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Evidence of relative sea level rise along the coasts of central Apulia (Italy) during the late Holocene via maritime archaeological indicators

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ABSTRACT

We investigated archaeological sites located along the coasts of central Apulia (Italy) to estimate the relative sea level changes which have occurred in this region since the Bronze Age, and test the most recent model of predicted sea level for this region. Surveys focused on six sites located on both the Adriatic and Ionian coasts of Apulia at the feet of the carbonatic Murge plateau, a tectonically stable zone as of the last 125 ka. The sites present the remains of ancient settlements, ranging from the Bronze Age (circa II millennium BC), to the Messapian and Magna Grecia Age (c. 2.5 ka BP), the Roman (c. 2 ka BP) and Middle Ages (c. 1 ka BP). The archaeological sea level markers investigated in these sites provided new insight into the history of the relative sea level changes which have occurred in this region during the last c. 3.3 ka BP. Data from 17 archaeological settlements from the above-mentioned sites, placed above or below the present sea level, were analyzed. The intervening relative sea level changes successive to their construction were estimated via the submergence of the functional elevations of significant architectural features related to the mean sea level at the time during which the settlements were functioning. The r.s.l. changes were estimated using detailed topographic surveys, tide analyses and/or hydrodynamic equations. Although not all archaeological markers allowed univocal interpretations, r.s.l. rise at about 2.25 ± 0.20 m as of the Bronze Age, and at least 0.90 ± 0.20 m in the last 2.0/1.5 ka was estimated. A comparison between the elevation of the marker and two different predicted sea level models seems to confirm a tectonic stability of the investigated region in the last c. 3.3 ka BP.

1. Introduction

The coasts of the Mediterranean Sea have been inhabited ever since prehistoric times, and still preserve evidence of ancient maritime installations and coastal settlements that all together testify the widespread occupation of the coastal areas, including those of Apulia. These archaeological sites can be used as indicators of the intervening sea level changes occurring after their construction; fortified coastal villages of the Bronze Age, as well as Messapic, Greek and Romans cities, harbours and fortifications witness the long-lasting life of the settlements up to the Middle Ages.

Anthropisation of the area was, in some cases, conditioned by the natural morphological changes of river mouths and of the coasts, with the eventual disappearing of entire settlements. These sites are currently the subject of shoreline and sea level studies based on geo-archaeological investigations, such as the one at the Roman harbour of Marseille (France), Leptis Magna (Libya), Troy, Miletus and Ephesus (Turkey), Baia (Italy), among others in the Mediterranean basin (Morhange et al., 2001; Goiran et al., 2005; Brückner et al., 2006; Marriner et al., 2006). In other cases, isostatic, tectonic and volcanic land movements, or natural and anthropogenic subsidence, interplayed causing the submergence or the uplift of coastal sites (i.e: Flemming and Webb, 1986; Pirazzoli et al., 1996; Sivan et al., 2001; Morhange et al., 2006; Antonioli et al., 2007, 2009; Stock et al., 2013; Anzidei et al., 2011a, b; 2014 and

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references therein). Exemplary is the case of Falasarna (Crete, Greece) that experienced dramatic co-seismic movements that uplifted the Roman Age harbour to about 8 m (Stiros, 2010). On the other hand, some coastal cities, such as that of Baia (Pozzuoli, Naples, Italy), were subjected to bradyseism that repeatedly raised and submerged the coastal installations subsequent to the volcanic activity of the Phlaegrean Fields (Dvorak and Mastrolorenzo, 1991; Morhange et al., 1999, 2006). Currently, flooding processes, apart from local effects, are a consequence of global changes, such as the eustatic sea level rise and the isostatic vertical land movements. The latter have been occurring since the end of the Last Glacial Maximum (LGM, i.e. 21 ka cal BP) (Lambeck, 2009; Lambeck et al., 2004a, 2004b; 2010a, b, 2011).

Along active tectonic coasts, the eustatic signal is hidden by vertical land movements; while, in those tectonically stable, it is possible to evaluate the eustatic contribution from the observed sea level rise, once the age of the submerged archaeological indicators is known. In the studies aimed to estimate the relative sea level changes, the geo-archaeological contributions play a key role, allowing the estimation of the intervening relative sea level changes along the coasts of the Mediterranean. Therefore, maritime archaeological surveys are crucial in the validation process of the mathematical models aimed towards the reconstruction of the predicted sea levels as a result of global or regional vertical deformations of the Earth's crust and mantle rheology (Lambeck et al., 2004a, 2011; Lambeck and Purcell, 2005).

In the perspective of the acceleration of sea level rise caused by global warming (Knauer, 2007; Veermer and Rahmstorf, 2009; Church et al., 2013; Kopp et al., 2016), and considering the vertical land movements that affect the active tectonic region of the Mediterranean basin (Serpelloni et al., 2013; Anzidei et al., 2014), the maritime archaeological sites play a key role in understanding the local and global causes of their submersion (Lambeck et al., 2004b). In this study, archaeological sea level indicators of coastal installations from the Bronze Age up to the Middle Ages, located between Bari and Taranto (Fig. 1), were used with the aim of collecting new data on the relative sea level changes which have occurred along these coasts during the last c. 3.3 ka. Results were coupled with the most recent interpretation of previous archaeological studies (Auriemma et al., 2004, 2005; Scarano et al., 2008; Alfonso et al., 2012), and with the comparison of the most recent sea level prediction models (Lambeck and Purcell, 2005; Lambeck et al., 2011). Our data will support previous results and new studies on: *i)* the relative sea level rise which occurred during the Holocene in the Mediterranean, and *ii)* trend and rates of vertical tectonics for the Apulia region.

2. Geological and geographic settlements

The Apulia region is a NW trending ridge of continental crust running from central Italy to offshore Greece that constitutes the SW margin of the Adriatic plate (Doglioni et al., 1994, 1996), which is placed in the complex geodynamic basin of the Mediterranean (Serpelloni et al., 2007, 2013). It represents the foreland domain of the southern Apennines to the West and the Dinarides to the East. This region displays a low tectonic activity level (Chiarabba et al., 2005; Battaglia et al., 2004) and was affected by crustal differential uplift and down-lift during the Pleistocene, up to the late Pleistocene (i.e.: Hearty and Dai Prà, 1992; Ferranti et al., 2006; Di Bucci et al., 2011; Mastronuzzi et al., 2011 and references therein).

The surface geology is characterised by the outcropping of a 6 km thick carbonate platform that developed during the Mesozoic, partially overlapped by calcarenite and clay units of the Plio-Pleistocene. Along the coasts, marine terraced deposits outcrop extensively in transgression on the Mesozoic and Plio-Pleistocene units. They are the result of the superimposition of both glacio-eustatic sea level changes and regional uplift, drawing a staircase of marine terraces, recognisable between a 160 m elevation and the present shoreline, which marks the local coastal landscape. Some display a thin sedimentary body composed of calcareous sandstones (locally named *panchina*). In some places, they are associated with dune deposits, whereas others are only abrasion platforms. The last interglacial marine terrace contain Senegalese fauna and fossils of *Persististrombus latus* (Gmelin) marking the oldest deposits of the last interglacial, correlated to the Marine Isotope Substage 5.5, of c. 132–116 ka BP (Ferranti et al., 2006), and allow the estimation of the long-term crustal uplift. The uplift of the Apulian foreland (Doglioni et al., 1994, 1996; Di Bucci et al., 2011) decreased, during the MIS 9.3, of c. 330 ka (Mastronuzzi et al., 2007). Since then, a detailed estimation of the Late Pleistocene uplift has been available only for the Taranto area, calculated at about 0.13 mm/yr. This has been given by the LIT (Last Interglacial Time) deposits (Amorosi et al., 2014; Negri et al., 2015) that decrease to zero in the southernmost part of the region (Ferranti et al., 2006; Mastronuzzi et al., 2007, 2011 and references therein). Therefore, based on these data, an overall tectonic stability of the coastal area of the Murge as of the last 125 ka BP (Ferranti et al., 2006; Antonioli et al., 2009) has been inferred. On the other hand, a few selected geomorphological and archaeological indicators would seem to suggest a very slight subsidence during the Holocene along the Adriatic coast of Apulia, even if some stable areas can be identified (Mastronuzzi and Sansò, 2002; Lambeck et al., 2004a; Antonioli et al., 2009). Unfortunately, the available data are insufficient to discriminate and detail different tectonic behaviours in Apulia, with the exception of the Gargano promontory (Patacca and Scandone, 2004; Piccardi, 2005; Ridente and Trincardi, 2006; Nicolai and Gambini, 2007; Anzidei et al., 1996).

The areas investigated in the present study are located in the central part of the Apulia region, namely the coastal area located at the feet of the Murgia carbonatic plateau where the Piana di Taranto and Brindisi, southward to the Soglia Messapica (Mastronuzzi et al., 2011). From a morphological point of view, they are characterised by the vast presence of gently sloping rocky coasts, inlets, and cliffs generally shaped on a sequence of: *i)* limestone/sandstone along the Adriatic side (Mesozoic Calcare delle Murge and Plio-Pleistocene Calcarenite di Gravina units); or *ii)* sandstone/packstone along the Ionian side (Calcarenite di Gravina and Pleistocene marine terraced deposits units).

The coastal archaeological sites described in this study (Fig. 1) have been partially submerged during the last three millennia circa. Indeed, about 20 ka ago, the sea level was about 130 m below its present position (Lambeck et al., 2004a) and only about 6 ka BP did it rise up to a few metres below its present level (e.g. Lambeck et al., 2004a, b; Auriemma et al., 2004, 2005; Antonioli et al., 2009). The last 6 ka have been characterised by slower rates in sea level rise. However, in the last decades, the global sea level has been rising up to 3.2 mm/yr (Church and White, 2011; Meyssignac and Cazenave, 2012; Jevrejeva et al., 2014 and references therein), while in the Mediterranean, it has been rising at a rate of 1.8 mm/yr (Wöppelman and Marcos, 2012; Anzidei et al., 2014) as a result of global warming.

3. Materials and methods

The study surveyed 17 maritime archaeological artefacts, located in six different sites, providing significant markers for the relative sea level changes along the central coasts of Apulia (Fig. 1; Table 1). Data collection and analyses were performed through five subsequent steps: *i)* elevation measurements of significant maritime archaeological structure markers with respect to the sea level

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