted beneath the Eurasian Plate within the Makran Subduction Zone (MSZ). Located at 23° latitude the climate setting is semi-arid to arid. The wave regime can be described as mesotidal, with a tidal range between 1.5 m and 2 m. The study area, located on the NE coast of Oman, is dominated by Palaeocene to early Eocene, folded limestone (Fournier et alii, 2006). These formations do not only form the coastal bedrock but also the Selma Plateau, which rises up to 1500 m above mean sea level (MSL) (see Figure 1). The limestones are heavily karstified, which lead to the formation of one of the world’s largest cave systems including the 58,000 m² large Majlis al Jin (Hoffmann et alii, 2016), as well as sinkholes like the 15 m deep Hawiyat Najm. A set of at least 12 staircased, wave-cut, marine terraces is observed parallel to the coastline and bordering the Selma Plateau. While the upper terraces are completely abraded and beach rocks are the only remaining sedimentary cover, the lower terraces are depositional and beach rocks occur alongside with alluvial, fluvial, and shallow marine facies (see Figure 1).

The terraces are dissected by erosional channels, locally known as wadis. The deepest of those cut through the entire limestone succession into the underlying rock unit. This unit belongs to the ophiolitic complex that was obducted onto Oman’s continental crust in the Late Cretaceous (Searle, 2007). Outcropping within Wadi Tiwi and Wadi Fins are the lowermost units of the ophiolitic sequence, namely peridotitic rocks, representing the upper mantle. These rocks are serpentinised. Peridotites act as an aquiclude and therefore form the base of the overlying karst-complex. Wells are common along this bedding plane. All water entering the ocean, be it groundwater from the karst complex or surface water drained through the wadis, is enriched in calcium carbonate. A coherence with intensive beach rock formation that is observed on every beach along the recent coastline seems likely.
Methods

By mathematical analysis within a digital elevation model (DEM), it was possible to determine the locations of paleoshorelines in the study area on the basis of changing slope angles in several profiles rectangular to the modern coastline (Schneider et alii, 2017). The hereby defined locations were correlated over the entire coastal section. Twelve terrace levels, reaching heights of up to 500 m above mean sea level, are clearly visible, they are named T1 to T12, T1 representing the lowermost and thereby youngest terrace level. Our age model is based on dating of the terrace surfaces with cosmogenic nuclei (Schneider et alii, 2017) the terraces can be allocated to the Marine Isotopic Stages (MIS) 5a to 17.

Geological mapping revealed several locations of paleobeach deposits with varying degree of erosion. Partly, only lag deposits were identified. A total of eight outcrops with suitable beach rock thickness offering the possibility to study vertical profiles were identified on terrace levels T1, T3 (MIS 5e and 7) and T7 (MIS 15). Log sections were drawn on all suitable outcrops for the sedimentological investigation (see Figure 2).

Figure 1. Terrace Morphology of the study area. The tilted Eocene and Miocene limestone formations are underlain by an ophiolitic complex. Beach rocks are found on the full width of the wave cut platforms.

Figure 2. Example of a sedimentological Log from an outcrop at the northernmost end of the study area. The profile shows a succession of several lithofacies on a gravel dominated beach.
Sedimentological structures and ichnofossils were measured and documented in a photograph and/or drawing. The locations were mapped with a GPS, coordinates are presented as meters within the Universal Transverse Mercator (UTM) projection, Zone 40Q using the WGS 1984 reference ellipsoid. As part of the facies analysis, the observed layers were grouped together in lithofacies based on their sedimentological properties. Finally, each outcrop was interpreted regarding its depositional realm taking the stratigraphic relations of different lithofacies into account.

Samples were collected from all layers that were suitable for producing thin sections. The samples were then turned into standard thin sections: 2 cm wide, 5 cm long and 25 μm thick for petrographic analysis.

Results

Eight lithofacies (Facies I to VIII) in six facies associations were identified (see Table 1):

The beach rock deposits of the study area can be divided into two groups based on their importance in sea level reconstruction: the first group is located directly at the shoreline angle. The second group is located between shoreline angles or in the area around Sur that does not show a terraced morphology at all. The age-model of the terraces is based on their allocation to sea level highstands during MIS 5a to MIS 17. This means that only the outcrops of the first group can be used as sea level index point since only the paleo-shoreline itself can be assigned to a certain point in time. Without facies analysis, the elevation of these beach rocks in comparison to a reference point alone is a very inaccurate parameter to quantify sea level change. An error of several meters must be assumed. Three outcrops, two at the shoreline angle of T3 and one at T7, show a sufficient thickness to perform facies analysis. They were allocated to a supratidal, an intertidal, and an estuarine setting. From a large uncertainty of several meters, these exposures are now allocated to a certain position relative to paleo sea level which results in a lowered uncertainty on a decimeter scale. The result is that the sea level highstands of MIS 5e (T3) and MIS 15 (T7) can now be determined more accurately.

### Table 1. Short description of the observed lithofacies and their allocation to facies associations.

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<th>Facies</th>
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<tbody>
<tr>
<td>I</td>
<td>Medium, well sorted sand, parallel lamination, large-scale trough cross bedding, seaward dipping beds, crab burrows. Meniscus and irregular crust cements</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Clast-supported, granule to boulder conglomerate, very large scale tabular cross beds, landward dipping foreset beds, coral fragments</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Poorly sorted, pebbly sandstone, alternating parallel laminae and layers of very coarse, coarse and medium sand, seaward dipping beds, small scale, trough cross stratification. Skolithos burrows, meniscus cements, microstalagtites</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Medium to coarse grained, pebbly sandstone, small scale, symmetrical ripples, very large Paleophybus burrows, micritic envelopes, isopachous crust cements</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Matrix-supported, poorly sorted, granule to boulder conglomerate, irregular/gradational top</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>Fine to medium, silty sand, parallel lamination, Chondrites, Thalassinoides, Phycosiphon, Planolites</td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>Moderately sorted, medium to coarse grained sandstone, lenses and bands of poorly sorted conglomerates, low-angle, tabular cross lamination</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>Sharp-based, conglomerate/sandstone couplets, well sorted, trough cross bedding, isopachous crust cement, granular pseudosparitic pore filling</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions

Facies analysis of Quarternary beach rocks is useful to reconstruct paleo sea level. The accuracy that can be reached by this method is in the order of decimeters. Both sandy, as well as gravelly beach rocks, are suitable. Furthermore, the facies analysis allows reconstructing changes in the local depositional environment in space and time. In our study, we were able to reconstruct the depositional realm of beach rocks at eight outcrops and demonstrated that the method works not only in sand dominated systems but also on gravel beaches. It was possible to identify six different lithofacies that can be allocated to the supratidal, intertidal, and subtidal sections of a coastline profile. Nevertheless, some challenges should be noted. First, the method requires a certain preserved thickness of beach rock, since bedding structures, which are crucial for facies interpretations, are rarely preserved in lag deposits. Exposures where the thickness of the paleo beach was below 1 m, did not lead to a reliable facies interpretation. Secondly, conclusions drawn from the cement have to be treated with caution. Our petrographic examination shows that a relative chronology for different cementation cycles can often be reconstructed even though recrystallization took place. Since it is known that the beach rocks were uplifted, the point in time when the regime changes from a marine to a continental setting is found in that chronological sequence. However, the differentiation between calcite and aragonite with petrographic methods alone is difficult if not impossible. Other methods, like Cathodoluminescence, need to be applied if the observed cement will strongly contribute to the interpretation.
References


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Wetland stratigraphic evidence for variable megathrust earthquake rupture modes at the Cascadia subduction zone

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Keywords: Paleoseismology, earthquake stratigraphy, sea-level stratigraphy, earthquake hazard, tsunami hazard.

Although widespread agreement that the Cascadia subduction zone produces great earthquakes of magnitude 8 to 9 was reached decades ago, debate continues about the rupture lengths, magnitudes, and frequency of megathrust earthquakes recorded by wetland stratigraphy fringing Cascadia’s estuaries. Correlation of such coastal earthquake evidence along the subduction zone has largely relied on relative position in a stratigraphic sequence and maximum-limiting 14C ages with errors of decades to hundreds of years. Offshore, a 10,000-year record of turbidites in marine cores is interpreted as an archive of strong shaking from great earthquakes, with an average frequency of about 500 years in northern Cascadia versus 200-300 years in southern Oregon and northern California. Onshore, fewer events marked by sharp (<3 mm) peat-mud (mud-over-peat) contacts in tidal wetland stratigraphic sequences, have been widely inferred to record sudden relative sea-level rise due to coseismic subsidence during megathrust earthquakes: 4-7 sharp subsidence contacts in 3500 years at estuaries in northern Oregon and southern Washington (500-800 year average recurrence), and 9-12 sharp subsidence contacts in over 6000 years in sequences in central and southern Oregon (500-900 year average recurrence). Improved understanding of the onshore and offshore records is critical to the assessment of earthquake hazard in western North America and of tsunami hazard in the Pacific basin. However, because dating the turbidite record is inherently much less precise than are age models for subsidence events in the most thoroughly studied tidal wetland sequences, accurate reconstruction of the times of Cascadia’s great earthquakes depends on the ages from the onshore record.

Although methods to reduce uncertainty in the limits of resolution of tidal stratigraphy for recording earthquakes of a particular magnitude, and ways to distinguish earthquake subsidence stratigraphic contacts from non-seismic contacts, have been discussed for decades (e.g., Nelson, 1992; Atwater, 1992; Darienzo et alii, 1994; Nelson et alii, 1996a; Atwater and Hemphill-Haley, 1997; Witter et alii, 2001; Kelsey et alii, 2002; Nelson et alii, 2006; Graehl et alii, 2014; Milker et alii, 2016), consensus about the threshold of resolution (minimum identifiable evidence of an earthquake) of tidal stratigraphy and, therefore, the completeness of Cascadia’s coastal record of great earthquakes, remains elusive. Although the most distinct, widespread contacts likely record close to a meter of coastal subsidence during the greatest megathrust earthquakes (e.g., M8.8-M9), other contacts may record <0.5 m of subsidence onshore of patches of low stress release on the megathrust during lesser megathrust earthquakes (e.g., M8.2-8.6), or from localized subsidence near upper-plate faults that slip during or independently of megathrust earthquakes (Nelson et alii, 1996b; Wang et alii, 2013; Kemp et alii, 2018).

At the Siuslaw River estuary in central Oregon (Lat. 43.96°N; Long. 124.058°W) a stratigraphy of 9-12 peat-mud contacts, similar to those described from many Cascadia estuaries, may record a greater number of megathrust earthquakes during the past 2000 years than at any other of the tens of tidal wetland sites to the north and south. Here, as well as at many tens of other Cascadia tidal wetland sites, peat-mud contacts mark the tops of couplets of tidal flat and low marsh mud gradually shoaling upward into middle and high marsh peat. Along core transects across an 800-m-wide, island marsh in the Siuslaw River, we traced the 9 most continuous of 12-15 peaty beds dating from the past 2000 years for 250-500 m, but we had difficulty correlating the 3-6 intervening beds >50-100 m. We attribute the sharper, more extensive upper contacts on peaty beds—two capped by sandy
beds probably deposited by tsunamis—to sudden coseismic subsidence of middle and high marshes, but origins for other upper and lower contacts bounding the peaty beds are unclear. Twice as many (42% vs. 23%) upper contacts on the 15 peaty beds are sharp (<3 mm) compared with lower bed contacts, but the >10-mm thickness of a third of upper contacts suggest gradual rather than sudden submergence. Only half of lower contacts are gradual enough to suggest slow marsh emergence during gradual post-seismic uplift, but the complex dynamics of marsh sedimentation during river flooding and channel migration along tidal rivers commonly leads to sharp transitions from mud to peat, even during periods of gradual relative sea-level rise. Some OxCal-modeled 14C ages for upper contacts of peaty beds beneath the island marsh match ages for similar subsidence contacts inferred to record great earthquakes at other onshore sites to the north or south, whereas ages for other upper contacts at the Siuslaw River do not.

Larger proportions of Siuslaw River cores consist of peat and muddy peat than do cores at many marsh sites to the north and south: 38±18% (1σ) of stratigraphic units in 28 Siuslaw River cores show peaty units (estimated organic component >50%). Along two core transects on the south shore of the river, 95% of units dating from the past 2000 years are peat or muddy peat (Fig. 1).

**Figure 1.** Simplified lithologies, stratigraphic unit contact correlations (dashed lines), and 14C ages (midpoint of calibrated age interval; x1000 yr BP) for three 25-mm-diameter gouge cores along a core transect across the mouth of a small inlet in the Siuslaw River estuary (latitude 43.96°N, longitude 124.058°W; modified from Fig. 2 of Nelson, 1992). The thick sequence of largely peat and muddy peat, accumulated in high and middle marshes fringing the mouth of the inlet, suggests that no large (>0.5 m), sudden, long-lasting (>several years) changes in relative sea level occurred in this part of the estuary during the past 2000 years. Because high and middle marshes in this region typically occur within an elevational range of <0.5 m, sudden subsidence >0.5 m would likely produce a distinctive peat-mud contact. If megathrust earthquakes of the past 2000 years ruptured offshore of the Siuslaw estuary, coseismic subsidence was apparently too small to produce such contacts.

_Crossing Southern Italy: a travelling meeting from Taranto to Siracusa_
In contrast, cores from similar high marsh sites at sites to the north and south typically show 10-50% peaty beds over the same time interval, and most contain a greater number of sharp upper peat-mud contacts. One explanation for the thick sections of peaty sediment at the Siuslaw River is that they record lesser amounts and (or) fewer episodes of subsidence (earthquakes) over the past 2000 years of relative sea-level rise than do sites to the north and south. Detailed foraminiferal and diatom reconstructions of sea-level history, focusing on upper and lower contacts (e.g., Shennan et alii, 1998; Nelson et alii, 2008; Milker et alii, 2016; Kemp et alii, 2018), and many tens of 14C ages on high-quality samples will be needed to determine if the earthquake history archived at the estuaries of central Oregon differs substantially from histories to the north or south.

References


Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
Holocene shore displacement and Stone Age palaeogeography of Hiiumaa Island, NW Estonia, Baltic Sea

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**Keywords:** Sea level change, palaeogeographic reconstruction, beach ridges, luminescence dating, Stone Age settlement, Baltic Sea.

Hiiumaa, with its area about 1000 km², is one of the largest islands in the Baltic Sea (Fig. 1). The island emerges from the sea due to post-glacial rebound, currently with a rate around 2.5 mm per year. Hiiumaa Island was inhabited already ca. 7600 years ago in the Late Mesolithic (Kriiska and Lõugas 1999). At that time, only 1% of its present terrain was above the sea level in the highest area in Kõpu. Altogether 15 Stone Age settlement sites, including 10 Late Mesolithic and 5 Neolithic sites, closely related with seasonal seal hunting are known from the Kõpu area. Shore displacement curves for Hiiumaa indicate constant linear lowering of relative Litorina Sea level since that time (Vassiljev et alii 2015).

Coastal landform system and a bog in south eastern part of the Kõpu area were investigated in order to clarify the Holocene shore displacement of the area and the relations between relative sea level changes and the locations of the Stone Age seal hunters’ settlement sites. Multiproxy approach combining sedimentary, ground-penetrating radar (GPR) and airborne LiDAR elevation data with luminescence and radiocarbon dating was used. Palaeoshorelines of the island were reconstructed based on dated coastal landforms.

**Figure 1.** Location of the study area (indicated by red rectangle). A: Present-day apparent land uplift isobases (mm per year; after Ekman 1996) and Stone Age hunter-gatherer coastal settlement sites in Estonia and Latvia. One dot may represent more than one site (after Habicht et alii 2016). B: Dry land area (dark grey), shoreline and Stone Age settlements during Litorina Sea maximum level around 7500 calii BP (sea level isobases in m a.s.l.) compared to present land areas (light grey). The shaded relief image is based on LiDAR data (Estonian Land Board, 2012). The Litorina Sea level is interpolated based on correlated relict coastal formations mapped on the LiDAR elevation model.
The results show two sets of coastal landforms, separated by unconformity corresponding to Ancylus Lake – Litorina Sea transition. The mean luminescence ages from the Ancylus Lake set provided values 10.0 and 9.9 ka while Litorina set was dated between 6.4–3.9 ka. Both sets of landforms are characterized by several extensive seaward-dipping reflectors clearly visible in GPR images. These are ground-truthed by coring as coarser grained strata in dominantly sandy beach deposits. Such features are suggesting the formation of these landforms in active wave regime at well-exposed coast. Seaward decreasing elevations of beach ridges and relict foredunes indicate continuous lowering of relative sea level during the Litorina Sea period.

Palaeogeographical modelling shows the palaeoisland with an open shore towards south east and a lagoon in south west during the Litorina Sea highest shoreline at ca. 7.7–7.0 calii ka BP (Fig. 2). This corresponds to the island’s earliest, Late Mesolithic occupation. The Stone Age seal hunters’ camps were established less than 100 m from their coeval shoreline on the top of older Ancylus Lake landforms on the open coast and some also on the shores of the lagoon. Younger sites are located successively at lower altitudes following the shore displacement induced by the post-glacial rebound.

This study provides new data about Holocene relative sea level changes on Hiiumaa Island, eastern Baltic Sea, and proves the shore-connected lifestyle of the people in the region from Late Mesolithic to Middle Neolithic.

Figure 2. A: Palaeogeographical reconstruction of the Kõpu palaeoisland at ca. 7500 cal BP with the relevant Stone Age coastal settlement sites indicated by red symbols and the location of sampling transect (black line) on LiDAR elevation model. B: Elevation profile of the sampling transect with luminescence ages.

References


EUSTASY, ISOSTASY AND TECTONICS

Tectonically uplifted marine terraces of Briatico, Vibo Valentia, Calabria, Italy

Chairs

Alessio Rovere, Timothy Adam Shaw
Ex-situ quantification of sea-level index points and its use in the reassessment of the last interglacial sea-level database

Precise predictions of future sea-level rise are essential for developing models of future climate change and shoreline protection strategies. These predictions are calibrated to the sea-level highstand in past warmer climates and need consequently accurate estimates of the paleo sea levels. Besides the Holocene, the most studied past period in sea level studies is the last major interglacial, the Marine Isotopic Stage (MIS) 5e between ca. 128 and 116 ka, when global sea level was ca. 6-9 m higher than today (Dutton et alii, 2015). The only direct observations of the relative sea level (RSL) in this time, can be made by the investigation of paleo RSL indicators. As RSL indicators, any geological feature can be used, that has a quantifiable relation to the sea level during the time of its formation. This relationship is called the indicative meaning and is described with two values (Shennan, 2015; Van De Plassche, 1986): the vertical distance between the feature itself and the sea level during its formation (i.e. the reference water level) and the possible height variability (i.e. the indicative range). Studies on the MIS 5e sea level have explored a large number of locations to assess the paleo sea-level elevation. Nevertheless, one of the fundamental problems with most of these studies, especially in contrast to Holocene sea-level studies, is the lack of reporting the indicative meaning as standardized tool to add an uncertainty to the RSL indicator.

The vast majority of reported RSL indicators can be described by using 10 geomorphological categories (Rovere et alii, 2016). For each of these categories, the upper and lower limit of the RSL indicator, which describe the indicative meaning, can be defined by using wave conditions and tidal levels.

Figure 1. Global maps with wave and tide conditions. a) Significant Wave Height, b) Mean Wave Period, c) Mean Lower Low Water, d) Mean Higher high Water.
Although the general categorization of RSL indicators helps in describing the indicative meaning in a standardized way, the corresponding limits are often hard to quantify on specific study sites. In the best case, this quantification should be done by investigating a nearby modern analogous landform and described alongside with the elevation measurement of the RSL indicators.

For many occasions it is difficult or impossible to determine the indicative meaning in-situ. This can be the situation, if no modern analog is present or the study analyses large regional or global datasets. In this case, different morpho- and hydrodynamic equations can help quantifying these limits according to the categorization of RSL indicators described above. In a new study (Lorscheid and Rovere, under review), we use different global wave and tide datasets (Fig. 1) in a range of empirical, hydrodynamic equations in order to calculate the indicative meaning ex-situ on a global scale.

After the validation of the equations by comparing the results to field-measured values, a statistical analysis for all global shorelines was performed. Along all shorelines wave and tide conditions have been extracted in a regular distance and these simple equations were applied to quantify the limits used to describe the indicative meaning of the 10 different RSL indicators from Rovere et alii (2016). Using this approach the indicative meaning of every RSL indicator can be established without an in-field investigation. Further the general performance of each RSL indicator in terms of describing the paleo sea-level can be investigated (Fig. 2). We will show that this approach is a valid and easy applicable method to establish the indicative meaning for regional or global datasets or if no site-specific data is available.

![Figure 2. Examples of general distribution of upper (UL) and lower limit (LL) of different sea-level indicators (here: tidal notches and beach deposits). The mean values of both limits indicates the border of the indicative range (IR) and its midpoint the relative water level (RWL).](image)

References


Quaternary uplift, elevated marine shorelines and neotectonic activities in north-eastern Oman

Keywords: Sea level change, marine terraces, uplift, quaternary, neotectonics.

Coastlines are one of the major geomorphological systems of the Earth. Because coastal landforms are created at or near sea level, old coastal structures elevated above the modern coastline indicates past sea level changes and tectonic deformation of the surface since those features were formed (Anderson et alii; 1999). Some of the most useful landforms for studies of sea level change and active tectonics are coastal terraces, including erosional terraces and uplifted coral reefs. Such coasts with coastal terraces were formed by multiple cycles of sea level changes during the glacial and interglacials of the Quaternary. Wave-cut platforms are usually cut when sea level is near its highest position in each interglacial cycle (Anderson et alii; 1999).

These landforms are prominent along many coastlines around the world, and are valuable archives for reconstructing paleo sea level and measuring tectonic uplift rates and related neotectonic activities. Sea level is important to studies of differential crustal uplift and active tectonics because it is manifested as a widespread geomorphic horizontal datum in the landscape. An impressive example of elevated and deformed marine terraces is the striking coastal geomorphology of north eastern Oman. Quaternary sea-level studies are incomplete in this area, as are quantified studies about Quaternary uplift of the coastal Hajar Mountain range.

We applied modern and high-resolution surveying technologies and remote sensing technologies to survey Quaternary terraces and reconstruct the local sea-level history and neotectonic activities in the area. We therefore quantified the vertical crustal movement and surveyed associated fault block movements in order to reconstruct the spatial and temporal uplift history of the north eastern Hajar Mountains.

The geology of the study area is dominated by Upper Cretaceous to Eocene limestone formations. These are underlain by serpentinitized peridotites of the Semail Ophiolite (Wyns et alii;1991). The rock sequences form the Hajar Mountains, a mountain range with elevations of up to 2100 m above the sea in the vicinity of our study area. The entire limestone formations are heavily karstified, forming large-scale limestone caves and open karst systems. Wave-cut marine abrasion platforms form a terraced landscape along the coast.

Our study area is located at the Gulf of Oman, between Quriyat and Qalhat, approximately 80 km south of Oman’s capital Muscat. We surveyed the uplifted marine terraces over a distance of 70 km with the aid of ground-based differential GPS (dGPS) measurements and high-resolution digital elevation models, derived from Tandem-X SAR data (Krieger et alii; 2007). We surveyed sea-level index points, such as bedrock – beach rock contact planes, uplifted coral reefs or paleo wave-cut notches in order to pinpoint paleo sea level.

Based on our data, we identified at least eight distinct terrace levels, reaching elevations of up to 300 m above present sea level. Not all terraces are preserved along the entire mapping area and the same state of preservation. While younger terraces are usually well preserved and can be observed along the entire coastal stretch, older ones are often fragmented, and their paleo-sea cliffs are decayed. It is generally more difficult to follow and correlate old terraces along the study area. Terraces levels older than MIS17 seem to remain in fragments, but their features are heavily degraded and thus cannot be identified by an exclusive remote sensing approach. We dated the terrace levels by dating alluvial fan deposits covering the abrasion platforms using OSL, and terraces surface exposure ages based on cosmogenic nuclides (10Be and 36Cl) on rounded quartz pebbles. Our dating results indicate that the terrace staircase was formed and uplifted at least since MIS 17 (700ka). Since then, each sea-level highstand during an interglacial period resulted in the formation of a terrace level within the coastal morphology. We conclude that the most prominent sea cliff (terrace 3) and its associated abrasion platform were formed during two MIS stages, when the older MIS 7 terrace was reworked by the MIS 5e sea level high stand. The oldest recorded and most elevated terrace is attributed to MIS 17, while the youngest and lowest terrace is assigned to MIS 5a.
The terraced study area is confined by two major faults towards the north and the south (Qalhat fault). The entire terrace staircase formation is dissected by predominately NW-SE trending faults swarms (Kusky et alii; 2005). Areas with intensified fault concentration, such as north of Shab and near Dibab, lack the distinctive terrace morphology. Faults swarms act as weak zones in the bedrock, why erosional processes and intensified wadi development degrade the terraces faster. Irregular wadi drainage patterns on younger terrace levels (MIS 5a and MIS 5e), such as compressed meandering and deflected drainage resulting from fault movements suggest neotectonic activities.

The precise dGPS-survey of the paleo-shoreline angles revealed a general northward dipping of the terraces (see Fig. 1). This dipping is not uniform across the entire study area and not uniform between different terraces at the same site. We observed a strong tilting of terrace 6 (MIS 13) north of Tiwi, while the younger terrace levels are just gently tilted. We attribute this to neotectonic activities between MIS 13 and MIS 11.

We calculated Quaternary uplift rates of the terrace sequence based on the paleo-sea level curve of Grant et alii (2014) from the Red Sea, cosmogenic nuclid derived terrace ages and the current elevation of the terraces. As the terraces are differentially uplifted, uplift rates are highest in the south and lowest in the north. We observed tempo-spatial variations of the uplift rates (see Fig. 2). While the uplift rate in north is declining (Dibab: MIS 15: 0.35 mm/y; MIS 5e: 0.23 mm/y), it is accelerating in the south (Qalhat: MIS 15: 0.43 mm/y; MIS 5a: 1.12 mm/y).

The crustal uplift expressed in uplifted marine terraces is restricted to a fault block between Quriyat and Qalhat in this part of Oman. While the neighboring northward block is subsiding, the block to the south is tectonically stable (Hoffmann et alii; 2013). We conclude a seismic potential on the confining faults, resulting from one block uplifting, while the neighboring blocks in the north and south are tectonically stable. Historical and archeological records reveal earthquake activities in the 14th century AD, related to the Qalhat fault (Rougeulle). We conclude neotectonic activities at least since MIS 17, which are also manifested on younger (MIS 5a and MIS 5e) terrace level landforms.

Various models have been put forward trying to explain the neotectonic deformation pattern. These include a migrating forebulge development in association with subduction processes along the Makran Subduction Zone (Kusky et alii; 2005). Other studies as Regard et alii (2009) in Peru or McNeill et alii (1999) at the Cascadia Subduction Zone report comparable outcomes.
Our results suggest that migrating flexural forebulge components connected to the Makran Subduction Zone can be held responsible for coastal uplift processes and for differential vertical uplift along the study area. Another factor which can also contribute to the differential uplift is the serpentinization and volume-expansion of Cretaceous peridotites underlying the Hajar Mountain Range (Kelemen and Matter 2008). Based on our results, neotectonic activities along the north-eastern coast of Oman cannot be ruled out. This is of special interest to local stakeholders, as major infrastructure projects are located within the vicinity of the critical fault zone.

Figure 2. Tempo-spatial variations of the uplift rate. Rate accelerates towards south. Locations are drawn in Fig. 1.

References

Postglacial Relative Sea-Level databases
from near to Intermediate field regions. A key tool to quantify the
on going isostatic signal along global coastlines

Reconstructions of relative sea level (RSL) since the last glacial maximum (~21 ka BP) have implications for investigation of crustal movements, calibration of earth rheology models, and the reconstruction of ice sheet extent, thickness, and deglacial chronology (Lambeck et alii, 2014; Peltier et alii, 2015; Roy and Peltier, 2015). In recent years, efforts have been made to create RSL databases following a standardized methodology (Hijma et alii, 2015). These regional databases provide a framework for developing our understanding of the primary mechanisms of RSL change during the last millennia (Khan et alii, 2015) and a long-term baseline against which to gauge the changes in sea level observed during the 20th century and forecast for the 21st century and beyond (Rovere et alii, 2016). Here, we present the results of recently compiled databases that span distinct spatial and climatic regions of the globe: the Atlantic and Pacific coast of North America and the Western Mediterranean Sea. Our re-evaluation of sea-level indicators from geological and archaeological investigations have yielded more than 2500 RSL data points, comprised of sea-level index points and marine/terrestrial limiting data (Engelhart et alii, 2015; Vacchi et alii, 2016). The indicators are derived mainly from salt and freshwater marshes or adjacent estuarine sediment, isolation basins, beach ridges, fixed biological indicators, beachrocks and coastal archaeological structures. We outline some of the common difficulties and provide potential solutions to analyse sea-level data in such different depositional environments. In particular, we emphasize problems related to the definition of standardized indicative meaning (i.e., the relationship between the indicator and paleo mean sea level) and to the re-evaluation of old radiocarbon samples. The presentation will further address complex tectonic influences and the framework to compare such large variability of RSL data points. The result is a comprehensive and quality controlled RSL database for a large portion of North American and Mediterranean coastlines that allows us to compare and contrast data from different geomorphological contexts in order to obtain basin-scale insights into the processes driving postglacial RSL changes.

The data better constrains GIA spatial variability and its role in the evolution of RSL in different coastal areas. We applied an innovative empirical Bayesian spatio-temporal statistical model (Kopp et alii, 2016) to this large dataset. The application of the model to RSL index points with wide spatial and temporal coverage enables calculating rates of RSL change through time and space (averaged 1 ka time-steps; figure 1). The model produces estimated rates of change regardless of data presence, but the rates are particularly robust where suites of index points are available and well distributed throughout the postglacial period. These results provided new insights into the pattern of on-going GIA processes in these regions. Finally, we identify some regions, such as the Labrador coast in Canada and the Mediterranean African coast, where further investigation is required to better constrain RSL evolution. Such investigations, carried out using the proposed framework employed herein
produce homogeneous and comparable RSL estimates, enabling a more meaningful assessment of RSL variability along the eastern Canadian coast.

References


Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
Quantifying the timing and amplitude of Holocene relative sea level in south-central Chile using geomorphology and stratigraphy

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Keywords: Sea level highstand, Holocene, MIS-5, tectonic uplift rate.

Estimating the amplitude and timing of Holocene relative sea level along tectonically-active coasts is challenging because it involves eustatic, isostatic and tectonic components. Here we present estimates of the peak amplitude and timing of the Holocene relative sea-level highstand along ~500 km of the south-central Chilean coast between 33-38S using geomorphic and stratigraphic markers (location of study area in Fig. 1). Using airborne LiDAR data, we mapped the shoreline angle—a geomorphic marker of past sea-level positions—at 83 paired locations including Holocene and MIS-5 marine terrace levels (Fig. 2).

The data were collected before the 2010 Maule earthquake (M8.8) that caused meter-scale coastal land-level changes. Elevations of these two markers vary substantially along the coast but are linearly correlated ($r^2=0.83$) suggesting constant rates of permanent tectonic uplift. The timing of the highstand was estimated from a compilation of 61 radiocarbon and luminescence ages recalibrated and reinterpreted to assess their indicative meaning. We find that the mid Holocene highstand occurred between 4 and 6 cal ka BP. Tectonic uplift rates between 0.1 and 1.5 mm/yr estimated from MIS-5c and 5e terraces (dated with 12 luminescence and 8 cosmogenic nuclide ages; Jara-Muñoz et alii., 2015) were subtracted from Holocene shoreline angle elevations to estimate the amplitude of the eustatic component. For an age range of the Holocene highstand between 4 and 6 ka, we obtained mean elevations between 3 and 3.5 m above modern mean tide level (Fig. 3).

Figure 1. Simplified geologic map and Quaternary faults of the study region.

Figure 2. Shoreline angle elevations of marine terrace levels in south-central Chile. Lines show linear interpolations. Inset shows relation between MIS-5e and Holocene levels at collocated sites. Note linear correlation. MIS-5 sites from (Jara-Muñoz et alii., 2015).
Our compilation of sea-level index points suggests lower values in the range of 1-2 m. Both estimates are in agreement with ICE-5G model predictions for a range of lithospheric thicknesses. Our methodology may be applied to tectonically-active coasts such as those bordering subduction zones, with implications for assessing coastal hazards under future sea-level rise.

Figure 3. Probability density functions for the elevation of the Holocene sea-level highstand along the south-central Chile coast corrected for tectonic component using MIS-5 uplift rates, for ages of 4 and 6 ka.

References

The Amplitude and Timing of Holocene Relative Sea-Level Changes from the Caribbean to South America

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Keywords: Holocene, relative sea level, database, highstand, South America, Caribbean.

The spatial and temporal variability of Holocene relative sea-level (RSL) change along the western Atlantic coastline from the Caribbean to southern South America are assessed using published (Khan et alii, 2017) and recently compiled Holocene sea-level databases. The databases contain sea-level index points and terrestrial and marine limiting data derived from geological and biological indicators from mangrove and salt marsh peat, beach rock, vermetids, microbial mats, and storm beaches. The compilation of the databases follows a standardized protocol (Hijma et alii, 2015) and allows comparison of regional RSL trends after consideration of vertical and temporal uncertainties and local scale processes including sediment compaction and paleo tidal-range change. We apply a spatio-temporal empirical hierarchical model to estimate magnitudes and rates of RSL change and the amplitude and timing of the mid-Holocene highstand along a latitudinal gradient (Fig. 1). Furthermore, we compare regional RSL trends with glacial isostatic adjustment predictions using the latest iteration ICE-7G_NA (VM7) model (Roy and Peltier, 2017). The RSL records are characterized by higher rates of RSL rise during the early Holocene. During the mid-Holocene, RSL records from Caribbean show RSL did not exceed higher than present levels. Moving south, RSL records from Suriname and Guyana show RSL at 2.0 (± 1.1) m at 3.7 ka. In central South America, RSL records from Brazil show RSL at 4.8 (± 1.4) m at 5.3 ka while RSL records from the Beagle Channel show RSL at 6.6 (± 2.1) m at 5.9 ka. The nature of RSL changes following the mid-Holocene towards the present (e.g. Angulo et alii, 2006) are assessed after full consideration of the data uncertainty.

Figure 1. Spatio-temporal empirical hierarchical model showing (A) highstand probability, (B) RSL height (m) and (C) RSL rates (m/ka) at 6-5 ka.
References


Insights into the glacial isostatic adjustment process in the Mediterranean basin from an analysis of globally distributed relative sea level records

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Keywords: Sea level, glacial isostatic adjustment, Holocene, Mediterranean, eustasy.

The Mediterranean Basin is a region of special interest in the study of Relative Sea Level (RSL) evolution due to the large database of biological and geological indicators of past RSL, the rich history of human habitation, and the exposure of coastal infrastructure to future RSL rise (e.g. Vacchi et al. 2016; Antonioli et alii, 2017; Wolff et alii, 2018). To understand past, present and future RSL evolution in the region, accurate models of the Glacial Isostatic Adjustment (GIA) process are necessary. These models enable the reconstruction of global and local sea-level change in response to the glaciation-deglaciation cycles that have dominated climate system variability over the past several hundred thousand years. Global and local sea-level change occur not only through the direct impact of the redistribution of water between the oceans and the continental cryosphere, but also due to the time-dependent response of the Earth’s shape to changes in ice loads at its surface.

The existence of large databases of geological and biological indicators of past RSL is crucial to refine global models of the GIA process. For instance, high-quality data that has become available for the U.S. East coast (Engelhart and Horton 2012) has enabled significant improvements in our understanding of the post-LGM recovery of North America, and in particular for the region peripheral to the former Laurentide ice sheet that once covered a large fraction of the continent.

Figure 1. (Left panel) Map of the location of the sites in the Vacchi et alii (2016) database of relative sea-level histories for the western half of the Mediterranean basin. (Right panels) Comparison of relative sea level reconstructions at selected sites in the Vacchi et alii (2016) data set with the predicted relative sea-level history at those locations for the ICE-6G_C (VM5a) (green) and the ICE-7G_NA (VM7) (black) models of the GIA process. Green data points represent sea-level index points, whereas blue crosses represent marine limiting data and orange crosses represent terrestrial limiting data. The number identifying each site matches the information found in the left panel. Adapted from Roy and Peltier (2018).
This information is especially useful when it is used together with the vast network of precise space-geodetic observations of crustal motion that are also available over most of the continental interior (Roy and Peltier 2015). This work has led to the latest ICE-7G_NA (VM7) model (Roy and Peltier 2017), which is a further refinement to the precursor model ICE-6G_C (VM5a) model of Argus et al. (2014) and Peltier et alii (2015).

As the Mediterranean Basin is another region where a large number of high-quality indicators of past RSL has been collected, it represents an excellent opportunity to test the global "exportability" of the latest ICE-7G_NA (VM7) model. This analysis is of substantial interest, as one may reasonably think of the Mediterranean Basin as providing similarly strategic complementary information concerning mantle viscosity structure and post-Last Glacial Maximum (LGM) deglaciation (in terms of the evolution of the nearby Northwestern Eurasian ice sheet complex and of the far-field influence of the Laurentide, Greenland and Antarctic ice sheets). This type of analysis directly benefits from the recent availability of a uniformly analyzed data set of geological and biological observations of past RSL evolution covering the Western part of the Mediterranean Basin (Vacchi et alii 2016).

Here, following Roy and Peltier (2018), we test the ICE-7G_NA (VM7) model predictions against high-quality reconstructions of past sea level evolution of Vacchi et alii (2016) for the western half of the Mediterranean basin (Fig. 1). We expand the discussion to include comparisons to other available data from the rest of the Mediterranean basin and from other key sites around the world from which high-quality data is also available. We focus on the most recent insights into the rheological properties of the Earth’s interior obtained from high-resolution RSL records from the U.S. East coast.

References


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BIOLOGICAL CONSTRAINS IN
PAST SEA LEVEL RECONSTRUCTION

Holocene algal rim at Acì Trezza, Catania, Sicilia, Italy

Chairs

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Improving mangrove proxies for sea-level reconstruction

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Keywords: Sea level, Holocene, mangrove, sedimentology, geochemistry, Pb dating.

Sea level reconstructions from low latitude locations over the past few thousand years tell us about global ice melt before the anthropogenic era (Milne et alii 2009).

Mangroves dominate coastal environments in the low latitudes, and generally accumulate sedimentary deposits in the upper half of the tidal range (Tomlinson 2016). Despite being an important far-field archive of sea-level change, mangrove sediments currently make poor sea-level proxies. Problems with microfossil preservation and a limited understanding of the sedimentation processes within mangrove environments makes interpreting these deposits challenging (Berkeley et alii; 2007; Woodroffe et alii; 2015). Our research aims to address some of these issues through a multi-proxy study of modern mangrove environments from the Seychelles archipelago in the Indian Ocean.

We seek to better understand modern mangrove sedimentation processes. A primary objective is to further investigate mangrove sedimentological sea-level proxies, using spatially and vertically-resolved particle size analysis, and by monitoring sediment accumulation rates through a mangrove forest. Here we present a dataset of surface sediment grainsize distributions and total organic carbon compositions at two mangrove locations on the island of Mahé, in the Seychelles archipelago. We also present preliminary estimates of contemporary mangrove sediment accumulation rates based on $^{210}$Pb chronologies and brick-dust marker horizons.

Figure 1. A) shows Seychelles archipelago location in the western Indian Ocean, and B) shows the location of two mangrove sites on the largest island, Mahé.
A second objective is to investigate new organic geochemistry sea-level proxies from mangrove sediments. We hypothesize that sea-level changes via their influence on salinity influence the environmental water composition of a mangrove environment over time, and therefore dominate the isotopic signature of plant lipid biomarkers. We present here preliminary results showing the distribution of lipid stable isotopes from mangrove surface sediments across a salinity gradient, which have potential to be past salinity and mangrove elevation proxies.

![Figure 2](image)

**Figure 2.** Site 1 (Barbarons): the mangrove zone is marked within the white dotted line. Orange circles are surface sample sites and blue lines are streams.

**References**


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\textbf{Holocene Relative Sea-Level Changes along the Northwest Cumbrian Coastline}

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\textbf{Keywords:} Cumbria, Holocene, sea level, foraminifera.

Three open coastal sites (Allonby, Cowgate Farm and Peletho) and one inner estuary site (Herd Hill) located along the northwest Cumbrian coastline and southern Solway Firth were investigated for Holocene relative sea-level changes (Fig. 1). Reconstruction of Holocene relative sea-level changes at each site was undertaken through detailed lithostratigraphical and biostratigraphical analyses, with high resolution foraminiferal analyses undertaken at all four sites. The chronology for the environmental changes recorded at each site was established through accelerator mass spectrometry (AMS) radiocarbon dating of selected samples and loss on ignition and particle size analyses were undertaken to aid in interpretation of the lithostratigraphical and biostratigraphical changes observed. Pollen analysis was also undertaken at Cowgate Farm and Herd Hill to provide a record of vegetation and environmental changes and act as a chronostratigraphic marker when compared to published pollen records of the region.

\textbf{Figure 1.} Location of the study sites at Allonby, Cowgate Farm, Pelutho and Herd Hill, marked in red. The contemporary saltmarshes utilised in this study are marked in black.
A local, foraminifera-based transfer function was developed in this study, which comprised of 72 contemporary foraminifera samples collected from three different contemporary marshes, namely Skinburness Marsh, Cardunock Marsh and Bowness Marsh (Fig. 1). In addition to the local training set developed in this study, regional (six sites), national (ten sites) and combined (13 sites) training sets were also utilised based on the available contemporary foraminiferal data for the United Kingdom (Horton and Edwards, 2006). For the fossil samples from Allonby, Cowgate Farm and Herd Hill, the national transfer function provided the most modern analogues, while the local transfer function provided the most modern analogues for the fossil samples Pelutho. However, the utilisation of transfer functions to reconstruct Holocene relative sea level at the sites was ultimately deemed unreliable, due to the poor preservation of calcareous foraminifera in the cores.

Ten new sea-level index points were produced in this study, constraining Holocene relative sea-level changes in the region between 8324 cal BP to 6018 cal BP. The general trend of relative sea-level changes recorded in this study is consistent with previous work done in the area (e.g. Huddart et alii, 1977; Lloyd et alii, 1999). It is likely that all sites have recorded the Main Postglacial Transgression, with Cowgate Farm and Pelutho potentially recording an earlier marine transgression as a result of the final drainage of the glacial Lake Agassiz-Ojibway in north-central North America.

The marine transgression recorded at Cowgate Farm (8200-8412 cal BP) now provides the earliest record of increased relative sea level in the region, and the date from Herd Hill of 5914-6179 cal BP now provides the second youngest date for the marine regression. The ten sea-level index points produced in this study have refined the trend of relative sea-level change for the coastal region situated between the southern Solway Firth and central Cumbria, where only one sea-level index point was available prior to this study. All sea-level index points produced in this study were obtained from intercalated samples and were corrected for compaction using geotechnical models, and palaeo-tidal changes were also incorporated into the calculations.

References

Reconstruction of spatial distribution and floral association of Holocene mangrove forests in Oman

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Keywords: Mangrove ecosystems, paleoenvironment, paleoclimate, sea-level change, Oman, Holocene.

We use sediments deposited within mangrove ecosystems as environmental archives. Such archives have the potential to study environmental changes in high resolution. The ecological boundaries of different mangrove species and associated organism are known and temporal as well as spatial variation of species composition can be used to quantify environmental factors such as temperature and salinity. Furthermore, the zonation within mangrove ecosystems clearly delineates the sea level (Woodroffe et alii 2016). Finally, mangrove ecosystems are known to have filter function as they trap fluvial sediments when they enter the sea. Hence, paleo-mangrove deposits can be used to identify pollutants within the coastal ecosystem. Preliminary studies have revealed the potential to identify heavy metals (Marchand et alii 2012) as well as microplastic (Nor and Obbard 2014). As mangroves are in decline worldwide, these pollutants may be released by erosion of the sediments.

Mangrove forests are sensitive ecosystems that can be found globally between 30° north and south fringing sheltered lagoons or coastal areas facing only little wave energy. Several species of plants are adapted to the intertidal zone. This zone marks the transition between the marine and the terrestrial realm. The species association is sensitive to changes in both: climate and sea-level. Therefore, these ecosystems are ideal archives that can be utilised to reconstruct environmental changes. We focus on the coastlines of the Arabian Sea in the northern Indian Ocean, specifically the shores of Oman and western India. Climate variability within our study area is linked to the Indian Monsoon circulation.

Figure 1. Sedimentary evidence for paleo-mangrove swamps as identified during recent field work. Whereas the lowermost dark units represent the mangrove swamps, the lighter upper ones are sabkha deposits.
The recent climate in Oman is arid and there are few mangrove forests. These are made up of only one species, *Avicennia marina*. This species is known to be the most tolerant in terms of environmental conditions. Archaeological and sedimentological evidence suggests that mangroves in Oman were more widespread and also enriched in species at the transition from Early Holocene to Mid Holocene (Berger *et alii* 2013, Lézine *et alii* 2002). Hence, either climate conditions were more humid at that time or sea-level was different. First field investigations were carried out along the shoreline of northeastern Oman in February 2018. A mapping of species association in shell middens is indicative for the environment exploited as a food source by early human hunters and gatherers. Occurrence of mangrove-adapted species like the gastropod *Terebralia palustris* verifies the existence of nearby mangrove forests at that time. Based on that we carried out shallow subsurface coring and trenching. Sabkha environments were the most promising locations for this. Here (Fig. 1-2) we identified fine-grained paleolagoon deposits of several metre thickness. First lab-results are promising, we currently carry out grain-size analyses as well as macro- and microfossil content. We concentrate on foraminifera and ostracods as they are known to be sensitive to ecological parameters like salinity, temperature, wave-energy etc. Species association will enable us to characterise marine paleoenvironmental settings. In addition to that we will conduct high-resolution pollen analyses on selected trenches to gain insight into terrestrial paleoenvironment and thereby into climatic conditions and variations. Our dating-approach is based on ^14^C-dating of molluscs and plant remains.

Next field campaigns will be carried out at the western Indian shoreline. By comparison to the Oman sites we expect to be able to reconstruct changes in the Indian Monsoon intensity and extend throughout the later part of the Holocene.

Figure 2. Fine grained lagoonal mud with remnants of mangrove roots were identified in various locations along the coastline of Oman.

References


Glacial isostatic adjustment (GIA) is considered the principal mechanism influencing variability in Holocene relative sea-level (RSL) in far-field tectonically stable regions such as the Sundaland of Southeast Asia (Fig. 1). The RSL record of Sundaland is characterized by a mid-Holocene RSL highstand coincident with decrease in meltwater input from large ice sheets. Predictions of RSL evolution from GIA models can be tested against field-based RSL reconstructions, and potentially be used to provide further constraints on the parameters controlling post-glacial recovery.

Here, we compare state-of-the-art GIA predictions with RSL reconstructions from Southeast Asia, focusing on Peninsular Malaysia, Borneo and select Indonesian islands in the South China Sea (Fig. 1).

**Keywords:** Southeast Asia, Holocene, relative sea level, glacial isostatic adjustment, far-field, coral microatolls, rock-encrusting oysters.

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**Figure 1.** Map of the SE Asia region showing predicted mid-Holocene changes in relative sea-level due to glacial isostatic adjustment (ICE-7G_NA VM7; Roy and Peltier, 2017) at 7,000 cal yr BP. Study sites (red dots) and the approximate boundaries of stable Sundaland (green dashed line) based on GPS observations from 1994 to 2004 (Simons et alii, 2007) are shown.
We use the ICE-7G_NA (VM7) model of Roy and Peltier (2017), which is a global GIA model that was constrained using both high-quality RSL records from the Atlantic coast of the United States and space-geodetic constraints on crustal motion over the North American continent. The model was further tested against a wide range of GIA-related observables from North America and from the Mediterranean basin. Our Holocene RSL records are based mainly on coral microatoll and rock-encrusting oyster proxies with vertical uncertainties from ca. 0.3 to 1.5 m (Fig. 2). Comparisons of eight sites on the relatively stable Sundaland enabled us to test the performance of this GIA model. For sites from more tectonically active northern Borneo, we used our GIA model predictions as an aid in isolating a potential tectonic contribution to the RSL record.

Figure 2. Examples of fossil coral microatoll (A) and rock-encrusting oyster (B) proxies that we use to reconstruct Holocene relative sea level in Southeast Asia.

References


IGCP Project 639
“Sea-Level Change from Minutes to Millennia”
Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
Taranto (Puglia) – Siracusa (Sicilia) 16 - 23 September 2018

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Vertical and lateral zonation of Foraminifera and Ostracoda in the German Wadden Sea – Establishment and first application of a transfer function for Holocene relative sea-level changes

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Keywords: Sea-level reconstruction, Holocene, German North Sea coast, transfer function, Foraminifera, Ostracoda.

The spatial variability of relative sea level (RSL) changes in the German Bight over the Holocene is not entirely resolved, hidden behind a plethora of different global to local driving factors, including vertical uncertainties associated with peat layers (indicative meaning, post-depositional compaction, no continuous data etc.), the most commonly used RSL proxy (Bungenstock and Weerts 2010). In light of rising seas and the anticipated future increase of the number of storm surge events (Woth et alii, 2006), however, detailed information on RSL histories and local controlling mechanisms is required to support future projections and to better prepare for future challenges in coastal protection. This study aims at deciphering Holocene RSL changes at the German North Sea coast in a higher vertical resolution by means of microfaunal assemblages and sedimentological data, especially for the last 2000 years where peat horizons do not exist. The study is embedded in the interdisciplinary WASA3 Project which aims at reconstructing the evolution of the Holocene coastal landscapes in the Wadden Sea area. Recent associations of Foraminifera and Ostracoda from low intertidal to supratidal settings in combination with environmental parameters (granulometry, C/N, TOC, salinity) have been investigated and quantified in vertical steps of 10–15 cm in order to generate a transfer function of RSL change. This was performed along two transects in the backbarrier tidal flat of the East Frisian island Spiekeroog (Fig. 1), which can be regarded as representative for the backbarrier settings of the East Frisian islands. The first transect is situated at the southern coast of Spiekeroog, while the second one covers the salt marsh and tidal flat on the opposite mainland (Harlesiel).

Figure 1. The study area. a: Overview map of the German Bight; b: Overview of investigated surface transects in the backbarrier tidal flat of Spiekeroog.

Transfer functions (TF) model the relation between elevation of sample points relative to mean sea level and relative abundances of foraminiferous species over time (Leorri et alii 2010). Ostracoda provide additional habitat and salinity information. Stratigraphical cross sections integrating archive and new drillings covering the backbarrier tidal flats and the near offshore of the island of Norderney provide important information on the fossil distribution of Holocene inter- to supratidal layers. This information is significant for the selection of newly taken sediment cores suitable for the application of the TF in order to elaborate a high-resolution RSL curve for the East Frisian Islands. Radiocarbon age estimates on peat layers will help to capture the chronological timeframe of the RSL curve. Our investigations in the south of Spiekeroog so far show a clear vertical zonation of foraminifer taxa between the salt marsh and the tidal flat (Fig. 2): Salt marsh samples contain similar numbers of Ammonia tepida, Haynesina germanica and the agglutinated marsh species Trochammina inflata and Entzia macrescens, whereas tidal flat samples are clearly dominated by H. germanica. Ostracods are more diverse and abundant in the lowest parts of the elevation transect. In the upper parts, they are rare and probably mostly allochthonous. Furthermore, local sandflat areas contain very few or no individuals at all suggesting an increased redistribution by the tidal current.

Three different TF models were derived for the indicative meaning (a: dead foraminifers only; b: dead foraminifers + ostracods; c: dead + living foraminifers + ostracods). Model a) provides a correlation value of 0.90 and an error of 25.8 cm, whereas the correlation of model b) lies at 0.93 and the corresponding error is 21.1 cm. Model c shows the best potential with a correlation of 0.99 and an error of 4.8 cm. A first application was tested on a core from the backbarrier tidal flat of Norderney situated at the rim of one of the main tidal channels. The core shows a basal peat (fen peat – related to the sea level) on top of Pleistocene sediments followed by lagoonal sediments characterised by typical salt marsh foraminifer taxa (supratidal). This layer is overlain by an intercalated bog peat, which is not related to the sea level. The upper limit of this peat is characterised by an erosional contact to the overlying tidal flat sediments (intertidal). The uppermost part of the core is characterised by another salt marsh layer, indicating that the recent surface must have been eroded or relocated due to the location at the rim of the channel.

The resulting curves of the TF show significant differences and even controversial oscillations especially for the upper ~1 m on top of the intercalated peat. The oscillations derived from the upper part of the core could be due to the relocation processes. Furthermore, compaction (especially of the peat) has to be considered. The curve resulting from model b) seems most likely due to the consideration of taphocoenosis, which gives a time average of seasonal effects influencing the microfaunal associations instead of only focusing on the season of sampling (living individuals). The additional use of ostracods actually enabled an improvement of the quality of the TF, but sediment cores for the application have to be chosen carefully with regard to local effects like compaction and relocation.

References
Seasonal distributions of salt-marsh foraminifera from Narrow River, Rhode Island, USA

Salt-marsh foraminifera are commonly used to reconstruct relative sea level. Similar to the vertical zonations of salt-marsh flora, assemblages of salt-marsh foraminifera are distributed into distinct vertical zonations. The strong relationship between salt-marsh foraminiferal assemblages and elevation within the tidal frame situate foraminifera among the most accurate sea-level indicators. Because of this, reconstruction of late Holocene sea levels from temperate locations are typically based on the identification and interpretation of fossil foraminiferal assemblages found in cores of salt marsh sediment.

In order to assign analogous paleo-marsh elevations to distinct fossil assemblages an understanding of the modern distribution and vertical zonation of foraminifera is required. This analogy is often established by sampling modern foraminifera on a single day (often in the summer field season) where it is assumed that instantaneous sampling of modern salt-marsh foraminifera is appropriate and sufficient to characterize the correlation between foraminiferal assemblages and elevation within the tidal frame. Nevertheless, seasonal variability of foraminiferal assemblages has been observed in multiple studies and sampling modern assemblages at a single time may or may not capture assemblages that are in equilibrium with their environment. This may result in the characterization of modern assemblages that are not typical of those found in a discrete sample of fossil sediment.

The potential implications of seasonality on foraminiferal assemblages and, therefore, reconstructions of sea-level change that utilize them, have been studied in the United Kingdom, Australia, the northwest Pacific coast of USA, and along the mid-Atlantic and Florida coasts of the USA but a lack of data exists for the northeastern coast of USA, where many sea-level studies have been performed. To assess this, we examined the role of seasonality on assemblages of foraminifera from a salt-marsh environment along the Narrow River, Rhode Island, USA. During a single year we analyzed living and dead assemblages of foraminifera, identified to species level where possible, from 48 samples, collected during each of the four seasons. Common species included Trochammina inflata, Jadammina macrescens, Tiphotrocha comprimata, Miliammina fusca, Reophax spp., and Haplophragmoides spp. Less common species included Siphotrochammina lobata, Arenoparella mexicana, Textularia spp., Ammobaculites spp., and Eggerella advena. Low marsh samples were dominated by Miliammina fusca and Reophax spp., while high marsh samples are identified by high abundances of Haplophragmoides spp. Statistical analyses of these samples will enable us to identify the influence of seasonality on modern foraminiferal distributions. The aims of this study at Narrow River are: (i) to identify patterns of seasonal variability in foraminiferal assemblages during a single calendar year; and (ii) to determine implications of seasonality for sampling strategies of modern foraminiferal assemblages for sea-level research based in the northeastern coast of USA.
Figure 1. (A) Location of Narrow River Marsh on the Rhode Island coastline, southern New England, USA. (B) Location of sampling stations (red circles) and tidal benchmarks (blue circles) at Narrow River Marsh. (C-G) Common foraminifera found in modern samples from Narrow River Marsh: (C) Milliammina fusca; (D) Trochammina inflata; (E) Jadammina macrescens; (F) Haplophragmoides spp.; (G) Siphottochammina lobate.

References

Crossing Southern Italy: a travelling meeting from Taranto to Siracusa
A microfaunal based sea-level indicator transferable to ancient Ainos (W-Turkey)?

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Keywords: Foraminifers, Aegean Sea, ancient harbours.

During our work in the Elaia, the former harbour city of ancient Pergamum, the absence of common sea-level indicators forced us to establish a new reliable indicator, which was found in the foraminifera associations in connection with the transgressive contact. The strength of this indicator is the exclusion of post-depositional compaction. Accompanied by a well-dated archaeological index point at a breakwater of the closed harbour basin, the micropalaeontological indicator enabled the establishment of a reliable regional sea-level curve (RSL curve) for the Bay of Elaia. It is in good agreement with other curves for the Aegean region and in general agreement with the glacio-hydro-isostatic model for the region. For the first time at a continental site on the Turkish Aegean coast our sea-level curve proves the today's sea-level peak (Seeliger et alii, 2017). In order to establish a RSL curve for the northern Aegean region we apply this indicator to the ancient site of Ainos (modern: Enez/ NW-Turkey).

Figure 1. Modelled RSL curve for the Bay of Elaia compared to other curves for the Aegean region. (a) Selected RSL curves for sites in the Aegean Sea as well as the modelled curve by Lambeck (1996) for the sea area west of Elaia. (b) Location of the study sites mentioned in Fig. 1a in the Aegean region. Same colours are used for each study site in Fig. 1a and b (Seeliger et alii, 2017).

References

Establishing a modern database of intertidal diatoms to reconstruct paleoequation land-level change

Coastal communities along the Cascadia subduction zone are at risk of flooding due to subsidence and inundation during earthquakes and tsunamis (Atwater, 1987; Witter et alii, 2003). Instrumental measurements and observational accounts are too short to identify the potential maximum magnitude (Mmax) and recurrence intervals of these hazardous events. However, coastal stratigraphy can record geologic evidence of great earthquakes and tsunamis on a centennial to millennial scale.

Some of the best reconstructions of earthquake subsidence and tsunami inundation are derived from the study of changes in microfossil (diatom, foraminifera, and pollen) assemblages preserved in coastal sediments because they provide precise estimates of environmental change. Diatoms are microscopic (5 μm to 200 μm), unicellular algae that thrive in nearly all aqueous environments (Admiraal, 1984; Palmer and Abbott, 1986). The siliceous valves of a diatom, and their unique morphological appearance, aid their preservation and identification in the sediments long after burial (Palmer and Abbott, 1986; Hemphill-Haley, 1996). Diatom preferences for environments with specific salinity and substrate characteristics are well documented and have led to the establishment of a salinity-based classification system (Denys, 1991, 1992; Vos and de Wolf, 1993). The distribution of diatom species along the intertidal reflect a vertical zonation of assemblages with respect to the tidal frame. For this reason, diatoms are suitable for use in environmental and relative sea-level (RSL) reconstructions.

Sea-level studies use modern and fossil diatom assemblages preserved in coastal sediments to reconstruct past RSL change (Palmer and Abbott, 1986; Shennan et alii, 1994; Zong and Horton, 1999). Using the key assumption that the modern relationship between diatom assemblages and their environment are unvarying through time, the distribution of the modern diatom assemblages with respect to the tidal frame serve as an analogue from which RSL reconstruction based fossil diatom assemblages can be derived (Juggins and Birks, 2012; Shennan et alii, 1996; Zong and Horton, 1999). However, the application of diatoms to RSL reconstructions is often restricted by the absence of a local or regional, quantitative modern diatom dataset tied to precisely leveled elevations.
We present the results of our local, quantitative modern diatom dataset that includes over 300 diatom species across 65 genera found at three tidal marshes located in Willapa Bay along the Cascadia subduction zone: (1) the Niawiakum River, (2) the Bone River, (3) the Naselle River (Fig. 1). Measured elevations cover tidal datums from 0.5 m above mean tide level to greater than highest astronomical tide. We apply results of the modern diatom dataset to a site located along the Niawiakum River where geologic evidence of multiple earthquake occurrences are preserved. Our analyses provide a reconstruction of past RSL change caused by subduction zone earthquakes during the past 2500 years.

References

Relative Sea-Level Changes along the Manila Subduction Zone Recorded by Coral Microatolls in West Luzon Island, Philippines

Recognized as one of the poorly understood subduction zones in western Pacific region, the 1500-km-long east-dipping Manila subduction zone is a potential earthquake generator that poses an imminent threat to coastal megacities and low-lying communities bordering the South China Sea (Fig. 1). While studies have been done to characterize the crustal structure, convergence rate, and current plate coupling of the Manila trench, little is known about its seismic potential. The Manila trench roughly parallels the west coast of Luzon Island, which is fringed by emergent paleo-reef terraces and fossil coral microatolls. Microatolls are geological proxies that record relative sea-level (RSL) changes and can be used to infer vertical deformation and strain accumulation along the megathrust through multiple seismic cycles. In this study, we are working to reconstruct past RSL and to understand the mechanisms underlying local and regional RSL change by examining coral microatolls in select localities in west Luzon. Ultimately, by combining these geological proxy data with geodesy, we hope to refine our understanding of the seismic hazards along the Manila trench.

Multiple generations of emerged fossil microatolls were observed along the coasts of Badoc and Cabugao municipalities in Ilocos Region. We collected slabs of fossil coral microatolls from three localities: Pagsanahan Sur, Sabang, and Salomague. The emerged fossil microatolls in Pagsanahan Sur and Sabang are all mid-Holocene (~7.8 to ~6.3 kyr BP) with the microatolls in Pagsanahan Sur at most 1.2 m above mean tide level (MTL) and those in Sabang standing at most 1.5 m above MTL. In Sabang, the fossil microatolls are at most 1.6 m above the modern highest level of survival (HLS) measured from small living microatolls in the area. Late Holocene fossil microatolls (~670 to ~880 yr BP) were observed in Salomague, about 2 km south of Sabang, and they were lower than the fossil microatolls at Sabang.

The fossil microatolls in the three localities are characterized by a cup-shaped morphology, which may suggest periods of gradual submergence interrupted by sudden emergence. Interestingly, we observed two sets of ages, the mid-Holocene and the late Holocene. The RSL pattern inferred from the mid-Holocene fossil microatolls could be explained by interseismic subsidence and coseismic uplift related to elastic strain accumulation and release along the Manila trench. The RSL signal recorded in the mid-

Keywords: Manila trench, paleoseismology, microatolls.
Holocene microatolls also includes a glacial isostatic adjustment (GIA) component, which we have yet to characterize, although models suggest that RSL during the mid-Holocene reached its peak after 7 kyr.

Meanwhile, the occurrence of one-thousand-year-old fossil microatolls at only slightly lower elevations that the mid-Holocene microatolls, as well as the absence of preserved coral microatolls in between these two age groups, suggests that there is little permanent vertical deformation retained since the mid-Holocene.

References

The role of the Sabellaria spinulosa reef in the coastal protection

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Keywords: Sabellaria spp., bioconstruction, worm reef, Adriatic Sea.

Polychaetes of the Sabellaria genus are able to create large and persistent bioconstructions (worm reef) in shallow marine environments. The polychaetes aggregate grains of sand to build massive reefs made up of millions of tubes in intertidal or subtidal environments. From a sedimentological point of view, Sabellaria bioconstructions can play an important role in the coastal protection by preventing the erosion of the beach and by stabilizing the sediments involved in bioconstructions (Naylor, 2005). Along the Gargano northern coast (southern Adriatic Sea) there is an impressive bioconstruction built by Sabellaria spinulosa, which is the first worm reef identified in the Mediterranean area of this species (Lisco et al., 2017).

In this work, the relationship between the presence of the Sabellaria spinulosa reef in the Torre Mileto area and the coastal erosion processes were analyzed to demonstrate the role of the reef in defending the coast. The Sabellaria bioconstruction starts to grow up on the Jurassic carbonate rocky substrates and, when the reef become stable, it spreads also on the adjacent sandy substrates. Moreover, along the sandy beaches close to the reef, granulometric analyzes have highlighted both the presence of numerous aggregates of different sizes in the coarser-grained classes (Fig. 1). This cohesive sedimentary material, which is supplied by the reef, accumulates along adjacent beaches located even after hundreds of meters. This sedimentary process increases the beach sediments grain size and the therefore the shear strength of the entire beach. Finally, the presence of the Sabellaria bioconstructions always induces a drastic increase of the time of permanence of the sands in a given beach as result of: 1) accumulation and cementation of sands in the reef, 2) successive erosion and formation of coarser-grained aggregates, 3) accumulation in the beach as pebbles, 4) reduction of grain-size for abrasion, 5) erosion and transport as single sandy grains.

In a beach that is subject to a severe coastal erosion, sands are subject only to the stage 5 and are directly carried out from the beach system.

References


Estimation of the reservoir age in the Mar Piccolo basin in Taranto (Southern Italy) by AMS 14C dating on Cerastoderma glaucum (Poiret, 1789)

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Keywords: Reservoir effect, C. glaucum, sea level change, Mar Piccolo.

The stratigraphic succession of the “Mar Piccolo” basin (Taranto, Southern Italy) is well known in the scientific literature dealing with last interglacial (Belluomini et alii, 2002; Amorosi et alii, 2014; Negri et alii, 2014) and its morphological evolution is influenced by sea level changes during Late Pleistocene-Holocene (e.g.: Mastronuzzi and Sansò, 1998).

In order to reconstruct the evolutionary model of the Mar Piccolo, as connected to the sea level rise, an Accelerator Mass Spectrometry (AMS) 14C dating campaign was carried out on Cerastoderma glaucum (Poiret, 1789).

C. glaucum is a benthic filter feeder mollusk that lives in waters characterized by different salinity values at various depths. In particular in the Mediterranean basin, C. glaucum, is associated with lagoons/inner basins environments. This means that it can be considered a sea level marker with max 2 meters of approximation (e.g.: Ferranti et alii, 2006; Antonioli et alii, 2009; Orrù et alii, 2014).

In literature, AMS 14C dating on C. glaucum are widely used in palaeo-environmental reconstructions though in lagoonal/basin systems large age offsets have been reported in different areas. These offsets can be explained as due to the combination of the marine reservoir effect (MRE) and hardwater effect (HWE) associated in the study area with freshwater flows coming from karst aquifer trough submarine springs, locally called “citri” (Fig.1).

Figure 1. (a) An example of Cerastoderma glaucum analyzed. (b) Localization of core samples and submarine karst springs (“citri”) areas (polygons in light grey).
In this study, 27 AMS 14C dating analysis carried out on C. glaucum sampled from different sediment cores up to a maximum of 30 meters from seafloor are presented. Only samples in physiological position with coupled valves were selected and analyzed.

The interpretation of the data was performed after the estimation of the local reservoir age calculated by analyzing live samples collected in 2017 (e.g.: Quarta et alii, 2007) and specimens sampled in the 1960’s and preserved at the Department of Biology (University of Bari).

The results show that for both the class of samples (2017 and 1960’s) an age offset ranging from 400 to 600 years can be estimated. The obtained results are connected to the chronological model of the sedimentary sequences for the Taranto area proposed by Lambeck et alii (2011).

This study was conducted within the framework of the Collaboration Agreement (ex article 15 of law 241/90) "Activities of common interest preparatories for the remediation, environmentalization and redevelopment of the Mar Piccolo of Taranto” between the Extraordinary Commissioner for Urgent Interventions of Remediation, Environmental and Regeneration of Taranto, University of Bari and the National Research Council.

References


EXTREME MARINE EVENTS:
TSUNAMI AND STORM SURGE

Wave impact on the Ionian coast of Torre Castiglione, Lecce, Puglia, Italy

Chairs

Gosta Hoffman, Jessica Pilarczyk
Coastal Evolution under Rising Sea Levels
and the impact on the Tsunami Hazard: A Theoretical Study

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Keywords: Coastal hazards, coastal evolution, numerical simulations.

Studies how sea level alters the future tsunami hazard are usually based on a static bathymetry, which is also known as the bathtub model. For the static bathymetry, sea-level change is the only process that changes the position of the coastline and near-shore water depth. However, coastal areas are not just changing due to sea level, there are a multitude of other processes that changes the overall geometry nearshore and onshore.

In this contribution, I study the impact of a dynamic bathymetry on the future tsunami hazard. In order to consider bathymetry that changes with time, I employ the model by Lorenzo-Trueba & Mariotti (2017) to simulate the evolution of a barrier-island-marsh-lagoon-marsh system. This model comprises of eight ordinary differential equations that describe the evolution of the different parts of the coastal system based on incoming and outgoing fluxes for the different subcomponents of the system. In my contribution at the conference, I will describe the different governing parameters in greater details. In this short abstract, I only focus on sea-level changes.

The governing equations of the model can be solved very efficiently, which makes it possible to use an ensemble approach to incorporate future sea-level change. RCP 2.6, RCP 4.5 and RCP 8.5 are utilized with (denoted DP 16) and without enhanced Antarctic contribution (denote K 14). In order to study the impact of the different sea-level scenarios, I employ pseudo realizations that are based on the percentiles of the different RCP scenarios from Kopp et alii (2017). It should be noted that these pseudo realizations have the same statistical properties as the realizations used in Kopp et alii (2017) to compute the reported percentiles.

The coastal system simulated with the model described above is part of a bathymetry that consists of a constant-depth portion and a sloping beach.

The earthquakes are placed about 2000-km away from the coast. The earthquake magnitude ranges from 7.0 to 9.0, and I applied 5 randomized depth below the ocean floor. The entire model framework consists of 6 sea level scenarios, 100 realizations per realization, and 11 different earthquakes with 5 different depth below the ocean floor. This makes a total of 330,000 individual model runs.

The tsunami evolution, including the inundation is simulated with the well-known tsunami code GeoClaw (LeVeque et alii, 2011). The tsunami-simulation output focusses on the maximum tsunami wave elevation offshore of the coastal system, the maximum tsunami-wave elevation passed the barrier island toward the mainland shoreline, and tsunami run up at mainland shore.

The tsunami hazard is linked to the minimum earthquake magnitude that causes the exceedance of given values for the maximum tsunami-wave elevations or run up. Compared to today (zero years), if the minimum earthquake magnitude, whose respective tsunami exceeds a given value, decreases then the tsunami hazard increases and vice versa. The barrier height is the most dominant parameter impacting the tsunami hazard. However, the lateral extents of the back barrier and mainland marshes are important as well because the marsh vegetation interacts with the tsunami flow and slows it down which reduces the maximum tsunami-wave elevation and run up.

As a teaser of the results, Fig. 1 contains the evolution of the dune height for the different RCP scenarios with and without advanced Antarctic contribution. We see that for the static bathymetry, the barrier height reduces quicker compared to the dynamic coastal system. For RCP 8.5 DP 16, a drowning of the barrier island takes place for some of the realizations toward the end of this century. It is also important to note that for RCP 8.5 DP 16, the barrier height does not fall below 1.5 m in the dynamic case. For RCP 4.5 and 2.6, the differences between static and dynamic bathymetry are less pronounced.
My contribution will also explore the effects of other climate-change impacts on the barrier-island-marsh-lagoo-marsh system and the respect influence on the tsunami hazard. The take-home message even just from looking at the barrier height is that the static bathymetry is not a good model to predict impact of climate change and sea-level change on the tsunami hazard. It should be noted that coastal evolution models are generally very poorly constrained, and there are neither validated nor verified in a strict theoretical sense.

Verification and validation of coastal evolution models are important, but equally important are the constraints that need to be applied. Better constrained coastal evolution models originate from a closer collaboration between those mainly focus on field studies and those mainly working on computer simulations.

References


Sedimentological evidence for large wave events in Oman

In this study, we aim at quantifying and determining recurrence intervals of tsunamis generated at the Makran subduction zone representing the boundary between the Arabian and Eurasian Plate. A long earthquake and tsunami history aids in understanding how a subduction thrust behaves beneath an accretionary wedge of unusually large volume. Evidently, the NE exposed coast of Oman has archived deposits of paleo-extreme wave events which can be interpreted as evidence for both: storms and tsunamis. We integrate field observations of these deposits with evidence from the archaeological record and combine them with thorough radiocarbon and OSL dating.

Block and boulder deposits

Large block and boulders are striking features in the coastal landscape south of Muscat. Our initial data (Hoffmann et alii, 2013) is extensively supplemented here, comprising of 41 dated boulders. The boulders are found along rocky coastlines with cliff heights not exceeding 8 to 9 m above mean high water (MHW); they are found 7 to 16 m inland from the cliff edge, reach a maximum volume of 45.6 m$^3$ and have a mass of up to 105 tons. Terrestrial laser scanning and aerial photography (Fig. 1) reveals two indistinct coast parallel ridges that are fining and wedging out landward. The top of the landward ridge is highest with its maximum point at 12.5 m above MHW. Locally, the boulders and blocks are imbricated and often incorporated in an unsorted fine-grained matrix of gravel and sand, together with coral and shell debris. The blocks and boulders are mainly angular, show heavily bio-eroded surfaces and are partly covered with remains of marine sessile organisms. Identified as such are oysters, barnacles, bryozoans and serpulidae. Their presence indicates an inter- to subtidal origin before dislocation which is seen as strong evidence for boulder movement by wave impact.

Figure 1. Aerial photography and high resolution digital elevation models reveal the distribution of block and boulders. The ages of boulder movement are on sessile marine organism and given in calibrated years BP.
Radiocarbon ages obtained for the marine shell remains attached to the blocks and boulders cover the last 7600 years, with two pronounced clusters identified around 1000 cal. yr BP and around 0 cal. yr BP. The spatial distribution is not random, as boulders with older shells are commonly located further inland, incorporated within the inland ridge, whereas the younger ones are concentrated in more seaward locations. Ages of 0 cal. yr BP are found for isolated individual blocks closest to the shore. The spatial distribution of blocks with different ages indicate multiple inundations by extreme wave events.

**Sandy Deposits**

Coast parallel sandy ridges show sedimentological evidence of deposition by extreme wave events as well. A small river outlet produces a cut bank in a ridge north of Fins (Fig. 2A). The ridge is discontinuous but can be followed for several kilometers along the coast; it is 3.3 m high. Gravel deposits were encountered at the base, overlain by medium to coarse sand with shells. This sequence represents a beach ridge. A distinct shell layer situated at 2.5 m above MHW is suspicious as it is not a typical beach deposit. The most common shell in this layer belongs to *Pinctada radiata*, a species that lives attached to hard substrata. The shells are often articulated and the mean shell size is ~6 cm. These observations are interpreted as evidence for a sudden dislocation from an offshore location. This interpretation is backed by the presence of well-preserved colonies of the worm snail *Thylacodes variabilis* which lives cemented to hard surfaces. These species construct delicate, irregular shaped shells, susceptible to mechanical damage when exposed to repeated wave action, which excludes deposition within the swash zone of a beach. Furthermore, coral fragments, barnacles, pebbles, cobbles and small boulders of up to 50 cm in diameter are incorporated in this layer.

The sedimentological characteristics of the shell layer within the coastal ridge point to inundation by an extreme-wave event. The timing of the event is constrained by dating of the deposits. OSL dating gives evidence for the deposition of the underlying beach ridge sediments from 6.5 to 2.7 ka. The event layer is dated to ca 1 ka by OSL and 1.5 ka by radiocarbon-dating of three articulated shells of *Pinctada radiata*.

Another profile in a coast parallel ridge with a suspicious layer was documented 100 km north in Athaibah. Here, a well sorted beach deposit is overlain by aolil sand that bears a shell layer 2.3 meter above MHW (Fig. 2B). Radiocarbon dating on two shells reveals depositional ages of around 800 cal. yr BP for the shell layer. While two OSL ages for the beach deposits from the lower part are around 1.1 ka, the results for all other OSL samples are inconsistent both internally and when compared to radiocarbon dating.

**Archaeological Evidence**

A temporary exposure in a construction site, located in a beach ridge in Seeb shows evidence of extreme wave impact as well. The site is 270 m inland from the shore, consists of 2.5 m of poorly sorted fine to medium sand, with incorporated shells, rock and coral debris, together with fish and mammal bones (Fig. 2C). Most of the shells are bivalves such as Cypraeidae, Strombidae and Conidae together with Turritellidae and Potamididae, in particular *Terebralia palustris*. Of the five radiocarbon ages on non-marine material, the lowest is treated as an outlier, but the others are around 1.0 ka cal BP. Anthropogenic remains comprise various types of pottery sherds. Silty intraclasts are documented at the base of the profile interpreted as erosional remnants of mud bricks.

*Figure 2. Coastal profiles from Oman. Numbers in Italics refer to calibrated $^{14}$C ages BP. The other numbers are OSL ages. A: Fins, B: Athaibah, C: Seeb.*

*Crossing Southern Italy: a travelling meeting from Taranto to Siracusa*
The archaeological finds are related to daily life including pottery, cooking pots and jar fragments. Turquoise-blue alkaline glazed pottery and white opaque-glazed ware bowls both date to the 8th to 9th century, and were imported from Iran and Iraq, respectively. Most abundant is sgraffiato decoration ware which dates to the 10th and 11th century. The sediment characteristics, the radiocarbon ages as well as the age of the artefacts indicate extreme wave impact around 1.0 ka BP.

Conclusions

The sedimentary archives as well as the coastal geomorphology along the Arabian Sea coastline indicates repeated inundation by extreme wave events in the last 7.5 ka. Both storms as well as tsunamis have to be considered. We conclude that the inundation events are infrequent and we suggest that the return period of extreme wave events capable of dislocating boulders and flooding large parts of coastal settlements are long (ca. 1000 years). This is around a magnitude larger compared to other megathrust earthquakes (Nelson et alii 2015).

Our results indicate that a large inundation event, interpreted as tsunami waves triggered within the Makran subduction zone, affected the shores of the Arabian Sea about 1000 years ago. The sedimentological, archaeological and historical evidence allow to conclude that the event was more severe than the 1945 tsunami that was caused by an MW 8.1 earthquake.

References


Shell layer along the Southern Gulf of Kachchh coastline: 
Geological evidences of 1945 tsunami along the Indian coastline?

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**Keywords:** Tsunami, sedimentary structures, grain size analysis, Java

On 28th November 1945, a tsunami originating from the Makran Subduction Zone, hit the Iranian, Pakistani, Omani and Western Indian coastlines (Pararas-Carayannis, 2006). The geological signatures of it, are yet to be discovered from the coastline other than Oman (Donato *et alii*, 2008). Here we report a 12 - 15 cm thick shell layer deposited in a palaemudflat environment along the Southern Gulf of Kachchh coastline explored using several short cores. The geomorphic setup suggest, it is a narrow active intertidal zone fringed by mangrove swamps and palaemudflats along with rocky coastline in vicinity. The site is close to mouth of Gulf of Kachchh, which is characterized by narrow intertidal zone with mangrove swamp followed by palaemudflat in landward side which is resting over Deccan Trap basalt. The sedimentology of the shallow core retrieved from the palaemudflats at an elevation of 2m amsl, suggest a 12 - 15 cm thick poorly sorted shell rich sand layer sandwiched between overlying (Thickness 8 - 10 cm) and underlying (Thickness 24 - 30 cm) mud layers (clayey silt horizons). The shell rich sand layer is spread for at least 220 m inland from the high tide line as it tappers on surface in its distal end. The shells are broken and having abraded surface. The shell rich sand layer shows a scour/erosion marks at the bottom contact with organic rich clayey silt horizon. The foraminifers are larger in shell layer compared to bottom layer of clayey silt. The grain size of the shell rich sand horizon, shows the presence of scattered granules along with coarse sand grains, indicating a bimodal particle size distribution. The grain size, sedimentology, geomorphology all point out to a extreme wave like conditions for the deposition of the shell rich sand layer (Morton *et alii* 2007). The absence of historical and instrumental record of large storms, along with the available AMS 14C chronology suggests that the event took place during the past few centuries, which hints at 1945 Makran tsunami being the only contender. The elevation and extent of the deposit sheds new light on the extent of 1945 tsunami event along the Indian coastline.

**Figure 1.** Tectonic setting of Northern Arabian Sea showing epicenter of 1945 tsunami and present study site.

**References**

Sea level and extreme waves in the Last Interglacial: open questions and research directions

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Keywords: Sea level, Last Interglacial, paleo storms, dynamic topography, GIA.

The Last Interglacial (LIG, 116-129 ka) was the last period in Earth’s history when atmospheric and sea surface temperatures were slightly warmer than today (Hoffman et alii, 2017; Turney and Jones, 2010). As a result, ice sheets were smaller and sea level was higher than today. This time is often regarded as an imperfect analog for a future warmer climate. The ‘imperfect’ notation refers to the fact that, while a future warmer climate will be forced by an increase of greenhouse gases, the Last Interglacial warmer conditions were caused by orbital forcings. Despite this, the LIG can be considered (as any past interglacial) as a ‘natural experiment in which climate boundary conditions varied considerably’ (Tzedakis et alii, 2009).

The only direct proxy for LIG sea levels are geological, sedimentological or biological sea level indicators. These are ubiquitous along the world’s coasts, and can be surveyed with high-accuracy using either leveling or differential GPS techniques (Rovere et alii, 2016) (Fig.1A). Despite decades of research on LIG sea level indicators (Fig.1B), two questions characterize Last Interglacial sea level reconstructions.

(1) How does uncertainty in field data and on estimates of tectonics, Glacial Isostatic Adjustment (GIA) and earth Dynamic Topography (DT) contributes to the total uncertainty on peak LIG eustatic sea level estimates?

The answer to this problem is complicated by the fact that recent studies highlighted that peak sea level estimates are affected by different sources of uncertainty. From the point of view of field proxies, the possibility that paleo tides and paleo waves were different in the Last Interglacial with respect to today has been recently suggested (Lorscheid et alii, 2017; Wilmes et alii, 2017), but the effect that this could have had on LIG sea level indicators has not been taken into account yet in interpreting sea level indicators. Recent studies show that, even at passive margins, tectonics might not be constrained within ±0.05 mm/yr, due to the combined uncertainties of GIA and sea level indicators (including age uncertainties) (Stocchi et alii, 2018). More uncertainties in GIA model predictions also stem from different ice histories, in particular with respect to the penultimate glacial maximum (MIS 6) (Dendy et alii, 2017; Rohling et alii, 2017). Moreover, DT has been shown to significantly affect the elevation of LIG sea level indicators, even at passive margins (Austermann et alii, 2017). All these uncertainties sum up in the calculation of eustatic LIG sea level, and they contribute to make the 6-9 peak sea level estimate (Dutton et alii, 2015) very uncertain.

(2) How well does field data support the possibility of a late-LIG sea level rise? And a mid-interglacial sea level fall?

Several studies suggest that the Last Interglacial was characterized by sudden meltwater pulses (Hearty et alii, 2007; O’Leary et alii, 2013). Other studies suggest that there was a mid-interglacial sea level fall, which would imply a significant ice sheet retreat (R. E. Kopp et alii, 2009). Uncertainties on field data interpretation, GIA responses and tectonics also affect the answer to this question (Dutton and Lambeck, 2012; Whitney and Hengesh, 2015). Therefore, there is a need for more reliable field data at various locations, with high-resolution dating and objective interpretations based on modern analogs (Rovere et alii, 2016). We remark that the maximum sea level rise rates during the LIG are in the range of 10 mm/yr. In light of the current sea level rise rate (~3 mm/yr, Hay et alii, 2015) and the accelerating rates of ice loss registered from Antarctica (The IMBIE team, 2018), understanding the occurrence and source of catastrophic ice collapses in the LIG is not only a scientific, but also a societal priority.

(3) Was the LIG characterized, at least in the North Atlantic, by storms more intense than today?

Models (Hansen et alii, 2016) and proxies (Hearty, 1997; Hearty et alii, 1998) suggest that the North Atlantic might have been characterized by LIG ‘superstorms’, generating waves higher than those seen in historical times. It has been instead proposed that at least one of the proxies (mega-boulders in Eleuthera, Bahamas) could
have been the result of LIG hurricanes comparable to modern ones (Rovere et alii, 2017). Nevertheless, understanding wave intensity in the Last Interglacial will necessarily stem from the identification and quantitative study of new proxies for wave climate.

Looking into the future of LIG sea level studies, it will be necessary to reduce uncertainties on both geophysical models and field data. The combination of field data with hydrodynamic models simulating waves and tides in the LIG will allow to improve our knowledge on coastal processes.

References


Geomorphological and Sedimentological Impacts of Hurricane Irma on Anegada, BVI

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Keywords: Tropical cyclone, overwash, foraminifera, coastal hazards, post-event survey.

Land-falling hurricanes pose an economic and environmental hazard to coastlines of the Caribbean and Gulf of Mexico. Patterns of their frequency and intensity remain unclear in part because detailed long-term records are limited to only a few locations, but also because of uncertainties associated with interpreting the geologic record (e.g., preservation/erosion of older deposits, distinguishing between storm and tsunami deposition). The seemingly unprecedented generation of four intense storms during the 2017 hurricane season highlights the uncertainty surrounding the geographic and temporal controls on hurricanes in the Atlantic region. We improved upon this uncertainty by conducting a post-event survey of Anegada, British Virgin Islands (BVI) three months after Hurricane Irma tracked 35 km south of the BVIs as a Category 5 storm. During this survey we documented the coastal areas affected by Hurricane Irma in an effort to: (1) document the storm surge characteristics and associated sedimentary deposit of a known Category 5 hurricane; (2) assess the depth of scour and distance of sediment transport by storm surge; and (3) use the Hurricane Irma deposit as a basis of comparison with older overwash records, including a series of inferred tsunami deposits preserved within coastal ponds (e.g., Atwater et alii, 2017).

Hurricane Irma’s storm surge was mitigated by a fringing reef system that spans the northern shore of the island. We measured maximum flow depths of up to 3 m along the northern and western sides of the island. In most cases, storm surge inundation was limited (up to 30 m) by thick mats of grasses and low-lying shrubs along the coastline. Erosion was significant in the northwest where up to 15 m of shoreline retreat occurred and steep erosional scarps were present. Deposition was limited to thin (<40 cm) lobes of sand on the south, east and northeastern sides of the island.

The Hurricane Irma overwash deposits consist of well-sorted carbonate sand that is capped by an aeolian layer. Intertidal bivalves and gastropods were observed in Irma sediments on the southern side of the island, whereas faint laminations within the overwash sand were found in trenches along the northern and western coastlines.

Hurricane Irma sediments contain high abundances of the reefal foraminifera *Homotrema rubra*, a red organism that bleaches and rounds predictably following detachment from the reef (Pilarczyk and Reinhardt, 2012).

Figure 1. a) map of Anegada showing major geomorphological features. b) Detailed map of Red and Bumber Well ponds, each of which contain evidence for overwash. Modified from Pilarczyk and Reinhardt (2012).
The high concentration of vibrantly coloured *Homotrema* within the overwash sediments contrasts with overlying and underlying sediments, which contain bleached and edge rounded individuals.

The presence of non-bleached *Homotrema* in Irma sediments suggests that the majority of sediment was sourced from the fringing reef to the north of the island, whereas species such as *Calcarina mayori* and *Marginopora vertebralis* indicate that a smaller portion of the sediment was also sourced from the reef flat. Further analysis will statistically compare the similarity between the Hurricane Irma sediments with those deposited by Hurricane Earl in 2010 and a series of paleo-overwash layers of inferred tsunami origin. Constraining the origin of overwash deposits at this location is essential to the establishment of effective coastal hazard mitigation policies.

References


Energy balance to transport massive boulders on rocky coast area

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Along the Italian rocky coasts it’s possible to recognize deposits made up mainly of boulders, isolated or accumulated in fields and berms (Mastronuzzi and Sansò, 2000, 2004; Mastronuzzi et alii, 2007), at elevations and distances variables from the shoreline. These singular geomorphological evidences are connected to extreme marine events such as storm surge that are frequent on rocky coast of Apulia region.

During a storm event, a high energy flux is produced, to allow the transport of boulders along the coast in different scenarios, like subaerial, submerged and joint bounded (Nott, 2003; Nandasena et alii, 2011). Evaluating energy flux needed to move boulders respect the energy flux deriving from a storm, it’s possible quantify the number of waves needed to move the boulders. Here an example of boulders transported on rocky coast is given by Torre dell’Ovo area, 45 kilometers south east of Taranto (Fig.1).

To do this, a geomorphological survey was needed to quantify all variables occurred in this dynamic process.

The main variables are the forces applied on the boulders:
• gravity, considering only the x-component applied for the boulder;
• friction forces, both in static and in dynamic conditions;
• water flow impacting the boulders.

To quantify the parameters determining these forces, laser scanner survey, calcarenitic samples measurements, video analysis have been conducted to evaluate the lithology, bulk density, a-b-c axis, A-axis direction, friction coefficients, volume and mass of the boulders (Fig. 2).

Figure 1. Rocky coast of Torre dell’Ovo; a) ubication of studied area; b) profile trace representative of area; c) profile of coast with evidence of boulders and geomorphological features.
In this geomorphological survey, the calcarenitic boulders were detached and transported from the shore platform, they have a weight comprise from 2 to 11 tons, while other bigger boulders have been detached and fallen seaward because the storm had not enough energy to move them. The energy flux to transport boulders has been estimated with Nandasena et alii, 2011, relationships for subaerial and joint bounded scenario. The water flow has been considered with wave data of AdB buoy of Taranto-Capo San Vito (buoy of Autorità di Bacino della Puglia) and wind data of AdB anemometer of Taranto for a storm event of 9-10 March 2010, chosen because had a bigger dissipation energy. A hydrodynamics analysis was made in Delft 3D to obtain the wave height in deep water of Torre dell’Ovo, the wave peak period and peak direction and to evaluate energy flux related to the storm surge. Comparing energy flux needed to transport the boulders with energy flux of storm surge, it’s possible to obtain the minimum number of waves needed to transport, that, for the boulders with a weight range from 1 to 3 tons, has a maximum value of 5892 waves, while for the bigger boulders a number of 45000 waves was estimated. Moreover a comparison with number of waves recorded at buoy (10800 waves for the event of 9-10 March 2010) has been made to validate the number of wave calculated to transport boulders and is evident that some boulders required a greater number of waves for their transport, so not all boulders were moved by storm surge but an event of greater energy was occurred.

References

Examples of high-energy deposits related to tsunami and storm waves in north-western Atlantic Moroccan.

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Keywords: Sedimentology, high-energy events deposits, tsunami, storms, Morocco.

The Institut Scientifique of the University Mohammed V (IS-UM5) is leading since 2008 a program for a new generation of Moroccan researchers on high-energy events.

The program aims at increase capacities of researchers, engineers and officials who conducive to earthquake and tsunami disaster sciences. The sedimentary record provides a promising key to reconstruct impacts of extraordinary waves. However, the differentiation between tsunami and storm surge deposits is extremely difficult, since most of their characteristics only indicate marine flooding. We until now, have about ten PhD students dealing with high energy deposits on the Moroccan coastal areas. The program includes training on inter-disciplinary research, sedimentology, mineralogy, geochemistry, etc.

This discussion-based training focuses on issues related to the use of scientific data, publication practices, international collaborative research, peer review, field school (Fig. 1). We discuss the most recent strategies to identify tsunami sand and mud deposits in coastal stratigraphy.

Multi - and transdisciplinary thinking are an important aspect of our education concept and are promoted in the paleotsunami deposits program. PhD students at IS-UM5 are supervised by a team of experienced scientists to ensure best possible guidance for their dissertation project. In addition, they can benefit from a large network of fellow PhD students from all over the world and from a range of disciplines.

With our educational activities, we closely cooperate with our partner institutions (national and international, and welcome trainees, PhD students and postdocs.

In order to pre-evaluate the local hazard, (i) potential tsunami triggering mechanisms (local – regional – far-field), (ii) local and regional historical accounts (including historical documents/tsunami catalogues, interviews with contemporary witnesses, etc.) on the effects of tsunamis and severe storms, and (iii) extreme atmospheric conditions, have to be analyzed. A holistic study of the sedimentary environments within the area of interest is essential since it will determine the sedimentary record of any extreme wave event.

Local reference deposits from either recent or historically well documented tsunami or severe storm surges guarantee the safest conclusions and should be favored over a schematic application of global “tsunami/storm signature types”.

In 2008, observation of large boulders in the rocky Témara area similar to those described in Portugal and Spain and assigned to the 1755 tsunami (Scheffers et alii, 2005; Whelan et alii, 2005), encouraged the sedimentological studies of the rocky coasts of Rabat and Larache (Mhammdi et alii, 2008). In estuarine areas such as Larache, where fine sediments dominate, several thin shelly levels were found within muddy marsh deposits analyzing some cores drilled in 2004. The shelly levels were interpreted as typical tsunami deposition because of their internal architecture and their position far from the shoreline (Mhammdi et alii, 2015).
More recently, the persistent winter storms related to the North Atlantic barometric lows have also had tsunami-like dramatic effects on Western Europe including Portugal (Santos et alii, 2014) and on the Moroccan coast (El Messaoudi et alii, 2016), with huge damage (METP, 2014), sediment redistribution (Aouiche et alii, 2016) including sporadic large boulder transport (Belkhayat et alii, 2017). This new setting also triggered interest on studies on storms as an underrated short-term coastal hazard.

Future studies should focus on event historical research (i.e. improving catalogues of tsunamis and storms), and on more detailed and regular observations and monitoring of the coastal areas before and after winter storms using geomorphological, sedimentological and remote sensing.

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