Millstones as indicators of relative sea-level changes in northern Sicily and southern Calabria coastlines, Italy

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ARTICLE INFO

ABSTRACT

New data are presented for late Holocene relative sea-level changes in two coastal sites of Sicily and Calabria, southern Italy. Reconstructions are based on precise measurements of submerged archaeological remains that are valuable indicators of past sea-level position. The archaeological remains are millstone quarries carved on sandstone coastal rocks and nowadays partially submerged which, to the authors' knowledge, are used for the first time as sea-level markers. Millstones of similar typology are located on the coast of Capo d'Orlando (northern Sicily) and Capo dell'Armi (southern Calabria). When the archeologically-based sea-level position is compared with the shoreline elevation provided by geological markers (Holocene beachrock, Late Pleistocene marine terraces), a refined understanding of relative sea-level changes and rates of vertical tectonic movements for these coastline locations is gained.

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1. Introduction

Archaeological remains in areas of small tidal range such as the Mediterranean Sea can provide significant information on relative sea-level changes during the last millennia. By using archaeological coastal structures whose successful functioning is well attested, a precisely defined relationship to sea level at time of construction is obtained. Along the Mediterranean shores, the historically increasing sophistication of human development has led to there being a number of archaeological remains that can be used to establish constraints on relative sea level. Several archaeological structures have been considered as palaeo-sea level markers: fish ponds, docks, piers, quarries, tombs, pavements, and bollards have furnished important improvements in the accurate evaluation of relative sea-level change during the last millennia (Schmiedt, 1966, 1972; Flemming, 1969; Flemming and Webb, 1986; Lambeck et al., 2004; Anzidei et al., 2006; Antonioli et al., 2007; Scicchitano et al., 2008; Auriemma and Solinas, 2009; Ferranti et al., in this issue).Quarries, in particular, may represent an important marker for the followings reasons: (i) their abundance along the

Mediterranean coast, (ii) the large use for a long period of the same kind of architectural structures, (iii) the transport techniques often operated by boats of different cabotage relating to the dimension of the blocks extracted and, as a consequence, (iv) their implicit relation with the sea level at the time of their use that affords a reconstruction of the palaeo-sea level.

Different typology of quarries can be distinguished in historical times. One of these is represented by quarries for the extraction of millstones for grinding olives during oil production, that in southern Italy is documented since around 2500 BP (Amouretti, 1986; Amouretti and Brun, 1993; Brun, 1997). Millstone dimensions and shapes were strictly related to the crusher systems used. One of these was characterized by the use of cylindrical or slightly truncated-cone shape wheels that turned perpendicularly above a subjacent horizontal wheel of similar size placed above a masonry base (Amouretti, 1986; Hadjisavvas, 1992; Brun, 1997; Rosada, 2007). This system is attested since the beginning of the Hellenistic period in Israel and Cyprus, and largely spread within the whole Mediterranean basin from the Roman to the modern age, until the XIX century, when traditional crushers were progressively abandoned (Amouretti and Brun, 1993). Millstones quarries developed mostly along the shore, as open-work, and on terrace levels. The heavy millstones were transported almost exclusively by river and sea, land transport being too complex and expensive (Bessac,

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1986). Coastal quarrying was the best logistic solution to the difficulties of stone transport, and is noted in literary sources and archaeological evidence (Orlandos, 1968, Fig. 14; Dworakowska, 1975; Rockwell, 1992, Fig. 56; Kozelj and Wurch Kozelj, 1993, Fig. 1, 4, 41; Felici Buscemi and Felici, 2004).

Various examples of millstone quarries are found in the southern coasts of Italy. Palinuro in Campania, Crotone, Roccella Ionica, Capo dell'Armi in Calabria, Capo d'Orlando, Giardini-Naxos in Sicily, represent the costal sites where millstone quarries, showing similar architectural features, are present. Despite their large geographical extent and their occurrence strictly related to the coastline, millstone quarries have not yet been used as archaeological markers for evaluation of sea-level changes during the late Holocene.

The aim of this paper is the analysis of two different millstone quarries located at Capo d'Orlando in northern Sicily and Capo dell'Armi in southern Calabria (Fig. 1), in order to place constraints on the recent sea-level change at these sites based upon the age and functional height derived from the quarries. The interpretation of their former functional height, at the time of their excavation, provides data on the relative position of land and sea. These data, when compared with modeled Holocene sea-level rise curves (Lambeck et al., 2011) based on eustatic and glacio-hydro-isostatic dynamics, provide accurate evaluations of vertical tectonic movements that affected the coastlines during the last millennia. As it was difficult to date the studied archaeological sites, analyses of morphological markers related to older sea levels, such as marine terraces, palaeo-shorelines, marine deposits and beachrocks, allowed better determination of vertical tectonic uplift rates that affected the Capo d'Orlando and Capo dell'Armi coastal sectors and, consequently, to constrain the age of the millstone quarries.

2. Geological setting

The studied sites are located in the southernmost portion of the Calabrian arc (Fig. 1). This prominent orogenic domain connects the Apennines and the Sicilian-Maghrebian orogens that developed during the Neogene–Quaternary Africa–Europe collision and Ionian slab roll-back (Malinverno and Ryan, 1986; Dewey et al., 1989; Boccaletti et al., 1990). Since Pliocene times, the contractional structures of the hinterland part of the orogen were superseded by extensional faults (Fig. 1), both longitudinal and transversal with respect to the arc, which caused the fragmentation into structural highs and marine sedimentary basins (Barone et al., 1982; Ghisetti and Vezzani, 1982; Kastens et al., 1987; Trincardi et al., 1987; Pepe et al., 2000, 2003). In eastern Sicily and Calabria, the contractional processes along the chain and the collapse at the rear have been followed by strong uplifting that is recorded by the flights of Quaternary marine terraces (Dumas et al., 1982; Ghisetti, 1984; Valensise and Pantosti, 1992; Westaway, 1993; Miyauchi et al., 1994; Bianca et al., 1999; Catalano and De Guidi, 2003; Tortorici et al., 2003). The elevation of marine terraces and their offset across the main faults has been used to establish the relative contribution of regional and fault-related sources to uplift. According to Westaway (1993), 1.67 mm/y of post-Middle Pleistocene uplift of southern Calabria was partitioned into ~1 mm/y due to regional processes and the residual to displacement on major faults. Shorter-term uplift-rate estimates are provided by raised Holocene beaches, terraces and tidal notches (Firth et al., 1996; Pirazzoli et al., 1997; Stewart et al., 1997; Rust and Kershaw, 2000; Antonioli et al., 2003, 2006; De Guidi et al., 2003; Ferranti et al., 2007).

The strong regional uplifting of the whole Calabrian Arc has been coupled with an important geodynamic change occurred in the region during the Middle Pleistocene, signalled by the end of frontal thrust displacement and stalling of subduction of the Ionian plate beneath the Tyrrhenian domain (Westaway, 1993; Wortel and Spackman, 2000; Goes et al., 2004). In this context, the belt between the southernmost sector of the Aeolian archipelago and north-eastern Sicily (Fig. 1), dominated by the Vulcano–Tindari fault system (Lanzafame and Bousquet, 1997; Billi et al., 2006), currently separates two geodynamic regimes (Argnani et al., 2007;
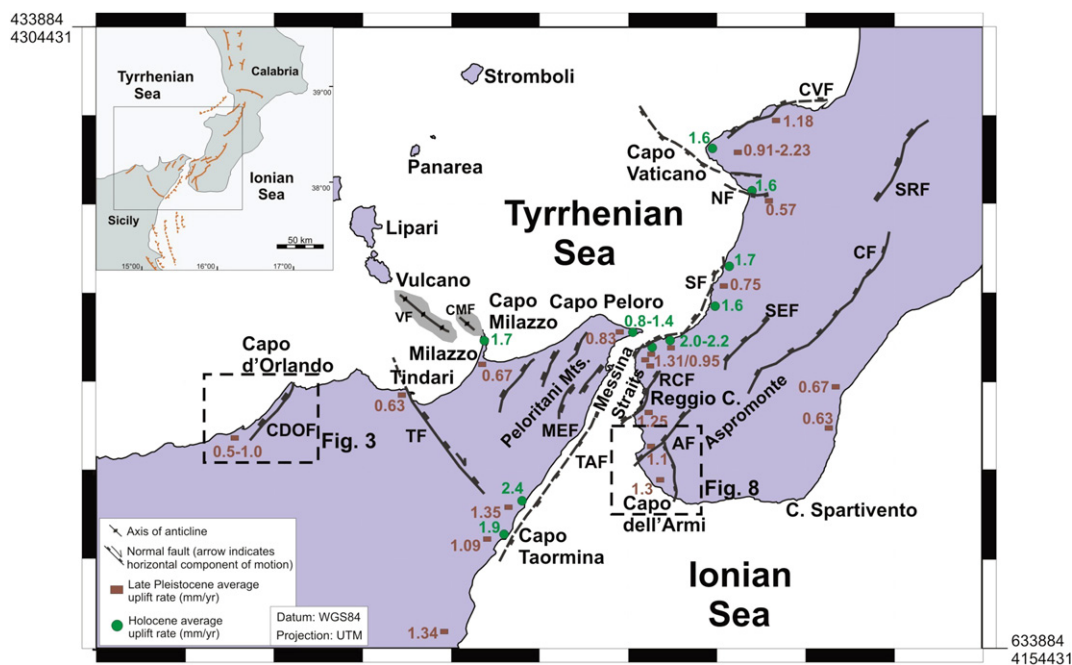

Fig. 1. Tectonic sketch map of North-Eastern Sicily and Southern Calabria. Quaternary faults: AF, Armo Fault; CF, Cittanova Fault; CVF, Capo Vaticano Fault; MEF, Messina Fault; NF, Nicotera Fault; RCF, Reggio Calabria Fault; SEF, Sant'Eufemia Fault; SF, Scilla Fault; SRF, Serre Fault; TAF, Taormina fault; TF, Tindari fault. The positive flower structures between Capo Milazzo and Vulcano island (from Argnani et al., 2007) are indicated in grey pattern (VF, Vulcano fold; CMF, Capo Milazzo fold). Late Pleistocene uplift rates after Ferranti et al. (2006), Holocene uplift rates after Antonioli et al. (2009).

Mattia et al., 2008, 2009). To the east, an extensional domain is dominated by incipient rifting that, characterized by strong crustal seismicity and volcanism, cuts across the Strait of Messina reactivating the normal faults of the Tyrrhenian sector of Calabria and the Malta Escarpment in the eastern Sicily offshore (Siculo–Calabrian rift zone; Monaco and Tortorici, 2000). Active WNW–ESE extension is documented by focal mechanisms of crustal earthquakes (Pondrelli et al., 2006), structural studies (Tortorici et al., 1995; Monaco et al., 1997; Jacques et al., 2001; Ferranti et al., 2007), and geodetic velocities (D'Agostino and Selvaggi, 2004; Mattia et al., 2009). To the west of the Vulcano–Tindari fault system, the southern Tyrrhenian Sea margin is characterized by moderate crustal seismicity, mostly related to an E–W oriented, regional belt of contraction and dextral shear (Nicolich et al., 1982; Boccaletti et al., 1990; Nigro and Sulli, 1995; Gueguen et al., 2002; Giunta et al., 2004). Focal mechanisms are mostly characterized by strike–slip and reverse-oblique kinematics compatible with low-dip NW–SE to NNW–SSE trending P-axes (Frepoli and Amato, 2000; Neri et al., 2005; Pondrelli et al., 2006; Giunta et al., 2009), roughly consistent with the general convergence between the European and African plates (Hollenstein et al., 2003; Lavecchia et al., 2007; Ferranti et al., 2008).

Capo dell'Armi is located on the south-eastern, Calabrian shore of the Messina Straits, about 20 km south of the town of Reggio di Calabria (Fig. 1). The Messina Straits are bounded by normal faults, marked by well preserved scarps, which dissect several, strongly uplifted, Pleistocene marine terraces and Holocene shorelines (Valensise and Pantosti, 1992; Ferranti et al., 2007). This area was struck by an M ∼ 7 earthquake on December 28, 1908, whose source has been related to normal faulting on planes trending nearly parallel to the Straits, albeit with different locations and dipping (see Valensise and Pantosti, 1992; Amoruso et al., 2002 and references therein). The displacement caused a coseismic down-warping of the area which was documented by leveling surveys performed one year before and immediately after the earthquake (Loperfido, 1909). The studied site is located at the footwall of the 18 km-long SW–NE trending Armo normal fault (Ghisetti, 1981, 1984). This Quaternary-age fault bounds the south-eastern margin of the Reggio Calabria basin from the crystalline upraised block of the Aspromonte ridge (Fig. 1). In this area, the MIS 5.5 terrace deposits include rich *Strombus bubonius* assemblages, as in the case of Ravagnese and Bovetto sites, where deposits are found at elevations of 130–140 m (Gignoux, 1913; Bonfiglio, 1972), and Nocella, where they crop out at an elevation of about 175 m (Dumas et al., 1987). The age attribution of these deposits to the 125 ka high-stand has been confirmed by TL determinations (Balescu et al., 1997). Recent activity of the Armo fault is shown by raised Holocene beach rock sediments found at its footwall by Pirazzoli et al. (1997), whose characteristics and age are discussed in detail in this paper.

Capo d'Orlando is located along the Tyrrhenian shore of northeastern Sicily about 70 km west of the town of Messina (Fig. 1). It is part of the footwall of a Pleistocene northwest-dipping normal fault (Carbone et al., 1998), here named Capo d'Orlando fault (Fig. 1), that controlled the geomorphologic evolution of the coast to the west of the promontory. The effects of regional and local Pleistocene tectonic processes in this area have been recorded by flights of terraces extending along this coastline. Different uplift rates have been determined by using morphological and paleontological markers. Stratigraphic and morphologic correlations with the MIS 5.5 terrace provided an uplift rate of 0.50 mm/y in the Tindari promontory, 25 km to the east of Capo D'Orlando (Gliozzi and Malatesta, 1982; Bonfiglio et al., 2010). However, bones of dated continental mammals found at Acquedolci (Bada et al., 1991), 15 km to the west of Capo d'Orlando, allowed stratigraphic and morphologic correlations with the MIS 5.5 terrace in the Capo d'Orlando

area and to establish lower rates of uplifting (see below). Longer-term uplift rates were obtained by 0.5–1.0 Ma marine deposits outcropping at about 500 m a.s.l. in the Naso village, 5 km to the south-east of this coastline (Catalano and Di Stefano, 1997). Present tectonic activity is documented by historical seismicity (Mongitore, 1743; Incudine, 1882; Working Group CPTI, 2004), with epicenters of the major earthquakes (I = VII − IX) located along a SW–NE trending alignment extending south of Naso (Fig. 3).

3. Millstones: historical exploitation

The use of millstones for grinding olives and oil production (Fig. 2a) was a fundamental technological innovation that reflects
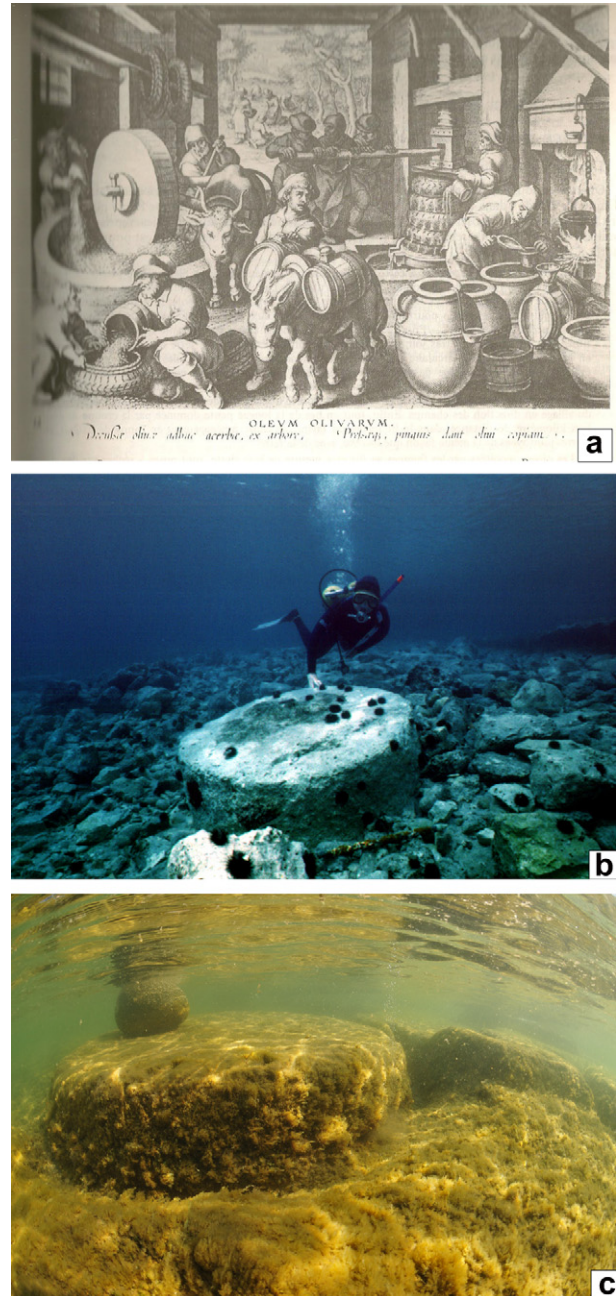
Fig. 2. (a) Old drawing reproducing millstones for grinding olives and oil production (from Amouretti, 1986). (b) Large stone disk (likely a millstone) retrieved in a shipwreck at Torre Santa Sabina bay (Adriatic coast of Apulia). (c) Submerged millstone at Capo D'Orlando (Tyrrhenian coast of north-eastern Sicily).
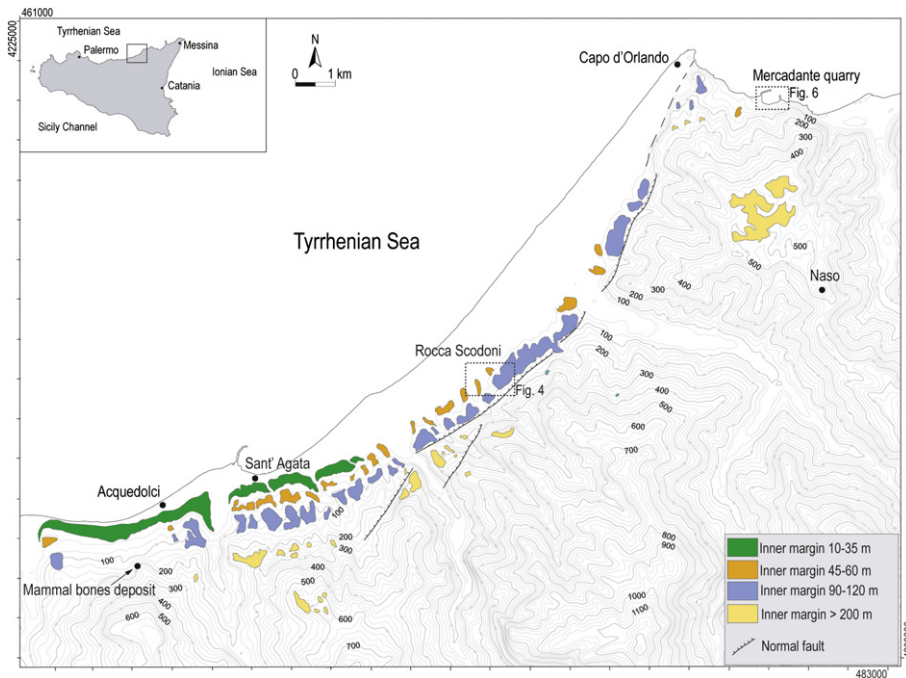
Fig. 3. Morphotectonic map of the coastal sector between Capo D'Orlando and Acquedolci showing location and heights of the marine terraces and relative inner margins (location in Fig. 1).

a marked economical improvement at the end of the archaic era, which in southern Italy occurred around 2500 BP (Amouretti, 1986; Amouretti and Brun, 1993; Brun, 1997). However, large uncertainties exist in the attempt to give archaeological age constraints to the millstones quarries, mostly because these artefacts were reused after the crusher closing down and also because of the limited knowledge on the Mediterranean rural archaeology.

The earlier records come from Chios (mid V century B.C.), Olinthos (IV century B.C.) and Corinto (before 146 B.C.) in Greece, and Maresha in Palestine (III century B.C.), and they refer to the first and most ancient type of crusher, the "*trapetum*" (from the Greek *trapetés*) described by Catone (De agricultura, 20–22; Res Rusticae, 23-24-25). The *trapetum* is formed by one or two grinding wheels with hemispherical or truncated- and rounded-cone shapes ("*orbes*"), that revolved inside a bowl (Boardman, 1958–1959; Moritz, 1958; Adam, 1984; Amouretti, 1986; Foxhall, 1993; Kloner and Sagiv, 1993; Brun, 1997; Rosada, 2007). A younger crusher system used a cylindrical or slightly truncated-cone shape vertical wheel ("*mola*") that turned on a subjacent horizontal wheel ("*sottomola*") of similar size placed above a masonry base (Amouretti, 1986; Hadjisavvas, 1992; Brun, 1997; Rosada, 2007). This system is documented since the beginning of the Hellenistic period in Israel and Cyprus, and largely spread within the whole Mediterranean basin from the Roman to the modern age, until the XIX century, when traditional crushers were progressively abandoned (Amouretti and Brun, 1993). This crusher system seems identifiable with the oil grindstone ("*mola olearia*") mentioned by Columella, who preferred it to the other systems (XII, 52, 3). The *m. olearia*, as the well known case from Settefinestre (Carandini, 1985, Fig. 349) and other rural (Mattingly and Hitchner, 1993; Frankel, 1993; Busana et al., 2009) or urban (e.g. Umag, Croatia; Matijašić, 2007) settlements attest, was operated by slaves or donkeys. A single *mola* was associated with numerous presses (*torcularia*): this is another reason for their limited number. The quarried millstones of Capo dell'Armi and Capo d'Orlando are identified as the *mole* or *sottomole* of this second type. A third millstone type exists, with taller and wider cylindrical wheels, diffused only in North Africa during the

Roman age (likely corresponding to the *rotula* of Roman literary sources). A variation of this type is only known from two sites (Volubilis in Marocco and Munigua in Spain), and had a cylindrical stem and rounded top (Brun, 1997). The second type, the oil grindstone (*m. olearia*), is very similar to crushers of the mediaeval (Comet, 1993) and modern age, active in Sicily until a few decades ago, and described by Bianca at the end of the XIX century (Acquaviva, 1995).

The dimension of the Roman, mediaeval and modern specimens of *mola* are analogous to those of Capo d'Orlando and of Capo dell'Armi. The Roman cylindrical olive millstones (*mole* or *sottomole*) have a diameter that varies from 1.00/1.10 m (Umag: Matijašić, 2007), to 1.15 m (Settefinestre, height 0.35), 1.50 m (Marea, Egipt; Cosa, *sottomola*; Antella, Firenze, *sottomola*: Carandini, 1985), 1.62 m (Desenzano, *sottomola*: Scagliarini Corlàita, 1994), up to 2.37 m (Granaraccio, Tivoli, *sottomola* made of two pieces: Carandini, 1985). Specimens from the XIX century Sicily crushers have diameters of 1.30 m. As regards the modern age, a slight change in dimension is perhaps outlined by Greek samples. From the Middle Age to the XVII century, a single large-sized wheel (over 1.5 m of diameter and 0.4–0.5 m of thickness), played by an animal, seems to prevail. Later, millstones of smaller dimensions (from 0.60 to 1.20 m of diameter, and 0.20–0.30 m of thickness) were produced (Amouretti, 1986). Notwithstanding size variations, their origin from the Greek–Roman *m. olearia* is evident.

The large extent of coastal exploitation is confirmed by the finding of several shipwrecked loads of millstones, of prevailing Greek–Roman (simple manual rotating type or adjustable rotating type and "Pompeian" type) and subordinately of medieval or post-medieval age (Beltrame and Boetto, 1997). As an instance, a large stone disk (likely a millstone) with dimensions analogous to those of the olive millstones of Capo d'Orlando (Fig. 2c) and Capo dell'Armi samples, was retrieved in a shipwreck within the shallow sea-bottom of Torre S. Sabina bay on the southern Adriatic coast (Fig. 2b; Auriemma, 2007). Finally, another cylindrical millstone quarry is noted at Letoianni, near Capo Taormina (A. Ollà and E. Felici, personal communication).

In summary, the second type of oil grindstone, the *m. olearia*, comparable to those in the quarries under consideration, was in use at least from the Hellenistic age, or, given the large dimensions, from the Roman Imperial age (I–II century A.D) to the XVII century. Because of the lacking chronological constraints for carving activity in quarries, constraints on age estimates for the studied millstones use geological (Holocene and MIS 5.5 age) vertical tectonic displacement rates of the coast.

4. Methods

Measurements of the current heights of archaeological and geomorphological markers with respect to the current sea level at the time of the survey were performed by an invar rod mechanical system. Data have been corrected for tides and pressure relative to mean sea level (MSL) using data from the tide gauges of Milazzo and Reggio di Calabria (Fig. 1; http://www.wxtide32.com and from the meteorological site www.wunderground.com).

In order to relate the archaeological structures to ancient mean sea levels, the former functional height at each location was defined. The functional height is defined as the height of a specific architectural part of an archaeological structure with respect to the mean sea level at the time of its construction and use. The height depends on the type of structure, its use, and the local tide amplitudes. These parameters also define the minimum height of the structure above the local highest tides. For quarries located in south-eastern Sicily, Scicchitano et al. (2008) proposed a minimum elevation of their original floor at 0.30 m above high tide to be always dry, which implies a minimum functional height of 0.60 m with respect to mean sea level. This estimate is in agreement with the observations collected at other coastal archaeological sites in the central Mediterranean area (Lambeck et al., 2004; Antonioli et al., 2007). For the millstone quarries found at Capo d'Orlando and Capo dell'Armi, analogous similar functional height seems to be realistic and a minimum elevation of their original floor at 0.60 m above the mean sea level has been assumed (Table 1). The floor of the quarry is considered to coincide with the base of the lowest relic wheel still attached to the bedrock because it never went extracted.

As regards the beach rocks surveyed along the coast, as well as in the area directly offshore, diving operations have been carried with the aim of mapping the base of the sedimentary body. Depths were measured by using a digital depth gauge. Tectonic uplift-rate estimations were performed for the beach rock at Capo dell'Armi considering the elevation radiometrically-dated samples. Finally, the elevation of morphological and sedimentological markers from marine terraces has been estimated from detailed topographic maps (1:10,000 scale).

5. Geological and archaeological markers

5.1. Capo d'Orlando

The coastal sector between Capo d'Orlando and Acquedolci (15 km to the southwest of the Capo, Fig. 3) shows morphological and sedimentological markers of Pleistocene sea level high-stands. Marine abrasion platforms with associated deposits have been observed at distinct elevations. In the Capo d'Orlando area, a higher depositional terrace is located at an elevation of ∼500 m a.s.l. Analysis of foraminifera and nannoplankton attributed an age between 550 and 984 ka to the terraced deposits (Catalano and Di Stefano, 1997). Hugonie (1974, 1979, 1982) and Robillard (1975), identified seven orders of marine terraces associated with three important abrasion platforms at lower elevations of between 220 and 30 m a.s.l. A sedimentary wedge rich in bones of continental mammals was found at the base of a carbonate palaeo-cliff in the Acquedolci area between 110 and 130 m a.s.l. (Fig. 3; Bonfiglio, 1989). Isoleucine epimerization dating of bones yielded ages of 200 ± 40 ka (Bada et al., 1991).

The geomorphologic survey recognized four orders of marine terraces located at elevations of 200 m, 120–90 m, 60–45 m, and 35–10 m a.s.l. (Fig. 3). Between Acquedolci and Capo d'Orlando (Rocca Scodoni, Figs. 3 and 4) the 45–60 m high terrace is characterized by an up to 10 m thick marine deposit constituted by coarse polygenic conglomerates, micro-conglomerates and crossed lamination sands in a fining-upward sequence (Fig. 5a, b). Here, the inner margin of this terrace has been recognized at ∼45 m a.s.l. and abuts an ancient cliff showing several *Lithodomus* holes (Fig. 5d), with some preserved fossilized shell inside, and other biological remains. A shell of *Spondylus* sp. (Fig. 5c) was collected in physiologic position from this deposit for geochronological analysis.

The Capo d'Orlando area, where the literary tradition places Agathyrnus, the legendary town founded by the homonymous son of Eolo, God of Winds, is characterized by several archaeological settlements since the late Bronze Age (Scibona, 1985; Pinzone, 2004; Spigo, 2004a). Thanks to its strategic position, the site was continuously colonized from the Archaic to the Hellenistic age as indicated by votive materials, probably belonging to a sanctuary, and by a IV-III century B.C. necropolis (Bonanno, 2004). Moreover, Roman remains are well-known and are represented by scattered material areas and inscriptions. In the Bagnoli-San Gregorio area (near the Mercadante quarry, Fig. 6) there was a little harbour, as the underwater finds indicate, and a probable villa and/or mansion with a thermal complex dated between the III and V century A.D. The complex bears evidence of damages possibly caused by one or more earthquakes (Spigo, 1995, 2004b; Ollà, 2004; Spigo et al., 2004).

Along the coast enclosed by the modern Bagnoli harbour, an ancient quarry of grinding wheels for oil (known as Mercadante
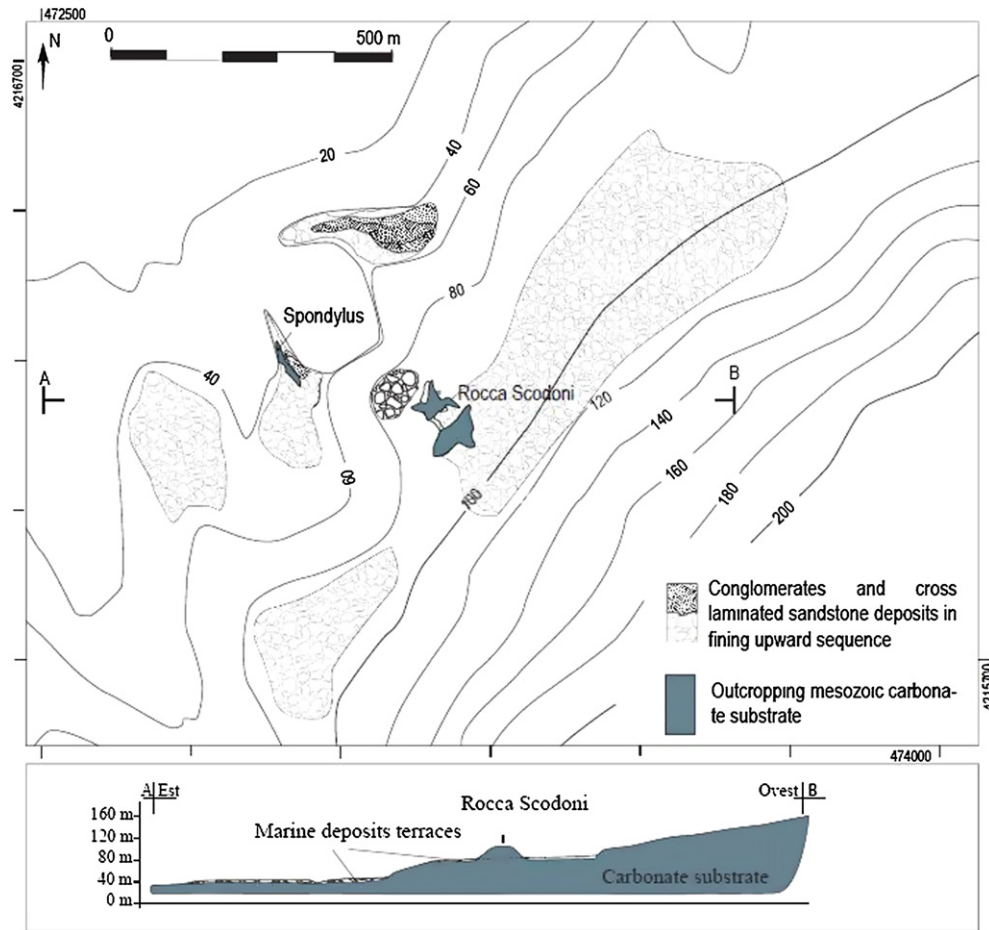
Table 1
Location, elevation and age of the archaeological and geological markers. Tidal correction applied for tide amplitude at the moment of surveys; tide data (Milazzo and Reggio Calabria) from http://wxtide32.com/ version 4.6 (2006\6\30). Atmospheric pressure data from www.wunderground.com. Functional height of the used marker above mean sea level. The ^{14}C AMS age of *Hinia* sp. shell collected from the Capo dell'Armi beachrock was determined by CIRCE Laboratorium, Caserta, Italy. The sample was calibrated using the program CALIB 5.0.1 (2-sigma, marine entry; Stuiver et al., 2005). Palaeo-sea level (for the archaeological markers) = corrected marker elevation − functional height. Predicted sea level from the Lambeck et al. (in this volume) model. Uplift rates are reported considering the age error bars and assuming uniform uplift over the entire period of time considered, and hence represent time-averaged estimates.

Site	Marker	Measured elevation (m)	Measurement Time (yy/mm/dd/hh)	Tide (m)	Atmospheric pressure (mbar)	Corrected marker elevation (m)	Functional height (m)	[14]C AMS age (yr BP)	Age (yr cal BP)	Palaeo-sea level (m)	Predicted sea level (m)	Uplift rate mm/yr
Capo D'Orlando	Quarry	−0.40	2009/09/15/07	0.31	1013	−0.09	0.60	–	–	−0.69	see Table 2	see Table 2
Capo Dell'Armi	Quarry	−0.40	2009/09/15/11	0.24	1013	−0.16	0.60	–	–	−0.76	see Table 2	see Table 2
Capo Dell'Armi	Beach rock	0.70 ± 1.00	2009/03/08/12	0.20	1013	0.50 ± 1.00	–	4760 ± 27	4870–5137	0.50 ± 1.00	−4.55	1.01 ± 0.25

Fig. 4. Detailed map and transect of Rocca Scodoni area (location in Fig. 3).

quarry) has been found (Fig. 6). The quarry is characterized by circular holes carved into the bedrock (Upper Oligocene–Lower Miocene Stilo-Capo d'Orlando sandstone, Carbone et al., 1998) in order to extract rock grinding wheels for oil production (Fig. 7a). The holes are clustered into an exploitation field, about 110 m long and 30 m wide, parallel to the present coastline and extending from the shoreline down to −0.6 m depth. The holes are up to 1.5 m dimension. All are presently submerged and they commonly show near-complete wheels preserved inside the holes (Fig. 7a and b). Elevation of the base of the extraction cuts of the holes hosting the non-extracted wheels has been measured with respect to the present sea level. Data have been corrected for tide and pressure at the time of the survey. The deepest structure has been found at a corrected depth of −0.09 m (Table 1), and it is represented by a sub-circular hole 1.35 m large associated to a well preserved about 30 cm thick wheel. Seawards, the seabed appears flat for a distance of 18 m, where at about −1 m depth a series of small steps deepens the bottom down to about −3.5 m depth (see transect in Fig. 6). Unfortunately, archaeological structures related to ship mooring, such as bollards or docks, have not been observed. Considering a depth for the deepest grinding wheel of −0.09 m b s l, and taking into account a functional height for the site of 0.60 m, it is possible to reconstruct a palaeo-sea level of −0.69 m below present sea level for the Mercadante quarry.

5.2. Capo dell'Armi

The eastern side of the Messina Straits (Fig. 1) is characterized by the occurrence of several Pleistocene marine terraces (Miyauchi et al., 1994). According to Dumas and Raffy (2004), the inner margin of the terrace hosting shells of *S. bubonius*, referable to MIS 5.5 (125 ka), is located at altitudes between 130 and 180 m. A detailed structural survey of the area revealed that the elevation of the MIS 5.5 terrace steps abruptly passing from NW (130–140 m, Bovetto–Ravagnese area) to SE (181 m, Capo dell'Armi area) across the Armo normal fault (Fig. 8). This occurrence is interpreted as reflecting an offset of the MIS 5.5 terraced deposits by the Armo fault, with the displaced portions of the same terrace resting in the hanging-wall and in the footwall of the fault (Fig. 8). The cumulative uplift rate varies from about 1 mm/y in the hanging-wall to 1.4 mm/y in the footwall.

The main Holocene morphological feature in this coastal sector is represented by a well preserved beach rock (Fig. 7c), developed from Capo Pellaro to Melito di Porto Salvo, with a ∼25 km linear extent along the coast (inset in Fig. 8). The beach rock forms a sedimentary body whose bottom reaches a −15 m depth (Fig. 7d), and with top up to 3 m high between the villages of Lazzaro and Capo dell'Armi. The beach rock body is organized into well developed layers dipping gently (at 5–10°) toward the sea. The surface of the beach rock shows clear abrasional furrows, indicating a former wave-zone position (Pirazzoli et al., 1997). Clasts included in the deposit range in size from fine sands to pebbles, the latter found in the deepest part of the body. The deposit is poor in macroscopic shell fragments, even though thin sections analyses revealed the presence of various planktonic foraminifera and fragments of bryozoa. AMS radiocarbon age determination of a well preserved shell of *Hinia* sp. collected at 0.7 m a.s.l. from the beach rock located just south-east of Capo dell'Armi (Fig. 7c) yielded an age of 4870–5137 cal BP (Table 1).
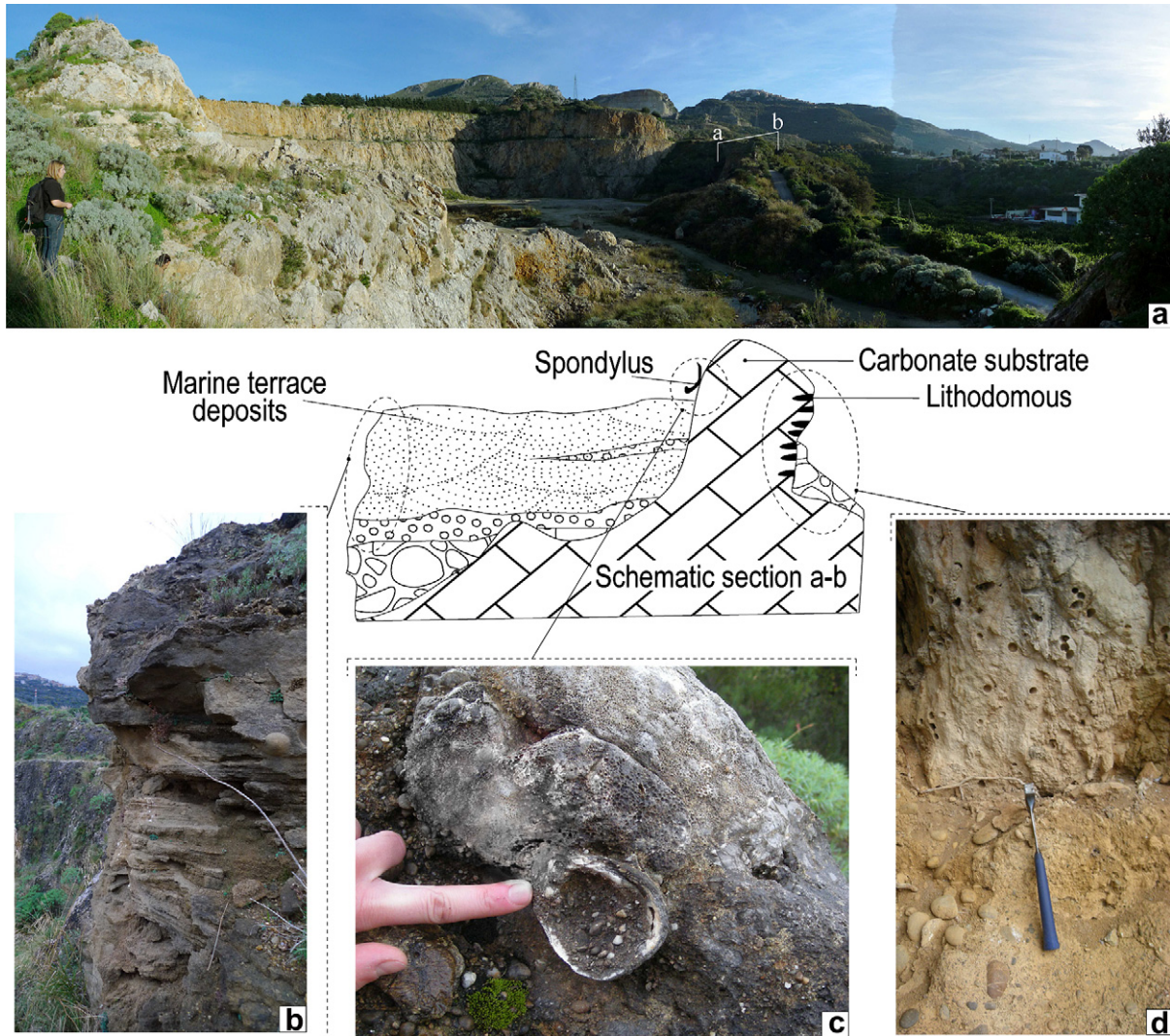
Fig. 5. Rocca Scodoni: (a) panoramic view and schematic section of the deposit; (b) micro-conglomerates and cross-laminated sands in a fining-upward sequence; (c) fossil shell of *Spondylus* sp.; (d) *Lithodomus* holes in the carbonate substrate.

Capo dell' Armi was known in Greek and Roman times as "Leucopetra" (Greek "white stone") (Thucydides 7, 35; Strabo 6, 259; Cicero, ad Att., 16, 7; Phil. 1,3; Plin., Nat. Hist. 3, 6, 73–74; Tabula Peutingeriana) because of the whitish crystalline rocks flooring the promontory, and was considered a sacred locale (Giangiulio, 1996; Poccetti, 1996; Chilà, 2002). The site was colonized since the Archaic Age. Remains of a settlement and a sanctuary used until the Hellenistic age have been found in the neighborhoods of Saline (Fig. 8). A large Roman villa was located along the right side of the San Vincenzo river (close to Lazzaro), probably coinciding with the later "statio" that is represented in the Tabula Peutingeriana. It is highly likely that the San Vincenzo river mouth (Fig. 8) during the Roman age was a haven for the anchorage of small boats (Schmiedt, 1975; Costamagna, 1991; Chilà, 2002), even if Turano (1970) identifies the bay to the south-east of the promontory as the site of the ancient Leucopetra harbour. The barbarian invasion during the V century A.D. forced the citizens to move landward leaving the coastal area, even though a renewal of commercial and economical activities took place during the Byzantine age.

Millstones for oil were found at Capo dell'Armi in a partially submerged quarry carved into the beachrock body at elevations of between 0.4 m b s l and 1 m a.s.l. (Fig. 7e). The millstones are very similar in shape, dimension and extraction techniques to those surveyed at Capo d'Orlando, and they are organized into an exploitation field as well. Several millstones were never finished or extracted. They are elliptical or sub-circular with the major axis ranging in size between 1.10 m and 1.30 m, the extraction cut is up to 0.25 m thick and 0.10 m large. Exposed millstones are well preserved, whereas the submerged ones are strongly eroded although their shape and dimensions can still be readily measured. The lowest elevation of the base of the extraction cut (see transect in Fig. 8) is located at a tide- and pressure-corrected depth of −0.16 m (Table 1). Taking into account a functional height of 0.60 m, as for Capo d'Orlando, palaeo-sea level, at the time of use of the field, was 0.76 m below the present sea level.

6. Discussion

The detailed surveys and precise measurements of archaeological and morphological markers can provide an important contribution to characterize the vertical tectonic history of two coastal sectors in Northern Sicily and Eastern Calabria (Table 1). On the other hand, it is possible, in areas whose vertical rate of tectonic deformation is well known, to date archaeological sites of uncertain age occurring along the coastline. These kinds of analyses are
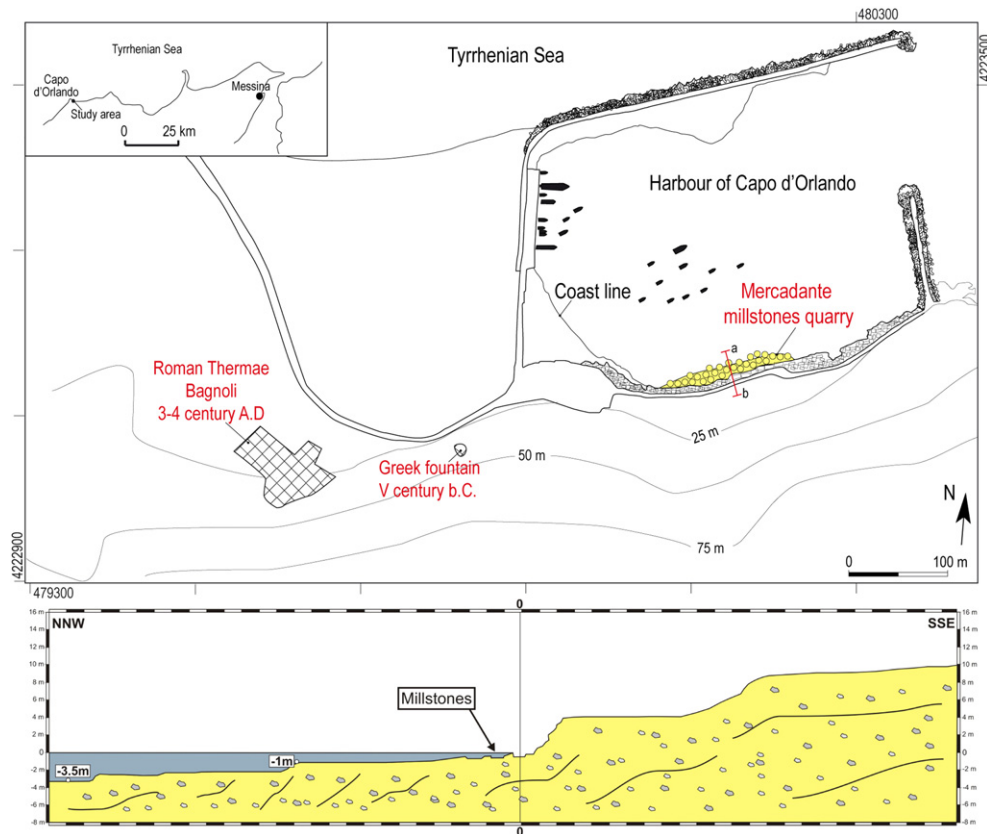
Fig. 6. Sketch map of the main archaeological sites close to the Capo d'Orlando harbour (location in Fig. 3) and transect of the Mercadante millstone quarry.

strictly related to the possibility of accurately estimating the functional height of the archaeological marker at the time of its construction and use (see Lambeck et al., 2004; Antonioli et al., 2007; Scicchitano et al., 2008).

As regards the age, millstones for oil surveyed at Capo d'Orlando and Capo dell'Armi are very similar in shape, dimension, extractive techniques (Chilà, 2002) and present position respect to the mean sea level. Unfortunately, it is not possible to obtain a precise chronological attribution of the Capo d'Orlando and Capo dell'Armi millstones based only on archaeological data. Considering typology and size, the millstones could cover a time span between the Hellenistic age (from 331 B.C.) or Late Republican Roman age (II–I century B.C.) at least to the XVII century A.D., that is from 2300–2100 to 300 BP. Since chronological constraints are weak, vertical tectonic displacement rates obtained by geomorphologic markers were used to place age estimates on the studied millstones.

Attention is focused on the marine terraces that border the coastal area between Capo d'Orlando and Acquedolci (Fig. 3). Taking into account the radiometric determination performed on the continental mammal deposit found at Acquedolci (200 ± 40 ka, Bada et al., 1991) and considering that this continental deposit lies on a marine platform located at 120 m a.s.l. (Bonfiglio, 1989), it is evident that the high-stand responsible for the development of the terrace must be older than the mammal remains, and it could be related to MIS 7. Stratigraphic and morphologic correlations between the terrace directly below and the terrace of Rocca Scodoni, located in the Capo d'Orlando area (Figs. 3 and 4), allow attribution of this latter terrace to MIS 5.5. Taking into account that its inner margin is located at an elevation range of 45–60 m, a long-term uplift rate of ~0.3–0.45 mm/y can be estimated. Tentatively,

it is possible to estimate the shorter-term rate of tectonic uplift for the area of Capo d'Orlando by considering different ages for the Mercadante millstone quarry, surveyed at a maximum depth of 0.09 m b s l (measured at the base of the extraction cut and corrected for tide and pressure). Various estimations of uplift rates were derived by attributing different ages (1000, 1500 and 2300 BP) and a functional height of 0.60 m to the millstone field. The tectonic uplift can be evaluated as the difference between the observed local palaeo-sea level positions and the predicted sea-level curve for the same locality (Lambeck et al., 2011) at the different model ages. This exercise results in uplift rates of -0.20, 0.10, 0.32 mm/y for the last 1000, 1500 and 2300 BP, respectively (Table 2). Comparing these values to the uplift rate obtained by geomorphologic marker, the older, Hellenistic age can be reasonably attributed to the Capo d'Orlando quarry because of the broadly similar rate estimate. Taking into account that the MIS 5.5 terrace and the quarry are located at the hanging-wall and at the footwall of the Pleistocene Capo d'Orlando fault, respectively, and that no historical seismicity can be attributed to this structure (Working Group CPTI, 2004), the comparable values of long- (~0.3–0.45 mm/y) and short-term (~0.3 mm/y) estimated uplift rates suggest that this structure is inactive and that uplifting is related to regional processes only.

The estimation of relative sea-level change and uplifting history at Capo dell'Armi is more complicated. Millstones are located ~0.2 m below the present sea level and are carved into a Holocene beach rock which reaches a maximum elevation of ~3 m in the area of the millstone field (Fig. 8). Radiocarbon dating of a fossil shell of *Hinia* sp. collected from the beachrock at a tide-corrected elevation of 0.5 m a.s.l., yielded an age of 4870–5137 cal BP. Taking into account that this gastropod typically lives in very shallow

Fig. 7. (a) Panoramic view of the Mercadante quarry at Capo d'Orlando. (b) Submerged millstone in the Mercadante quarry. (c) Beachrock at Capo dell'Armi and fossil shell of *Hinia* sp. collected inside the deposit. (d) Submerged bottom of the beachrock at Capo dell'Armi. (e) Millstone quarry at Capo dell'Armi.

beach environments, an elevation error of ±1 m was adopted. Comparing elevation and age with the predicted sea-level curve (Lambeck et al., 2011), an uplift rate of 1.0 ± 0.2 mm/y can be estimated for the last 5 ka BP. This value is comparable, within error, with long-term estimation obtained using the elevation of the MIS 5.5 terrace both in the hanging-wall and footwall of the Armo fault (Fig. 1). As regards the archaeological markers, as at Capo d'Orlando, various estimations of uplift rates were derived by
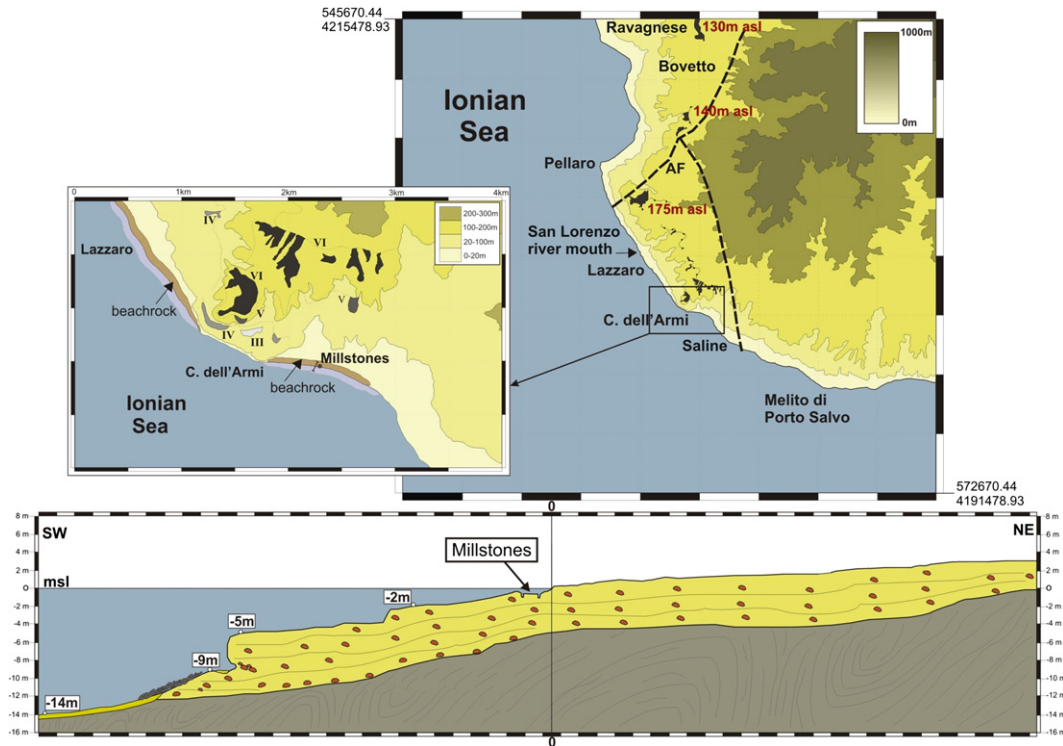
Fig. 8. (a) Morphotectonic map and transect of the coastal sector between Pellaro and Melito di Porto Salvo (location in Fig. 1). Elevations of inner edge of the MIS 5.5 marine terrace are reported (from Atzori et al., 1983; Dumas and Raffy, 2004, modified).

attributing the same different ages (1000, 1500 and 2300 BP) and functional heights of 0.60 m to the millstone field (Table 2). None of the considered scenarios fit with the uplift-rate value obtained by geological markers, even though the oldest age attribution yields the highest value of uplift rate (∼0.3 mm/y, Table 2). Taking into account that the Capo dell'Armi millstones seem to be coeval to those at Capo d'Orlando, an age attribution of 2300 BP seems reasonable.

The different values of uplift rate obtained by geological and archaeological markers at Capo dell'Armi could be explained by an uplift scenario characterized by a cyclical occurrence of coseismic events related to the activity of the Armo fault. The MIS 5.5 terrace and the 5000 a beachrock have been probably affected by regional uplifting and fault-related footwall deformation. Taking into account the Hellenistic age of the millstone quarry and its location at the hanging-wall of a splay of the Armo fault (Fig. 8), the present elevation of the quarry could be explained by local subsidence related to the activity of this splay. Inherent in this explanation is the implication that, in the short term, the splay has focused slip instead of the main branch located to the NW toward Pellaro, which has accommodated the major offset of the MIS 5.5 terrace (Fig. 8). In

the short term, local subsidence may prevail over regional uplift, a fact observed also in Northern Calabria (Ferranti et al., in this issue). Displacement related to the 1908 earthquake caused a coseismic down-warping of the Capo dell'Armi area of about 10 cm which was documented by the leveling survey of Loperfido (1909). Obviously, this subsidence cannot entirely justify the submerging of a Hellenistic quarry in this area, and further investigations are required to explain the occurrence of millstones holes down to about 0.2 m b.s.l.

7. Conclusions

Analyses of archaeological and geological markers at Capo d'Orlando and Capo dell'Armi yield important implications for the study of relative sea-level changes:

- When precisely dated, millstone quarries can represent a good marker of relative sea-level change in consideration of their strict relation with the shoreline at time of their use. Unfortunately, millstone quarries discovered at Capo d'Orlando and Capo dell'Armi could not be dated with precision. Given the typology and size (1.50 m diameter), their chronological range is very wide, between the Hellenistic (from 331 B.C.) or Late Republican Roman age (II–I century B.C.) at least to the XVII century A.D. (2300–2100 to 300 BP).
- Uplift rates estimated for the Capo d'Orlando area by archaeological and geological markers are comparable, attributing an Hellenistic age to the Mercadante quarry. These rates can be reasonably related to the regional process of uplift of the westernmost sector of the Calabrian Arc, as no active tectonic structures occur in the area.
- Uplift rates estimated for the Capo dell'Armi area by archaeological and geological markers are different. Raised geological

Table 2
Estimations of uplift rate for the studied sites, obtained by attributing different ages to the archaeological markers. Values of marker elevation, functional height and palaeo-sea level are reported in Table 1.

Age attribution (years)	Predicted sea level (m)	Uplift rate (mm/yr) in the Capo d'Orlando area	Uplift rate (mm/yr) in the Capo dell'Armi area
1000	−0.49	−0.20	−0.27
1500	−0.85	0.10	0.06
2300	−1.42	0.32	0.29

markers can be related to the combination of regional uplifting and coseismic events related to the activity of the Armo fault. In this context, the minor uplift of the Capo dell'Armi millstone quarry when compared to long-term estimates can be explained by its location at the hanging-wall of a splay of the Armo fault, where historical subsidence phenomena are documented.

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