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Reconstructing past sea level through notches: Orosei Gulf

Nikos Georgiou[1], Paolo Stocchi[2], Alessio Rovere[3], Elisa Casella[4]

[1] University of Patras, University Campus 265 04 Rio Patras, Greece, ngeorgiou@upatras.gr
[2] NIOZ - Royal Netherlands Institute for Sea Research, Coastal Systems (TX), Utrecht University, P.O. Box 59, 1790 AB Den Burg, Texel, the Netherlands, Paolo.Stocchi@nioz.nl
[3]Leibniz Centre for Tropical Marine Research (ZMT), Fahrenheitstraße 6, 28359 Bremen, Germany University of Bremen, Center for Marine Environmental Sciences (MARUM), Leobener Straße 8, 28359 Bremen, Germany, arovere@marum.de
[4] Leibniz Centre for Tropical Marine Research (ZMT), Fahrenheitstraße 6, 28359 Bremen, Germany, elisa.casella@leibniz-zmt.de

A tidal notch with a maximum height of 10.5m and almost 60km of lateral extent was carved during the Last Interglacial (127-116ka BP) along the West-Sardinian coast, in the Orosei Gulf. We present the results of the detailed mapping of the Orosei tidal notch using the Structure from Motion – Multi-View Stereo (SfM-MVS) reconstruction method. Although its geometry is laterally constant, the notch depth differs due to local factors. Results of SfM-MVS reconstructions, together with local parameters, were used as input in a geometric model that simulates the notch shape based on randomly sampled relative sea-level curves. The modeled profiles best matching with the real shape of the notch are those characterized by a bimodal geometry. Extracting information from this rocky imprint is considered crucial to better understand past changes in sea level, which are in turn significant to better gauge sea-level variations in warmer climate conditions.

I. INTRODUCTION

Physical, chemical, and biological processes are responsible for the erosion of the carbonate rocky coasts of the Mediterranean Sea. These erosional processes have shaped the morphology of the rocky shorelines by leaving imprints such as tidal notches, especially in the Mediterranean and the Tropics [1],[2]. The Mediterranean Sea constitutes one of the most ideal places for studying paleo sea-level changes due to the microtidal regime and the low wave energy that allow the formation of very precise paleo-sea level and tectonic activity indicators (Fig. 1a) [3]. Relative sea level changes stem from the contribution of glacio- and hydro-eustasy, glacio- and hydro-isostasy, tectonic processes and sediment compaction and isostasy. Coastal geomorphological features that can be found in tectonically stable sites, can keep record of the combined eustatic and isostatic signals, thus providing insights into the past ice-sheets fluctuations and solid Earth rheology [4]. Orosei Gulf in Sardinia (Fig.1b) is considered a relatively tectonically stable site and is characterized by the presence of a continuous, lateral, 60km tidal notch (Fig.1c, 2) [5], [6]. Orosei tidal "fossil" notch is an imprint carved during the MIS 5e, a past warm period when the sea level was higher than the present one. Its shape consists of a double, smoothed notch that reaches the maximum elevation of 10.5m (Fig.2) [5], [7].

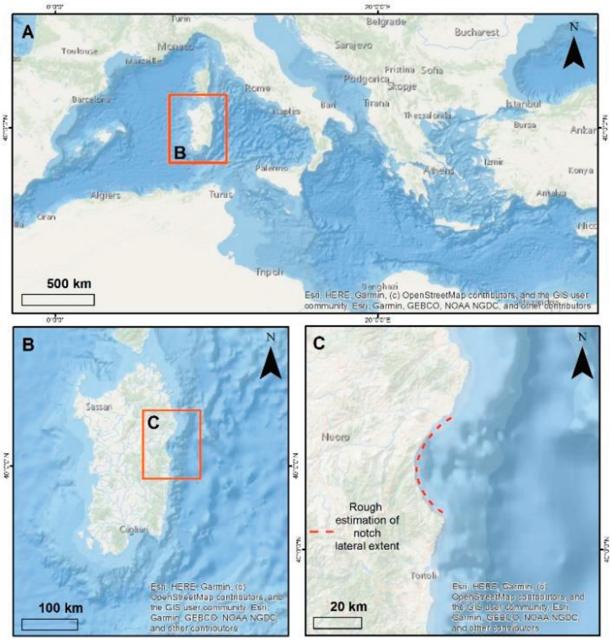

Fig. 1 a) Map of the Mediterranean Sea pointing out the location of Sardinia island, b) Map of Sardinia pointing out the survey area (Gulf of Orosei), c) Gulf of Orosei and roughly estimated indication of the Orosei notch lateral extent.

It is believed that the preservation of this imprint is owed to its burial by talus deposits during MIS4-2 glacial periods [6]. This publication describes the cost-effective and accurate methodology of SfM - MVS to reconstruct the 3D model of the Orosei notch. Also, the SfM - MVS results as well as local parameters were used as inputs in a geometric model used for notch reconstruction [8]. Thus, it was possible to reproduce a series of possible MIS5e local relative sea-level curves that simulated better the development and geometry of the notch.

II. MOTIVATION

This unique geological remnant is one of the best-preserved, tectonic-free, past sea level testimonies since the last time when sea level was at a higher level than today. Hence, detailed 3D reconstruction of the Orosei site by using advanced mapping methods is considered essential for the preservation of this finding but also the analysis of the morphological characteristics. This could give the possibility to scientists to reconstruct possible relative sea-level curves during the notch formation (~110-130 ka BP-MIS5e) through modeling.

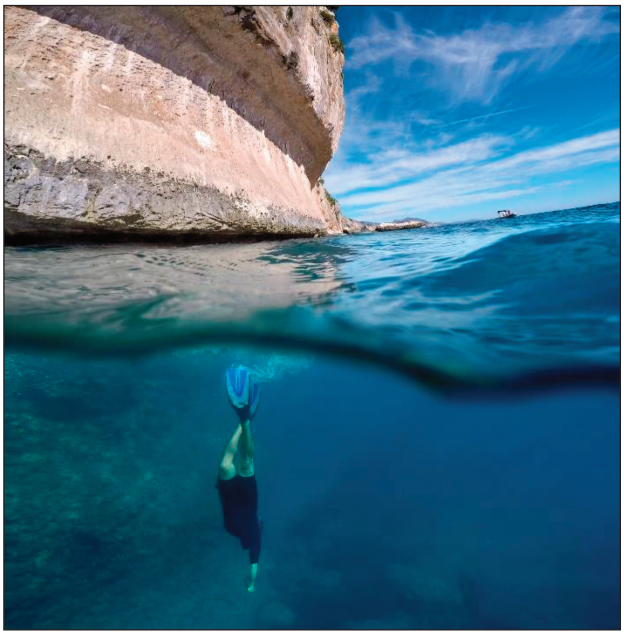

Fig. 2 Photograph of the Orosei notch and the subaqueous environment (diver:Paolo Stocchi, credits: Nikos Georgiou)

III. METHODOLOGY

A. SfM - MVS approach

To map the Orosei site, a field trip was organized during the summer of 2019 in Sardinia. Surveys along the lateral extent of the Orosei cliff were conducted by boat, in good weather conditions to avoid obstruction by waves and excessive ship motion, but also photograph the notch at its maximum exposure. A cost-effective method of 3D reconstructing the Orosei notch, which is generally an inaccessible area, is the SfM - MVS approach. SfM - MVS merges photogrammetric principles with advances in 3D computer vision algorithms [9]. The approach requires as input data a set of overlapping photographs of the study area. The photo shooting was operated onboard while keeping the vessel at a constant distance from the cliff. Stainless rulers-scale bars were manually placed on the notch to use them as scales for the reconstruction of scaled 3D models. A Canon EOS 77D camera with 55mm focal length, resolution of 6000x4000 pixel, and pixel size 3.84 x 3.84 μm was used for the process.
The post-processing of the data collected was performed using Agisoft Metashape (www.agisoft.com) software. Metashape generates 3D models and orthorectified images from overlapping photos. The first step of this process is accomplished through photo alignment using the SfM algorithm [10]. The algorithm produces a 3D point cloud of the surveyed area, the relative position of the photographs collected, and the internal calibration parameters (focal length, principal point location, three radial, and two tangential distortion coefficients)[11].

121 photos were used to build the ortho-mosaic and the 3D model shown in Fig. 3a. Photos were collected at a distance from the cliff of about (flying altitude) that the photogrammetry was performed is 60 1.1m. The resolution of the ortho-mosaic is 3.97mm/pix. The reprojection error is 1.02 pix, while the control scale bars error was estimated to 0.0046m. The area of the cliff that was mapped is 3070 m^2.

The 3D model was then interpreted in GIS software (ArcGis 10.1). Due to the great resolution of the 3D model produced (Fig. 3b), it was resampled to 1m cell size on the x axis and 0.1m on the y axis. Thereafter, vertical profiles were extracted from the 3D model at an interval of 1m (Fig. 4). The average profile generated by the extracted ones is named as Original Notch (**OrN**).

B. Notch modeling

The Matlab$^{®}$ code we used is originally set to generate repeated random relative sea-level curves at a selected time step (every 100 years) and within a specific time range (MIS 5e limits) using a Monte Carlo Simulation [12].

Thereafter, every random sea-level curve is used as an input in **Equation 1** [8], which is used to generate a modeled notch (**ModN**). Every ModN is then correlated with the **OrN** by using the standard deviation method. Every ModN that deviates less than 20% is then saved.

More specifically, the quadric polynomial equation and input parameters used for the construction of the ModN are described below:

$$\mathbf{d(z)= az^2 + bz + ER*dt} \qquad (1)$$

where **d(z)** is the depth of the notch indentation each time and **ER** is the erosion rate after 1 year (**dt**). Coefficient **b** is the gradient of the bedrock, where the notch is created and is set as zero in our case due to the vertical Orosei cliff. Coefficient **a** describes the curvature of the notch and is defined as:

$$a = \frac{\mathbf{ER*dt}}{(\mathbf{eb-zs1})\mathbf{x}(\mathbf{eb-zs2})} \qquad (2),$$

where **eb** represents the random sea-level curve generated for each iteration of the code. **Zs1** and **Zs2** are the roof and bottom of the notch and are expressed as extents of the tidal range: **zs1= eb-tide/2** while **zs2=eb+tide/2**. The code is set to run in a loop process until a user-defined number.

The parameters used for the code were selected based on the available literature regarding Sardinia Island and Orosei site. The modern tidal range, which is similar to that of MIS5e [13], was acquired by the Porto Torres and Cagliari tide gauge (https://mareografico.it) and is less than 0.5m.
Vertical tectonic displacement could be included in equation (1) as the extent of the modeled sea-level curve (eb). However, Orosei is embedded into a relatively tectonically stable area [6], [13]–[15], thus the tectonic parameter was considered negligible.
The massive Mesozoic carbonate units (limestones) of Orosei belong to the Monte Bardia Formation that consists mainly of steep cliffs, thus the gradient of the cliff is set to zero (**b**) [16].
Different annual erosion rates were tested during the notch modeling, which ranges between 0.001-0.32mm/yr based on [17] who performed measurements using micro-erosion and traversing micro-erosion meter on a vertical limestone slab in the Gulf of Trieste.

IV. RESULTS & DISCUSSION

A. SfM - MVS reconstruction

SfM - MVS reconstruction is a cost-effective and valuable tool [18] for mapping inaccessible and remote areas with high precision. The best-preserved part of the Orosei notch was mapped for the first time in great detail, thus an ortho-mosaic and a 3D model were created (Fig. 3a,b). The notch mapping showed that the geometry of the indentation consists of a double notch. The lower and more extended one is a smoothed curve that begins from few centimeters above present sea level and ends at about +8.5 m height (Fig.4). The first 4m present a gradient of 27-50° while from +4 to +8m height the inclination increases significantly presenting a maximum of 85°. The upper notch is significantly smaller and is confined from +8.5 to +9.6m height. Although there is a general trend in the notch geometry, the indentation depth varies along with the lateral extent. The floor of each vertical notch profile begins from almost the same position (0,0) but the maximum concavity depth, as well as the notch roof depth, varies from -3.8 to -7.8m depth and from 0 to -6m respectively (Fig. 4).

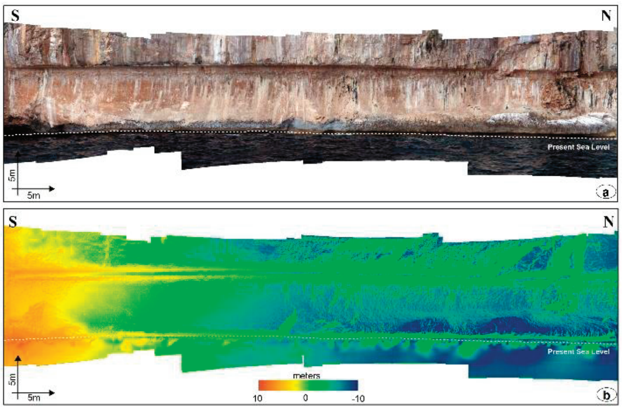

Fig. 3 a) Part of the ortho-mosaic of the Orosei notch, b) 3D model as derived by SfM-MVS method.

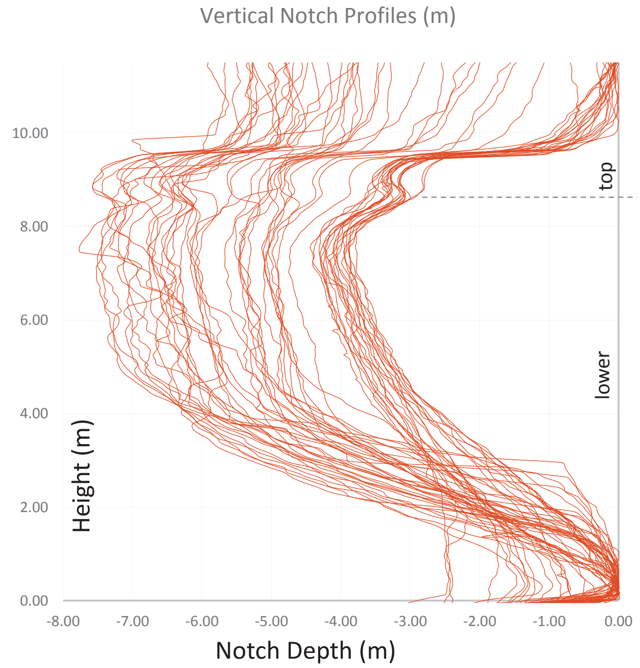

Fig. 4 Vertical Orosei notch profiles as derived after the GIS analysis.

This result confirms that notch morphology is affected by a variety of site-specific factors. While regional and climatic induced factors mostly affect the relative sea-level (RSL), local factors can also contribute to the notch geometry especially in tectonically stable areas [19] (e.g fractures, geomorphology, and at lower rate mineralogy [20]).

For example, the presence of a boulder in front of the notch could shift the local hydrodynamics (wave regime) and as a result the weathering rates. In addition, processes volcanic intrusions or tectonic displacement (e.g. continental margin down-faulting, contractional uplift) may have also played an important role on this consistent crust [13].

B. Notch Modeling

To avoid a misleading result in the notch modeling due to the different indentation depths of the notch, the average depth value of each elevation at a 10 cm interval was used as the OrN, while the minimum and maximum depth values for every elevation that derived from photogrammetry (Fig. 4), were used as the standard deviation limits.

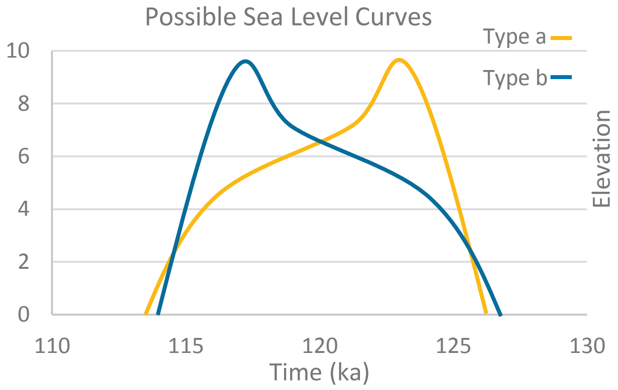

Fig. 5 Successful bimodal modeled Sea Level Curves (Type a,b)

Every time, the Matlab code was set to run as a loop for 100.000 iterations, while different values of erosion rate and tidal range were tested. It was observed that different values of the parameters might result in similar notch geometry, thus in similar sea-level curves as also described by [19]. The first results from the modeled notches that fulfilled the criteria set by the authors (ModN matches more than 80% with the OrN), originated from hundreds of random sea-level curves that could be summed in two types of sea-level curves (Fig. 5). The two bimodal curves presented in Fig. 5 are almost identical. They both present a high rise of the sea level up to ~+9 m height that lasted for a few years and a slowdown of the sea level which is observed from +7m to +5m. After that, the sea level begins to drop at a greater rate.

The difference between them is that the peak of the first sea-level curve (Fig.5a) at ~+9m is observed at an earlier period during MIS 5e and then it stabilizes at a lower level for few thousand years. The second type of sea-level curve (Fig.5b) performs the adverse course. It rises slowly up to +5m where the sea level rise rate drops and then reaches the peak of ~+9m at a later period than curve type ‘a’. Regardless of which type of sea-level curve is being used for modeling the notch, both of these curves can generate similar notch geometry.

However, curve type ‘b’ which proposes a later peak of the sea level at the end of MIS5e, coincides with modeled sea-level curves estimated for the Mediterranean Sea by [13] and also with sea-level curves estimated by uranium dated fossil coral reefs from the tectonically stable Western Australia [21]. The two different peaks at curve type ‘a’ and ‘b’ possibly reflect the melting imprint of each of the ground and marine-based ice-sheets (Greenland, West Antarctic).

V. CONCLUSIONS

The tidal notch at Orosei is an example of an erosional sea-level indicator that can supply information on the patterns of sea-level change in the Last Interglacial (MIS 5e). A detailed 3D model and an ortho-mosaic of the Orosei site were acquired by using the SfM - MVS approach, proving that this method is an efficient and cost-effective tool that can provide scientists with very accurate data even at inaccessible areas. Analysis of the notch data showed that local factors can alter the local erosional rate. However, the notch geometry remained unaffected along the mapped lateral extent. Orosei notch consists of a lower, smoother, and wider indentation that starts from a few cms above the sea level and reaches up to +8.5m height and a smaller indentation on the top part that continues up to +9.6m. SfM-MVS results were used as an input parameter in a notch reconstruction geometric model in order to generate the possible sea-level curves that shaped the Orosei notch. The first results showed that two types of bimodal curves simulated better notch formation. Both types of sea-level curves presented a high peak at +9m height that lasted few decades and a greater period of relative sea level slowdown between +5 and +7m. This showed that different sea level curves and also different parameters can produce similar notch morphology.

Curve type ‘b’ matched with already existing modeled and coral-dated sea level curves from relatively tectonically stable sites in the Mediterranean and Western Australia respectively.

This work also suggests that SfM-MVS reconstructions and notch profile modeling is a valuable tool combination for the relative sea level reconstruction. Yet, the effects of local processes should be taken under consideration.

Further work in this project is expected to supply more detailed sea level curves for the MIS5e period that can be compared to the MIS1 sea level fluctuation and to the climatic conditions that prevailed. It can be used to reveal the effect of the glacio-isostaty by the melting of the grounded and marine-based ice-sheets and as an analogue for future sea level change scenarios.

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