

New insight on the 1st century BC paleo-sea level and related vertical ground movements along the Baia - Miseno coastal sector (Campi Flegrei, southern Italy)

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Abstract – The study area is located along the western border of the Campi Flegrei (CF) caldera, occupied since the first Greek colonization of southern Italy (800 BC), and that still preserves archaeological traces of past coastal conformations. The study aims to present new additional data regarding the RSL position during the 1st century BC, considering also the accompanying changes of the coastal landscape and the implications in terms of human adaptation. By surveying the coastal sector between the modern Baia and Miseno, with a multidisciplinary approach by means of direct and indirect methods, a RSL at -4.0/4.2 m BSL related to the 1st century BC was detected through the measurements of the submersion of structural elements of three fish tanks. Comparing this value with the eustatic models in stables areas we can affirm that during the last 2100 years the coastal sector suffered an overall subsidence of about 3 m, which has caused a coastal retreat ranging between 50 and 150 m.

I. INTRODUCTION

The Campi Flegrei volcanic district is one of the most susceptible and dangerous area inside the Mediterranean region and during the Holocene was affected by sudden Vertical Ground Movements (VGM), called bradyseismic crisis, that caused strong variations in the coastal landscape [1][2]. Abovementioned VGM can be precursors of eruptive phases and whose older modifications of the Phlegrean coastal area are recorded

on La Starza marine terrace which was uplifted 30-40 m asl about 5 ka BP [3][4]. Instead, the historical ones are testified by several archaeological remains nowadays submerged.

The study of the VGMs arouses increasing interest in the international scientific community and in the last few years several researches have been carried out in order to identify the proper border of the caldera and to understand the different behaviours of its sectors. Currently the CF caldera and its surroundings areas are in uplift, with an average maximum deformation value of about 0.7 cm/month from July 2017 (<http://www.ov.ingv.it>), as precisely monitored by 30 permanent GPS stations distributed in the Neapolitan volcanic district [5].

In the study area only limited measurements of ancient VGM and related RSLs [6][7] have been made in the most famous submerged archaeological sites of the CF, leaving out many other archaeological targets scattered along the coast. Among these targets, the *piscinae* related to the maritime villas built along the CF coastal sector between the 1st century BC and the 1st century AD, are certainly the best markers for the relative sea level variations studies. This kind of structures can provide crucial information about the VGM affecting the CF caldera in the last millennia, but they also help to understand the coastal geomorphic response to these behaviours.

In this study, three Roman fish tanks located along the north-western border of CF's caldera have been carefully

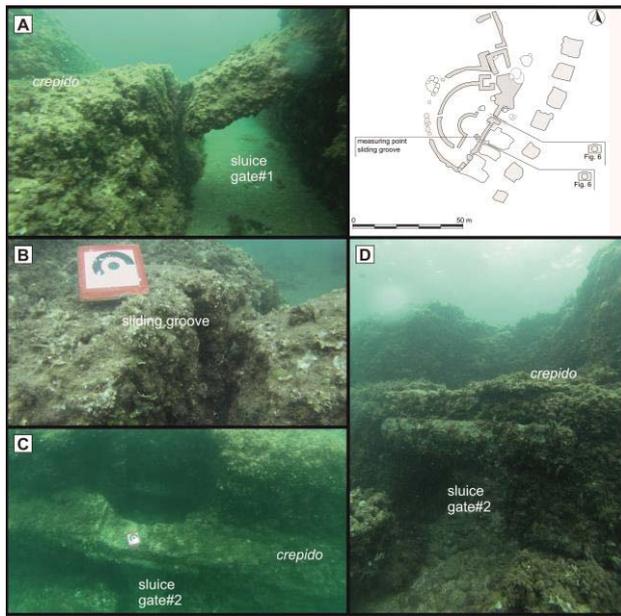


Fig. 1. Underwater photos of the Baia archaeological site

analysed to evaluate the relative sea level variation during the 1st century BC and the related coastal changes.

II. METHODS

A. Archaeological sea level markers: the fish tanks

During the last 50 years, the archaeological remains of the Roman fish tank built directly into the rock or on rocky and sandy coast (according to Varro and Columella) and located into the Mediterranean basin were used to investigate the RLS position during Roman Time [8]. There are three constructional elements directly linked to the sea level at the time of fish tank's construction [9][10]:

Crepidines: Foot-walks border surrounding the tank with a functional height about 20 cm.

Cataractae: Closing gates originally made of a lower horizontal stone flanked with two vertical posts with grooves to guide the vertical movement of the gate. The top of the sliding grooves was always located 20 cm above the highest tide level.

Channel system: Canals responsible for the tidally controlled water exchange.

B. Investigations and data corrections

The coastal sector was investigated with a multidisciplinary approach by means of direct and indirect surveys [11] and several on-site investigations were carried out by a team consisting of an underwater archaeologist and two geomorphologists.

The measurements concerned predominantly the *cataractae* and the *crepidines* and in order to obtain the submersion of the archaeological markers with respect to

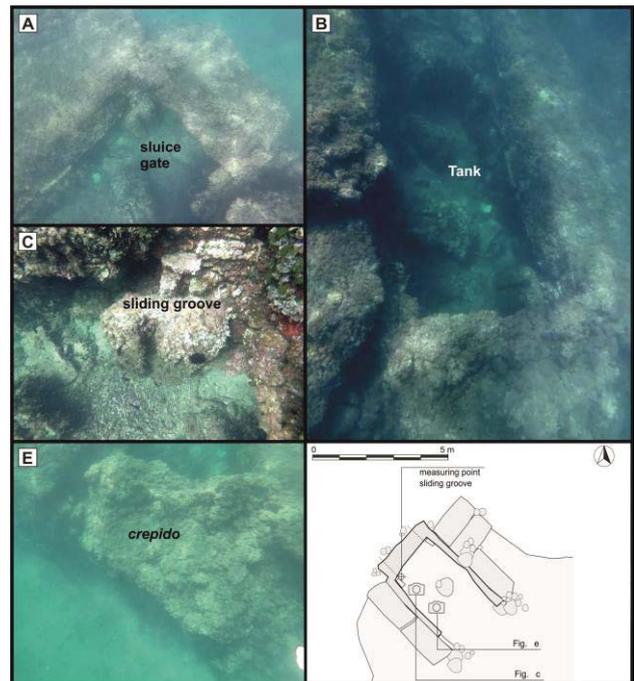


Fig. 2. Underwater photos of the Bacoli archaeological site

the MSL (S_{2018}) in the year, corrected with respect to tidal level (h_i) and the barometric condition (Δh_p) at the exact moment that the measurements have been taken, the LEONI and DAIPRA's formula (1997) was used:

$$S_{2018} = M + h_i + \Delta h_p \quad (1)$$

Secondly, the ancient RSL was determined through the formula proposed by Lambeck et al, 2018 by indicating with S_{2018} the submersion (in m) related to the present mean sea level and with T the local tidal range (about ± 0.2 m for the entire area of the Gulf of Naples):

$$\frac{\text{Threshold}}{S_{2018} + T/2} \quad (2)$$

$$\frac{\text{Lowest Crepido/Top of Sliding Grooves}}{S_{2018} - 0.20 - T/2} \quad (3)$$

C. Geomorphological and GIS analysis

Geomorphological and geoarchaeological data were analysed and overlaid by using GIS software. In the first instance, LIDAR (Ministry of Environment, 0 – 200 m asl) and bathymetric (CARG project, 0 – 20 m BSL) data were interpolated in order to obtain an accurate onshore-offshore DTM, with 1x1 m cell size. Matching archaeological informations with geomorphological analysis, we were able to distinguish between natural landform and anthropic shapes and retrace the ancient coastline position related to the time of the sea level markers' construction. The DTM calculation provided a high-resolution 3D view of the emerged – submerged

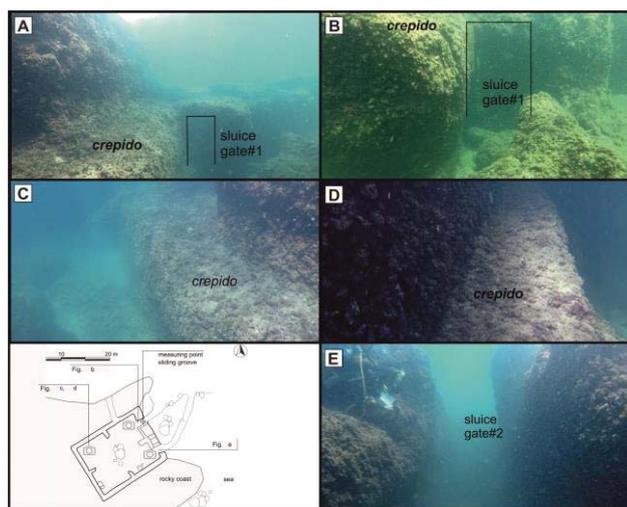


Fig. 3. Underwater photos of the Miseno archaeological site

landscape useful to detect traces of former sea levels, to positioning the archaeological structures nowadays submerged.

Moreover, at Baia -where the archaeological structures are well preserved- a side scan sonar morpho-acoustic survey was carried out.

III. RESULTS

A. Baia

The fish tank linked to the properties of Cesar in Baiae, built during the 1st half of the 1st century BC (Fig. 1) shows an external wall crossed by four *Cataractae* and protected by 7 pilae and an outer perimeter with a semi-circular shape and a maximum radius of 25 m.

The top of the sliding groove of the better-preserved cataracta is actually located at -3.6 m MSL (Table 1). By correcting this measurement with respect to Formula (1), a RSL at -4.20 m BSL was deduced.

B. Bacoli

The rectangular tank (Fig. 2), related to the presence in Bacoli of the roman lawyer Hortensius Hortalus, has a length of 7.0 m, width of 2.5 m and a bottom located at -4.5 m BSL. By correcting with the Formula (1) the measurement of the preserved sliding grooves, located at a depth of -3.56 m, a RSL at -4.0 m BSL was deduced (Table 2) and precisely dated by the historical sources at 70-50 BC.

C. Miseno

The 15 m x 12 m rectangular tank at Punta Terone (Fig. 3), caved directly into the Capo Miseno Tuff sea cliff and probably built together with the construction of Misenum military harbour (30- 10 BC), shows the inner *crepido* today located at -3.0/-3.2 m MSL and the remnants of the grooves of a former sluice gate actually located at -3.8 m BSL. By correcting this measurement

using the (1) Formula, a RSL at -4.2 m BSL was deduced (Table 3).

Table 1. Table of RSL measurements carried out at Baia

Measuring Point	Submersion [m]	Corrections [m]	RSL [m]
Top Sliding Grooves	-3.80	0.40	-4.20

Table 2. Table of RSL measurements carried out at Bacoli

Measuring Point	Submersion [m]	Corrections [m]	RSL [m]
Top Sliding Grooves	-3.60	0.40	-4.00

Table 3. Table of RSL measurements carried out at Punta Terone

Measuring Point	Submersion [m]	Corrections [m]	RSL [m]
Top Sliding Grooves	-3.80	0.40	-4.20

IV. DISCUSSION AND CONCLUSION

The first result obtained from the analysis of direct measurements, together with a detailed photographic documentation of considerable importance for each archaeological site (Fig. 1,2,3), along with morpho-acoustic interpretations was a precise evaluation of the 1st century BC RSL along the coastal sector between Miseno and Baia. In fact, by measuring the submersion of the top of the sliding grooves of each sluice gate, the relative sea level during the 1st century BC (period of maximum anthropogenic occupation of CF coast) was measured between -4.0 and -4.2 ±0.20 m asl. The accuracy of this evaluation is ensured by an almost absent temporal uncertainty, related to the accuracy of the historical sources, and the quality of the adopted sea level indicators with a vertical uncertainty of just 0.20 m;

Taking into account that the altimetric range between the three measurements varies within the value of the vertical uncertainty, a period of relative sea level stand can be assessed for the most of the 1st century BC.

By comparing the 1st century BC RSL measured in this study with the eustatic SLs proposed from GIA models, we can affirm that in the last 2100 years the study area suffered the effects of a net volcano-tectonic subsidence ranging between 2.95 and 3.11 m exacerbated by an eustatic sea level rise of 1.15 m described by GIA models

[12][13]. Furthermore, the original position of the coastline during the same period was reconstructed through the overlay between the georeferenced geoarchaeological data derived from the direct surveys, the morpho-acoustic data derived from the indirect surveys and the three-dimensional topographic data obtained from both the Lidar and the Multibeam measurements. This reconstruction demonstrated that the joined effects of the volcano-tectonic subsidence and the eustatic sea level rise produced a coastline retreat ranging between 50 and 150 m till now.

This result underlines the complexity of the VGM and related morphological responses within the Campi Flegrei, highlighting significant differences compared to the framework of knowledge so far acquired, and demonstrating the variability of VGM between the borders and the centre of the caldera. In fact, above all, in the central sector between Pozzuoli and Baia, several authors [4][14] hypothesize a relative sea level rise between the 1st century BC and the 1st century AD from -7 to -10 m, which does not emerge from our measurements along the caldera border.

In conclusion, it is possible to affirm that the coastal sector between Baia and Miseno during the last 2100 years was affected by VGM that led to a resulting total subsidence of about 3.0 m.

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