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# Numerical approach to the study of coastal boulders: The case of Martigues, Marseille, France

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ABSTRACT

The coastal area extending east of the city of Martigues, between the bays of Bonnieu and that of Chariot, is characterized by an alternation of gently sloping rocky coast and 5 m high cliffs composed of Miocene limestone. The foot of the cliff is marked by a well developed notch and a discontinuous wave-cut platform; at its base, the sea bottom reaches a maximum depth of about 4.5–6 m. The emerged area shows boulders placed up to 10 m inland of the coastline at around 2 m above s.l. and, weighing as much as 35 tonnes. A geomorphological survey was conducted by means of a Terrestrial Laser Scanner to estimate boulder sizes. The particular focus of the proposed study was to estimate the minimum wave height required to detach and transport two boulders, originally joined together as one bigger one and weighing approximately 25 tonnes, from the wave-cut platform onto the surf bench. Hydrodynamic models developed by various authors were used to calculate the minimum wave height necessary to move them. The data obtained from the resulting hydrodynamic equations were compared to wave-climate data collected over the last 15 years by the buoy off the coast of Marseille, in the Gulf of Lion. The present study seems to confirm that it would not have been necessary to have a tsunami impact (among other things, never recorded in the last 20 years) to move a 25 tonnes boulder. Indeed, hydrodynamic equations suggest that the boulder might have been broken and only subsequently moved due to the impact of waves generated by an extreme storm which would have occurred prior to December 2003. This hypothesis seems to be in agreement with the morphology of the sea bottom, hydrodynamic features of the area as well as eyewitnesses.



## 1. Introduction

In recent years, scientific debate on coastal dynamics has focused also on the effects of extreme wave impact on coastal areas, thus increasing the awareness of the high risks these impacts pose on all human settlements as well as on the environment. Indeed, examples of hurricane impacts which have occurred in the last fifteen years, inducing exceptional waves and devastating tsunamis, underline the fact that morphological effects cannot be underestimated neither in purely scientific terms nor in application to the Integrated Coastal Zone Management (ICZM) (i.e.: Mastronuzzi et al., 2013). In particular, an important field of science dealing with coastal morphodynamics studies large boulder accumulations distributed along the coastline of the Mediterranean basin as an attempt to reconstruct the sequence of the high energy event that distribute boulders along the coast using historical or chronological data (i.e.: Mastronuzzi and Sansò, 2000, 2004; Morhange et al., 2006; Mastronuzzi et al., 2006, 2007; Scicchitano et al., 2007; Maouche et al., 2009; Vött et al., 2010; Mastronuzzi and Pignatelli, 2012; Shah-Hosseini et al., 2013; Anzidei et al., 2014; Biolchi et al., 2016). The study of extreme waves impacting all along the coasts of the world over the past 25 years suggested that boulder accumulations are the consequence of impacts of both storm surges and tsunamis (Mastronuzzi and Sansò, 2004; Goto et al., 2007; Barbano et al., 2010; Bourgeois and MacInnes, 2010; Regnauld et al., 2010; Paris et al., 2010; Richmond et al., 2011;

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Jaffe et al., 2011, 2012). Unfortunately, a method by which it is possible to unequivocally identify the nature of the impact has yet to be found. Using the sizes and shapes of boulders surveyed along the coast, many authors developed hydrodynamic equations to build a model able to recognize the origin of their deposits (Nott, 2003; Noormets et al., 2004; Imamura et al., 2008; Pignatelli et al., 2009; Nandasena et al., 2011; Benner et al., 2010; Engel and May 2012). These hydrodynamic equations have been widely used by various authors to investigate the origin of past boulder accumulations in many coastal areas of the Mediterranean basin (i.e.: Mastronuzzi and Sansò, 2004; Shah-Hosseini et al., 2013; Biolchi et al., 2016).

In particular, the rocky Mediterranean coast of Southern France, along the coastal area of Martigues, near Marseilles (Fig. 1), is characterized by the presence of large boulders placed at various distances from the coastline and and elevations above sea level, thus, testifying the impact of exceptional wave(s) that scattered boulders from the midtidal and subtidal zones (Vella et al., 2011) inland. The origin of the extreme events responsible for their transport and accumulation remains unclear, even though a series of surveys conducted, using classic, modern and even digital techniques (Shah-Hosseini et al., 2013) have attributed them to exceptional storms that occurred during the Little Ice Age (LIA). Nevertheless, the possibility that multiple events, including a tsunami, may have been the cause cannot be ruled out. Particular focus was placed on two boulders, "A" and "B", indicated by the local inhabitants as originating from a single one, "C".

In a previous paper, Shah-Hosseini et al. (2013) using the large presence of bio-encrustations as bio-indicators, reconstructed the four phases of the breaking and the transport of the initial boulder ("C" in this paper, but M7 in the original one): ì - detachment of the original boulder from its initial intertidal position; ìì - a submersion phase, attested by the development of Vermetids on the Lithophyllum bissoides encrustation; ììì - breakdown into boulders, M5 (= "B") and M6 (="A") followed by the overturning of the latter; ìv - transport of the block to the supratidal zone. With the main aim to confirm this geomorphological model by means of a digital and mathematical approach, a detailed laser scan survey of the two boulders and of the local topography was carried out together with a bathymetric survey of the coastal area right next to them. This allowed us to: ì —accurately reconstruct the present size of the boulders building their digital model; ìì - reconstruct their original shape; ììì — test the wave hydrodynamic equations developed by various authors to test their validity in a case study where the impacting wave is known to have been caused by a storm; ìv - reconstruct the sequence of events responsible for the breaking, transporting and depositing of the boulders.

## 2. Geographical, geological and wave climate settings

The present study was performed in an area located between the Bay of Bonnieu and that of Chariot, South of Martigues, near Marseilles, along the Mediterranean coast of France (Fig. 1). The coastal area is oriented northwest-southeast, and is characterized by a gently sloping rocky surface shaped in highly fractured bioclastic limestone. This Burdigalian marine limestone (Colomb et al., 1975) is characterized by bioclastic and pinkish conglomeratic calcarenite with *Chlamys*, *Ostrea* and *Pecten*, about 10 m thick overlying in discordance on Cretaceous (Urgonian) limestone. The outcrop is dense with faults and fractures presenting rough stratigraphic joints separating 50 cm to 2 m thick layers. Limestone beds gently dip to the southwest (<10°). Despite a lack of apparent finite

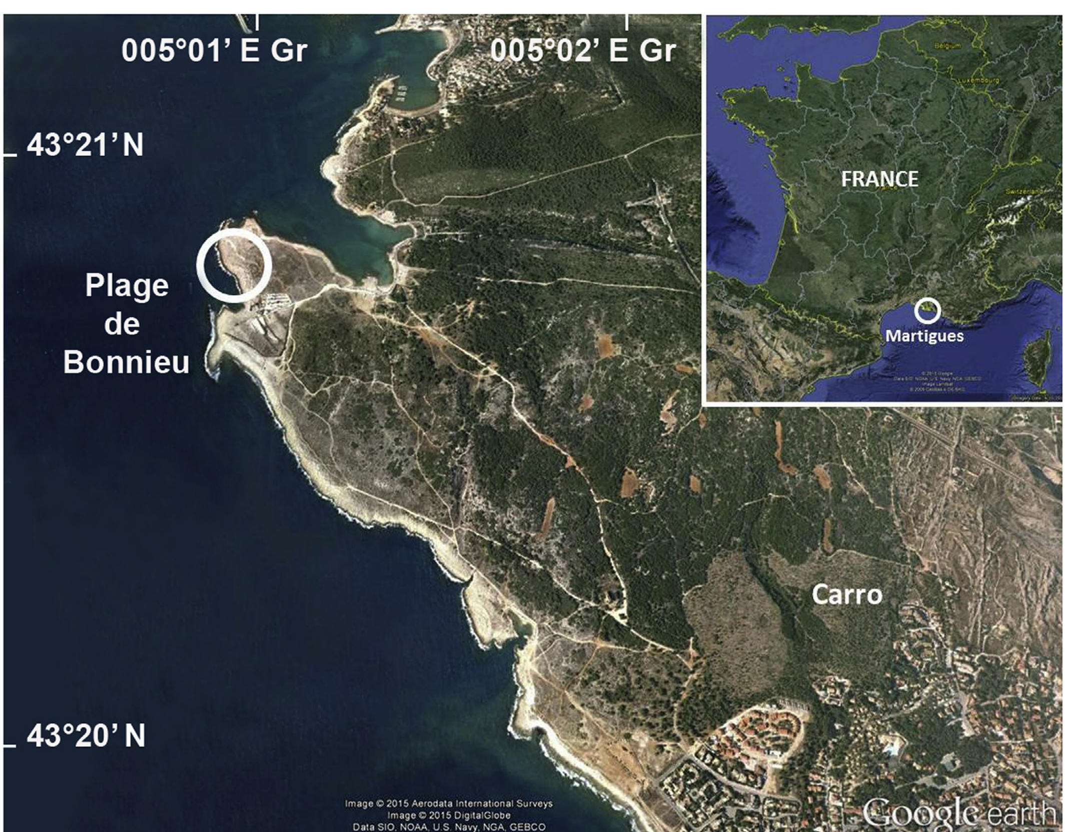


**Fig. 1.** Geographical position of the studied area (from Google Earth).

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