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Giovanni SCICCHITANO [1,2 *], Cecilia Rita SPAMPINATO [3,2], Fabrizio ANTONIOLI [4], Marco ANZIDEI [5], Valeria LO PRESTI [6] & Carmelo MONACO [2]

COMPARING ANCIENT QUARRIES IN STABLE AND SLOWLY UPLIFTING COASTAL AREA LOCATED IN EASTERN SICILY, ITALY

Abstract: Scicchitano G., Spampinato C.R., Antonioli F., Anzidei M., Lo Presti V. & Monaco C., *Comparing ancient quarries in stable and slowly uplifting coastal area located in eastern Sicily, Italy.* (IT ISSN 0391-9838, 2018).

The coast of the Mediterranean still preserves several remnants of ancient coastal quarries that has been often used to provide insights on the sea-level changes occurred during the last millennia. The southeastern coast of Sicily (Italy) is characterized by the occurrence of more than fifty ancient quarries that have been detailed surveyed and studied from archaeological and geomorphological point of view. Most of these quarries are presently partial submerged and some of them for this reason have been used as marker of ancient sea level, providing important data on relative sea level change and tectonic mobility during the late Holocene. We selected six important and well known ancient quarries located in coastal sectors characterized by different tectonic rates of uplift, e.g. in a stable area (Marzamemi) and in a significant uplifted area (Augusta). The elevation of the deepest floors of the lowest level of the quarries has been measured by an invar rod with respect to present sea level, and corrected for tide at the time of surveys. These data were compared with predicted sea level rise curves for the Holocene using a glacio-hydro-isostatic model. The comparison with the curve for the southeastern Sicily coast yields a tectonic component of relative sea-level change related to regional uplift. Uplift rates ranging between ~ 0 and 0.4 mm/a have been estimated.

Key Words: Mediterranean coast; coastal quarries; southeastern Sicily; relative sea-level changes; archaeological sea-level markers; coastal active tectonics.

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This study was motivated by discussions at the workshops of MOPP-MEDFLOOD (INQUA projects 1203 and 1603P).

Riassunto: Scicchitano G., Spampinato C.R., Antonioli F., Anzidei M., Lo Presti V. & Monaco C., *Confronto tra antiche cave localizzate in zone costiere stabili e in debole sollevamento della Sicilia orientale (Italia).* (IT ISSN 0391-9838, 2018).

Le coste del Mediterraneo preservano varie evidenze della presenza di antiche cave di estrazione di pietra che sono spesso usate come indicatori del cambiamento del livello del mare durante gli ultimi millenni. Le coste della Sicilia sudorientale sono caratterizzate dalla presenza di più di cinquanta cave antiche che sono state mappate ed analizzate dettagliatamente da un punto di vista archeologico e geomorfologico. La maggior parte di queste cave sono attualmente sommerse e per questo sono state analizzate come indicatori del livello del mare durante l'Olocene. Abbiamo selezionato sei cave tra le più conosciute ed estese localizzate nell'area, alcune site in aree stabili (Marzamemi) ed altre site in aree a significativo sollevamento tettonico. Le altezze dei pavimenti più profondi dei livelli più bassi delle cave selezionate sono stati misurati e corretti per la marea. I dati sono stati comparati con una curva di predizione dei livelli del mare durante l'Olocene che tiene in considerazione della componente glacio-idro-isostatica, fornendo indicazioni sulla tettonica dell'area di Augusta intorno a 0,4 mm/a e confermando la stabilità dell'area di Marzamemi.

Termini chiave: costa del Mediterraneo, cave costiere, Sicilia sud-orientale, variazioni relative del livello del mare, marker archeologici del livello del mare, tettonica attiva costiera.

INTRODUCTION

Archaeological sites in areas of small tidal range can provide significant information on relative sea-level change during the last millennia using man-made coastal structures whose successful functioning requires a precisely defined relationship to sea level at time of construction. Along Mediterranean shores, in particular, the 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 (Flemming, 1969; Schmiedt, 1966; 1972; Caputo & Pieri, 1976; Pirazzoli, 1976; Flemming & Webb, 1986; Anzidei & *alii*, 2013; Lambeck & *alii*, 2004; Antonioli & *alii*, 2007; Scicchitano & *alii*, 2008). The interpretation of their former functional height, at the time of their construction provides data on the relative position of land and sea. These data are compared with predicted Holocene sea level rise curves (Lambeck & *alii*, 2011) which take into account eustatic and glacio-hydro-isostatic factors. The eustatic component is global and time-dependent while the isostatic factors vary with both location and time. The accuracy of these predicted values is a function of the model parameter uncertainties that define the earth response function and the ice load history. The glacio-hydro-isostatic component along the Italian coast has been also compared with field data at sites not affected by significant tectonic processes (Lambeck & *alii*, 2011). By comparing ages and elevations of paleo-sea level indicators with the predicted curve for the Holocene, it is thus possible to accurately evaluating vertical tectonic movements of coastal regions (Lajoie, 1986). Along the south-eastern coast of Sicily, between Augusta and Siracusa (fig. 1), several important archaeological sites, spanning the period from the Bronze Age to the Greek archaic period, have been selected and investigated with the aim of evaluating significant vertical movement along the coast (Scicchitano & *alii*, 2008; Lo Presti & *alii*, 2014). Vertical tectonic rates between 0.3 and 0.8 mm a^{-1} have been calculated using presently submerged markers such as docks, piers, quarries, tombs, pavements, and bollards very well known in the archaeological literature. Although south-eastern Sicily results particularly rich in coastal archaeological sites, various in typology and age, the most common are represented by stone quarries. This is explained by the strong consider-

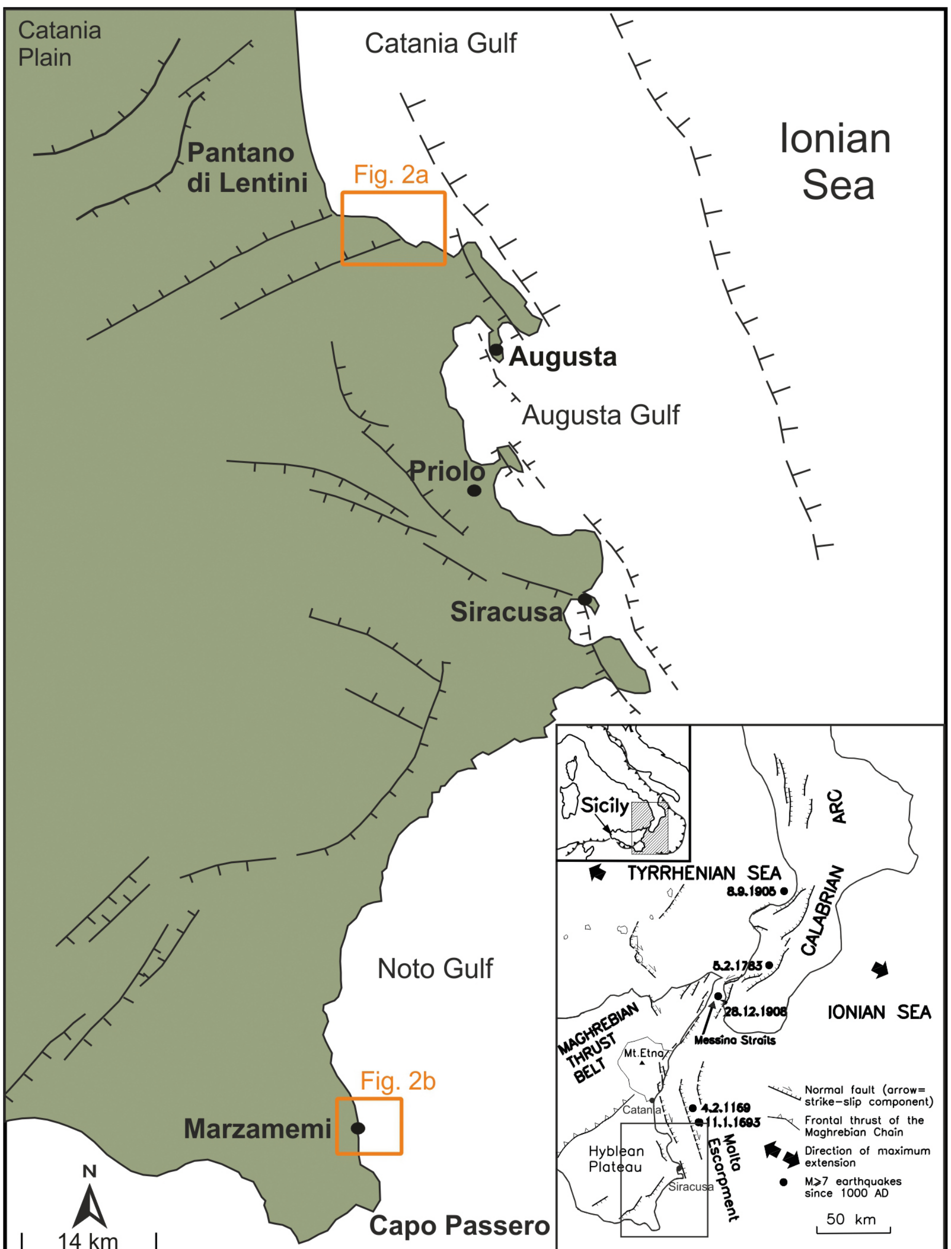

FIG. 1 - Geographical position of the studied sites along the Ionian coast of southeastern Sicily. Inset shows the seismotectonic features of Eastern Sicily (Monaco & Tortorici, 2000) and its location in the central Mediterranean area. The orange rectangles show the location of the study areas.

ation in which the carbonatic stone of Siracusa was taken into account as a prestigious material for building and of the methodology of transport of stone in ancient time that preferable occurred by sea (Dworakowska, 1975). Along the south-eastern coast of Sicily more than 50 distinct quarries have been found, surveyed and studied (Lena & Basile 1986; Buscemi & Felici, 2004; Scicchitano & *alii*, 2008; Lena & Rustico, 2010). Although some of them show different technology and age of use, they have been attributed almost the same age of beginning exploitation, probably occurred during Greek Archaic period (2.7-2.5 ka BP).

In this paper we show new data on relative sea-level change and vertical rate of tectonic movements evaluated through the analyses of ancient coastal quarries located in two different location of southeastern Sicily (fig 1): Augusta (fig. 2A), where a significant uplift rate has been reported by several authors (Bianca & *alii*, 1999; Scicchitano & *alii*, 2008; Dutton & *alii*, 2009; Spampinato & *alii*, 2011), and Marzamemi (fig. 2B), known in geological literature as a tectonically stable area (Ferranti & *alii*, 2006; Spampinato & *alii*, 2011). Analysed quarries are very similar in exploitation techniques and methodology and have been attributed to the same age of use (2.7-2.5 ka BP; Lena & Basile, 1986; Buscemi & Felici, 2004; Scicchitano & *alii*, 2008; Lena & Rustico, 2010).

The aim of this paper is to compare two different coastal areas showing different long term vertical tectonic rates and verify if these vertical tectonic movements are also recorded in historic times.

GEOLOGICAL SETTING

South-eastern Sicily (fig. 1) is characterized by thick Mesozoic to Quaternary carbonate sequences and volcanics forming the emerged foreland of the Siculo-Maghrebian thrust belt (Grasso & Lentini, 1982). This area, mostly constituted by the Hyblean Plateau, is located on the footwall of a large normal-oblique fault system that since the Middle Pleistocene has reactivated the Malta Escarpment (Bianca & *alii*, 1999), a Mesozoic boundary separating the continental domain from the oceanic crust of the Ionian basin (Scandone & *alii*, 1981; Hirn & *alii*, 1997). Since the Early-Middle Pleistocene, active faulting has contributed to continuous extensional deformation in eastern Sicily, where normal faults are mostly located offshore and control the Ionian coast, joining the NNW-SSE trending system of the Malta Escarpment to the south (see inset in fig. 1; Bianca & *alii*, 1999; Monaco & Tortorici, 2000; Jacques & *alii*, 2001; Gutscher & *alii*, 2015; Polonia & *alii*, 2016). This area is marked by a high level of crustal seismicity producing earthquakes with MCS (Mercalli-Cancani-Sieberg) intensities of up to XI-XII and M_w 7, such as the 1169, 1693 and 1908 events (Postpischl, 1985; Boschi & *alii*, 1995). According to most published geological data and numerical modelling, the seismogenic source of these events should be located in the Messina Straits and the Ionian offshore (the Malta Escarpment) between Catania and Siracusa (Postpischl, 1985; Valensise & Pantosti, 1992; Piatanesi & Tinti, 1998; Bianca & *alii*, 1999; Monaco & Tortorici, 2000; Azzaro & Barbano, 2000; Scicchitano & *alii*, 2010).

Normal faulting was coupled with a strong regional uplifting of Calabria and north-eastern Sicily, which progressively decreases toward the north and south, spectacularly documented by flights of marine terraces developed along the coasts (Cosentino & Ghiozzi, 1988; Westaway, 1993; Bordoni & Valensise, 1998; Ferranti & *alii*, 2006). According to Westaway (1993), post-Middle Pleistocene uplift rate of southern Calabria was 1.67 mm a^{-1}, 1 mm a^{-1} of which is due to regional processes and the residual to coseismic displacement. The uplift has been locally accommodated in the upper crust by repeated coseismic displacement (Ferranti & *alii*, 2017); the highest values have been found in areas located in the footwall of the main active faults where a fault-related component is cyclically superimposed on the regional signal (Valensise & Pantosti, 1992; Westaway, 1993; Bianca & *alii*, 1999; Monaco & Tortorici, 2000; De Guidi & *alii*, 2003; Scicchitano & *alii*, 2011a; Spampinato & *alii*, 2012).

The southeastern Sicily coastal area is located at the southern tip of the reactivated fault system of the Malta Escarpment (fig. 1). In this area, the vertical component of deformation has been recorded by several orders of Middle-Upper Quaternary marine terraces and paleo-shorelines (Di Grande & Raimondo, 1982), which indicate long-term uplift rates ranging between 0.4 and 0.7 mm a^{-1} (Bianca & *alii*, 1999; Dutton & *alii*, 2009). This uplift rate gradually decreases toward the stable areas of the southeastern corner of Sicily (Antonioli & *alii*, 2006; Ferranti & *alii*, 2006). Vertical component of deformation has been documented also for the Holocene (Spampinato & *alii*, 2011). In particular, analysis of archaeological coastal sites located between Augusta and Siracusa (fig. 1) suggested uplift rates between 0.3 and 0.8 mm a^{-1} (Scicchitano & *alii*, 2008). Furthermore, dating of a serpulid encrusting a speleothem sampled inside a submerged cave located in the tiny offshore of Siracusa suggested an uplift rate of about 0.4 mm a^{-1} (Dutton & *alii*, 2009), in agreement with the results of the archaeological analysis. Data collected by several boreholes drilled in various coastal plain located between Marzamemi and Catania, revealed uplift rates ranging between -0.28 and 0.11 mm a^{-1} for the southern sector, between 0.16 and 0.62 mm a^{-1} for the central sector, close to Siracusa harbour, and between 0.74 and 1.31 mm a^{-1} for the northern sector close to Augusta harbour (Spampinato & *alii*, 2011). In the north of the Augusta harbour, at the boundary with the Catania plain (fig. 1), vertical deformation has been detected also in recent time, in correspondence of a normal fault intercepting the coast line, where analysis of high precision geodetic levelling data describes a vertical deformation between different stations crossing this tectonic structure (Spampinato & *alii*, 2013).

MATERIALS AND METHODS

The selected quarries have been surveyed with particular attention to the submerged area. Measurements of the current altitude of significant archaeological markers with

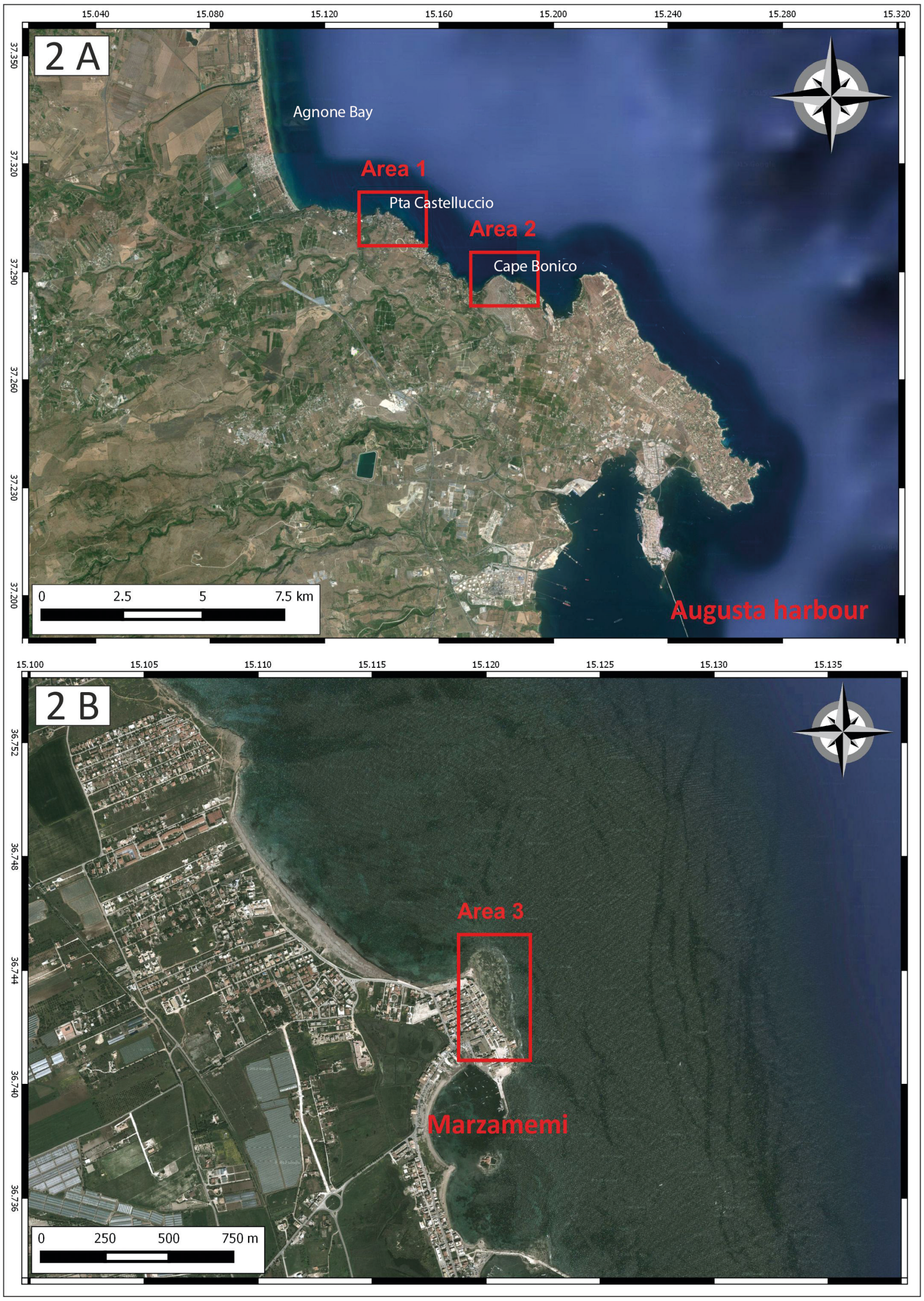

FIG. 2 - A) Google Earth detail of the Augusta area (see fig. 1 for location); B) Google Earth detail of the Marzamemi area (see fig. 1 for location).

respect to the current sea level at the time of the survey were performed both with GPS RTK (Real-Time Kinematic) and invar rod mechanical systems. All measurements were made in two days of operations performed on July 2013. To achieve a precise measurement of the elevation of the investigated sites discussed in this paper, we have used instrumental tidal data from the operational tidal networks (http://www.mareografico.it/ and http://www.IOC-sealevelmontoring.org). We have analysed the time series of tidal recordings at the individual stations located nearby to the investigated archaeological sites to determine a local mean sea-level (msl) (in particular: the TG Catania). We then used the estimated local msl values to correct the elevation of the significant parts of the quarries with respect to the sea-level measurements during field surveys.

For each site, we assumed as sea level marker the elevation of the deepest cutting line and/or the floor of the lowest level of the quarry, assuming that they correspond to the time of beginning of the exploitation. An error of 0.20 m has been taken into account. Functional structures such as stairs carved in the rock, dimension of the blocks, both ones detached and abandoned and those carved in the rock but not detached, dimension and thickness of extraction imprints were analysed as well. To compare the archaeological markers and to relate them to ancient msl, we defined their former functional height as a parameter to estimate sea-level change at each location (Lambeck & *alii*, 2004). 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 (Auriemma & Solinas 2009). This 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 quarry platforms (presently submerged or partially submerged), we assumed a minimum elevation of their original floor at 0.30 m above high tide to be always dry, which suggests a minimum functional height of 0.6 m with respect to mean sea level (Auriemma & Solinas, 2009). This estimate is in agreement with the observations collected at other coastal archaeological sites (Lambeck & *alii*, 2004; Antonioli & *alii*, 2007; Scicchitano & *alii*, 2008; 2011b; Auriemma & Solinas, 2009; Lo Presti & *alii*, 2014).

SITE DESCRIPTION

We selected six different quarries in three distinct areas (fig. 2A, B), two of them located north of the Augusta harbour and the other located close to the southernmost corner of Sicily in the small village of Marzamemi (fig. 1). There, we surveyed and measured the deepest and best-preserved sea level markers such as floors or cutting line (tab. 1).

Area 1

It is located between Castelluccio Cape and Timpe di S. Calorio (fig. 3A), in a promontory characterized by high cliffs, facing eastward S. Calorio bay and westward Agnone bay (fig. 3A). The Quarry 1 is located on the external part of the promontory; it is a small quarry partially submerged, showing one main level with various exposed parts of the floor and some cutting lines often well preserved. Point 1 was measured in the deepest portion of the floor (fig. 4A) and, corrected for tide; it lies at -0.58 m below sea level (tab. 1). The Quarry 2 is located on the eastern side of the small bay of S. Calorio (fig. 3A), a narrow portion of coast (fig. 4B), about 50 m long and 7 m large, exposing evidence of exploitation in one main level for the floor, on the base of which Point 2 was measured with a corrected depth of -0.12 m (tab. 1). No deepest markers have been identified in this quarry, but it results bad preserved and deeply eroded. Imprints of extracted blocks show dimension ranging in length between 170 and 220 cm, about 70 cm large and 50 cm thick. The Quarry 2 was intensely exploited with an estimated volume of extracted rock of about 600 m^3 (Buscemi & Felici, 2004). The Quarry 3 is located about 300 m eastward and it is wider with respect to the previous ones (fig. 3A). The Quarry 3 was exploited in two distinct layers, a deeper one where point 3 was measured at -0.61 m below sea level, and a shallower one where the point 4 was surveyed at -0.44 m depth. Dimension of the extracted blocks ranges between 130x60 and 190x80 cm; some blocks result carved into the rocks but still attached to it (tab. 1). In particular, point 3 was measured at the base of a very well preserved cutting line boarding one block in place and totally submerged (fig. 4C). A volume of about 1000-1500 m^3 of carved rocks has been estimated for the quarry (Buscemi & Felici, 2004).

Area 2

It is located about 3.5 km eastward from the Area 1 (fig. 2A); in this sector, two quarried sites were analysed on the northern corner of the Cape Bonico promontory (fig. 2A). The Quarry 4 is a small quarry, located west of Cape Bonico, that shows well preserved submerged evidences of exploitation (fig. 4D); most of these are cutting lines lying at about 0.11 m (Point 5) and 0.13 m (Point 6). The Quarry 5 is one of the biggest occurring in this coastal sector. It is represented by a wide area, partially submerged, showing evidence of intense exploitation also in recent times, as evidenced by the presence, in the emerged parts, of holes realized with mechanical drill. Submerged part of the quarry shows evidence of ancient use and, although there is no evidence of a well defined floor, it is possible to identify several cutting lines, not intensively eroded, often defining blocks still attached to the rock. In this quarry six distinct points (Point 5, 6, 7, 8, 9 and 10) were measured, all of them related to cutting lines (tab. 1), the deepest one lying at -0.13 m below sea level (fig. 4E), the shallower one at -0.06 m. The size of the extracted blocks is normally 100x50 cm.

Area 3

It is located about 60 km southwards (fig. 1), in a small village called Marzamemi (fig. 2B), and it is partially covered by buildings. The Quarry 6 is probably the biggest quarry located in southeastern Sicily, with a surface of about 36,800 m^2 and several levels of exploitation (fig. 3C). It is carved into a marine terrace of Tyrrhenian age (Lena & *alii*, 1988; Lena & Bongiovanni, 2004). The Quarry 6 also shows evidences of different exploitation techniques; several imprints carved in the rock testify the extraction of huge blocks that were after subdivided into smaller ones by using wedges. The quarry is vertically divided into three distinct levels: the shallower down to -0.4 m depth, the medium down to -1.05 m depth (fig. 4H) and the deepest down to -1.5 m depth (fig. 4F). Various markers are present in the quarry, some of these directly related to the exploitation, such as floors and cutting lines, and some others related to the infrastructures linked to the quarry, such as stairs carved in the rock connecting different levels of the quarry. In this quarry, 9 points have been measured (tab. 1) most of which are floors; the deepest one (Point 20) is the base of a stair located in the seaward part of the area. The shallower points range in depth between -0.56 m and -0.76 m below sea level, the deepest lie between -0.95 m and -1.34 m below sea level (fig. 4F-G).

DISCUSSION

The coastal quarries can be used for determining sea level changes and, although it is not always possible to date them with accuracy, the territorial context, the block

TABLE 1 - Location and elevation of the archaeological markers. Tidal correction applied for tide amplitude at the moment of surveys; tide data from http://www.mareografico.it/ and http://www.IOC-sealevelmontoring.org. Atmospheric pressure data fromwww.wunderground.com. Functional height of the used marker above mean sea level.

Point n.	Site name	Archaeological indicator	Quarry n.	Elevation (m)	Tide (m)	Corrected Elevation (m)
1	Cape S. Calorio	floor of quarry	1	-0.8	0.22	-0.58
2	S. Calorio Bay	floor of quarry	2	-0.35	0.23	-0.12
3	S. Calorio Bay	cutting line	3	-0.82	0.21	-0.61
4	S. Calorio Bay	cutting line	3	-0.65	0.21	-0.44
5	Cape Bonico	cutting line	4	-0.30	0.19	-0.11
6	Cape Bonico	cutting line	4	-0.32	0.19	-0.13
7	Cape Bonico	cutting line	5	-0.32	0.19	-0.13
8	Cape Bonico	cutting line	5	-0.29	0.19	-0.10
9	Cape Bonico	cutting line	5	-0.25	0.19	-0.06
10	Cape Bonico	cutting line	5	-0.28	0.19	-0.09
11	Marzamemi Quarry	floor of quarry	6	-0.7	0.14	-0.56
12	Marzamemi Quarry	floor of quarry	6	-0.8	0.12	-0.68
13	Marzamemi Quarry	floor of quarry	6	-0.9	0.12	-0.78
14	Marzamemi Quarry	floor of quarry	6	-0.9	0.14	-0.76
15	Marzamemi Quarry	floor of quarry	6	-1.2	0.14	-1.06
16	Marzamemi Quarry	floor of quarry	6	-1	0.15	-0.85
17	Marzamemi Quarry	floor of quarry	6	-1.2	0.15	-1.05
18	Marzamemi Quarry	floor of quarry	6	-1.1	0.15	-0.95
19	Marzamemi Quarry	floor of quarry	6	-1.4	0.15	-1.25
20	Marzamemi Quarry	floor of quarry	6	-1.5	0.16	-1.34

module or the relative metrological system and architectonical elements left in situ are significant archaeological indicators (Auriemma & Solinas 2009). For this reasons and considering the abundance of this typology of archaeological settlements along the coast of southeastern Sicily, we applied a rigorous selection in order to identify the quarries for which an accurate dating was consensually attributed by archaeological literature. The aim of our selection was not only to find well-aged quarries, but also to choose those that were related to the same age of exploitation and possibly located in areas characterized by different tectonic settings.

The area of Marzamemi (AREA 3; fig. 2B) has been tectonically stable since the late Quaternary (Antonioli & *alii*, 2006; Ferranti & *alii*, 2006). For this area, Spampinato & *alii* (2011) have estimated a vertical deformation rate of about -0.085 ± 0.195 mm a^{-1} during the Holocene. The Quarry 6 of Marzamemi, moreover, has been intensely studied from an archaeological point of view and its age has been accurately constrained. In fact, Lena & Rustico (2010), using a morphometric and petrographic comparison between blocks found in the Marzamemi quarry and blocks used for buildings located in the nearby area, suggested a beginning of exploitation of the quarry in the V century BC (about 2.5 ka BP) and a second period of extraction of blocks aged between the VI and the IX century AD. Furthermore, it is possible to attribute the development of the deepest levels of the quarry to the Greek Archaic period, since during Byzantine age those levels were already submerged and not available for exploitation. Measurements in the Marzamemi quarry suggest the occurrence of three different levels: the shallower down to -0.4 m depth, the medium down to -1.05 m depth and the deepest down to -1.5 m depth; according with performed analysis, it is possible to attribute the deepest level to the first use of the quarry, occurred about 2.5 ka ago.

The area of Augusta (Area 1 and 2; fig. 2A) is characterized by a significant tectonic vertical deformation estimated for late Quaternary at rates of about 0.5 mm a^{-1} (Bianca & *alii*, 1999; Dutton & *alii*, 2009; Spampinato & *alii*, 2011). As for Marzamemi, also quarries located in northern Augusta area have been previously analysed by an archaeological point of view; according to Bernabò Brea (1968), exploitation techniques are clearly similar to those

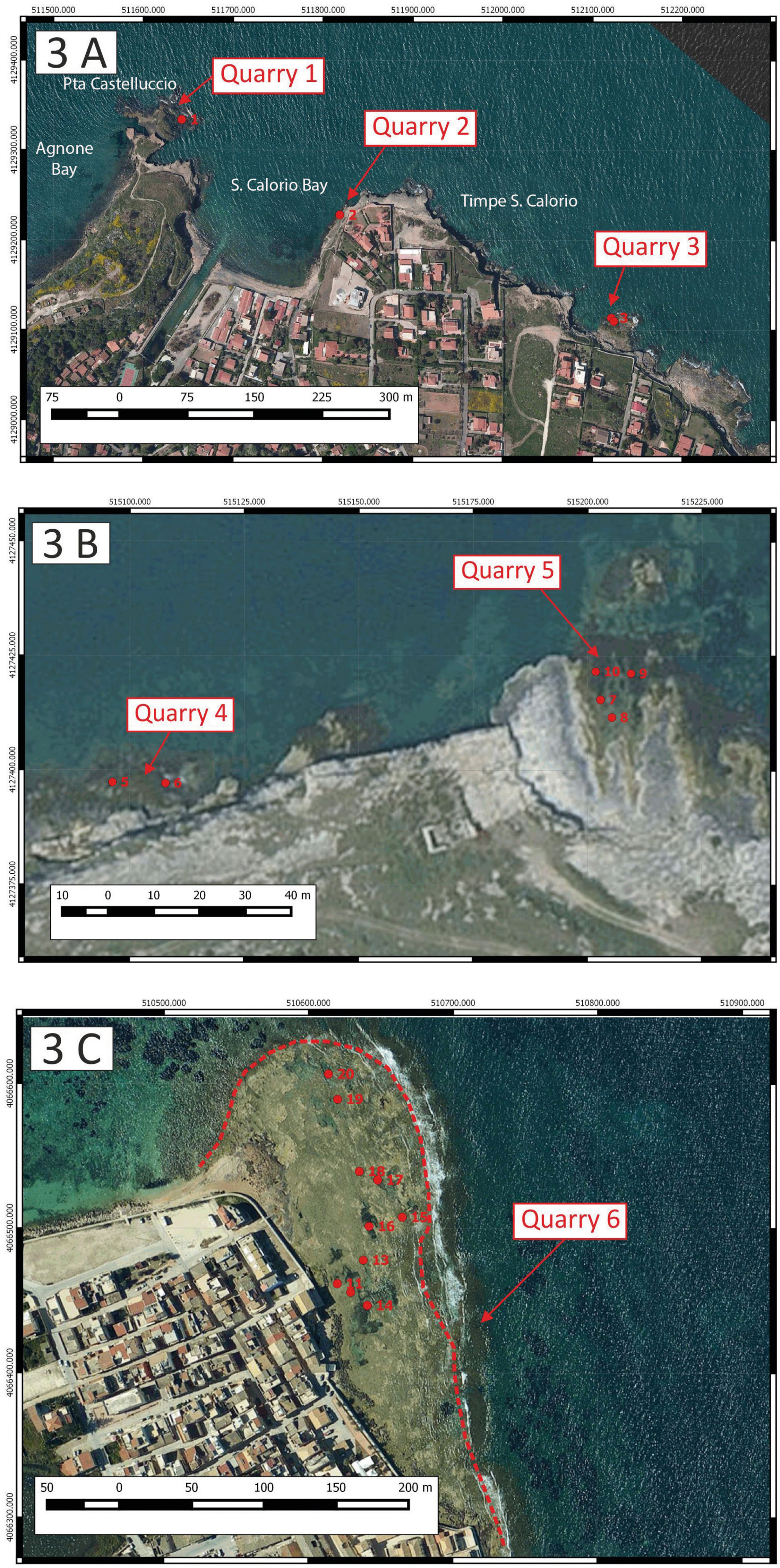

FIG. 3 - A) Google Earth detail of AREA 1 (see fig. 2A for location); B) Google Earth detail of AREA 2 (see fig. 2A for location); C) Google Earth detail of AREA 3 (see fig. 2B for location).

TABLE 2 - Uplift rates estimated for the quarries. 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.

Quarry n.	Site name	Archaeological indicator	Corr. elevation (m)	Functional elevation (m)	RSLC (m)	Age (ka BP)	RSL Lambeck & *alii*, 2011 (m)	Vertical Tectonics (m)	Tectonic Rate (mm a^{-1})
1	Cape S. Calorio	floor of quarry	-0.58	0.6	-1.18 ± 0.2	2.5	-1.72	0.54	0.21 ± 0.08
2	S. Calorio Bay	floor of quarry	-0.12	0.6	-0.72 ± 0.2	2.5	-1.72	1.00	0.38 ± 0.08
3	S.Calorio Bay	cutting line	-0.61	0.6	-1.21 ± 0.2	2.5	-1.72	0.51	0.20 ± 0.08
4	Cape Bonico	cutting line	-0.13	0.6	-0.73 ± 0.2	2.5	-1.72	0.99	0.38 ± 0.08
5	Cape Bonico	cutting line	-0.13	0.6	-0.73 ± 0.2	2.5	-1.72	0.99	0.38 ± 0.08
6	Marzamemi Quarry	floor of quarry	-1.34	0.6	-1.94 ± 0.2	2.5	-1.72	-0.22	-0.08 ± 0.08

used in Greek Archaic period, and the ancient towns that at that time could have expressed political influence on the quarries were Megara or Leontini. Buscemi & Felici (2004) related blocks extracted in the northern Augusta quarries with those found in the foundations of a tower composing a defence system surrounding the ancient town of Leontini during the V century B.C. (about 2.5 ka BP). In reasons of these considerations, we can affirm that development and first exploitation of the Marzamemi quarry is coeval with the Augusta quarries.

In order to obtain rates of vertical deformation, we compared ages and elevations of point surveyed in the quarries with the predicted curve for the Holocene (Lambeck & *alii*, 2011). For this analysis, we selected only the deepest points measured in each quarry (floors or cutting lines; tab. 2), taking particular care that these points were not heavily affected by erosion or mobilized by processes not related exclusively to tectonics (subsidence, sediment compaction, anthropic action). These data have been corrected for tide, as described in material and methods section, and, to compare them to ancient sea level, we defined a former functional height of about 0.6 m above mean sea level at the time of the first exploitation (Lambeck & *alii*, 2004; Antonioli & *alii*, 2007; Scicchitano & *alii*, 2008; 2011b; Auriemma & Solinas 2009; Lo Presti & *alii*, 2014). Applying functional height to the corrected elevation is thus possible to reconstruct the paleo-sea level, and considering a predicted values of sea level of about -1.72 m below present at the considered age of 2.5 ka BP (Lambeck & *alii*, 2011), it is possible to calculate the rate of vertical deformation of the analysed coastal areas (tab. 2).

For the Marzamemi area, a rate of about -0.08 mm a^{-1} has been estimated, in good agreement with Spampinato & *alii* (2011) that calculated for this area a rate of about -0.085 ± 0.195 mm a^{-1}. As regards the Augusta area, tectonic uplift of 0.2-0.4 mm a^{-1} have been estimated, probably related to regional processes combined with the activity of WSW-ENE trending Quaternary faults located north of the town (Westaway, 1993; Bianca & *alii*, 1999; Servizio Geologico d'Italia, 2011; Spampinato & *alii*, 2013). Analysis performed in the AREA 2 indicated an uplift rate of about 0.38 mm a^{-1} consistent with the rate calculated by Dutton & *alii* (2009). On the contrary, the rate estimated for the AREA 1 are halved with respect to AREA 2, being characterized by values ranging between 0.20 and 0.21 mm a^{-1}. This result is particularly strange considering the short distance between the two areas. We propose two hypothesis to justify these discrepancies: i) the age of the quarries located in AREA 1 is different from 2.5 ka BP, ii) some tectonic structure influenced the position of the quarries in AREA 1. In tab. 3 are reported examples of uplift rates estimated for Quarry number 3, located inside the AREA 1, considering different ages of use ranging from 3 and 2 ka BP. As you can see, the uplift rate increases only if we take into account an age older than the one estimated by archaeologists. This hypothesis seems poor of consistency considering the large number of archaeological and historical constraints supporting the idea that the quarry was exploited during the Greek Archaic period. The other hypothesis considers the possibility that tectonic structures could have controlled and influenced the coastal sector where the quarries are located.

Two WSW-ENE trending Quaternary faults are marked north of Augusta in the official geological map of the Italian geological service (fig. 5; Servizio Geologico d'Italia, 2011). Furthermore, Spampinato & *alii* (2013), through the analysis of high precision levelling of the last 40 years, pointed out that the northern fault, intercepting the coastline just north of the AREA 1 (fig. 5) is still active. Levelling data

TABLE 3 - Tectonic rates estimated for quarry n. 3 for different ages.

Quarry n.	Site name	Tectonic Rate (mm a^{-1})	Age
3	S. Calorio Bay	0.34 ± 0.07	3.0 ka BP
3	S. Calorio Bay	0.2 ± 0.08	2.5 ka BP
3	S. Calorio Bay	0.035 ± 0.1	2.0 ka BP

FIG. 4 - A) Quarry 1 (AREA 1), with location of Point 1 measurement of the deepest portion of the floor; B) Quarry 2 (AREA 1) with location of Point 2 measurement of the floor; C) Quarry 3 (AREA 1), with location of Point 3 measurement of the cutting line; D) Quarry 4 (AREA 2), with location of Point 6 measurement of the cutting line; E) Quarry 5 (AREA 2), with location of Point 7 measurement of the cutting line; F) Quarry 6 (AREA 3), with location of Point 17 and Point 18 measurements of the floor; H) Quarry 6 (AREA 3), with location of Point 19 measurement of the floor.

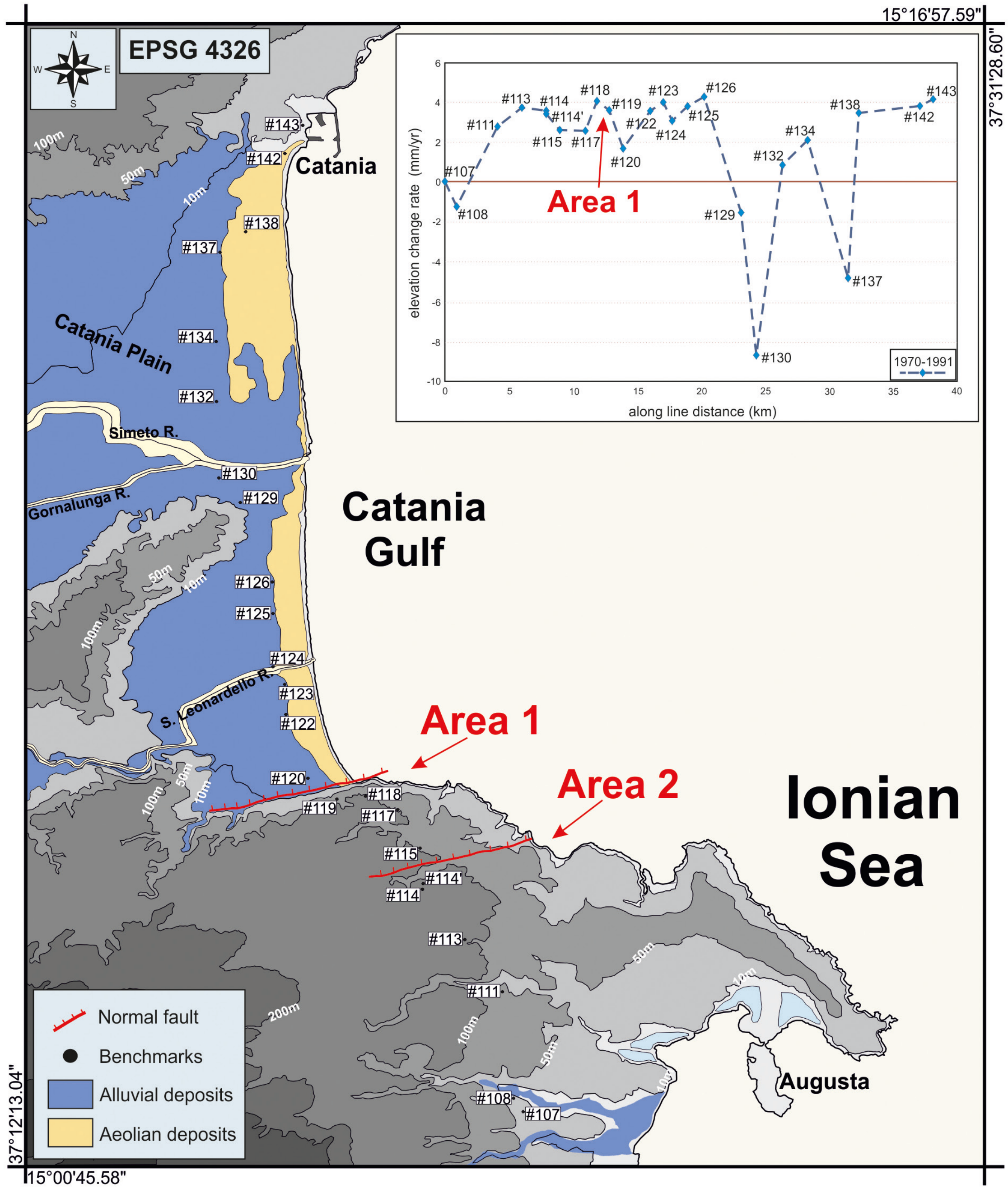

FIG. 5 - A) Morphotectonic map of the Augusta area with the normal faults located in Area 1 and Area 2, and numbers identifying benchmarks of the geodetic levelling (modified after Spampinato & *alii*, 2013). B) Inset shows the diagram expressing the relative movements of the benchmarks during the last 40 years (modified after Spampinato & *alii*, 2013).

(see inset in fig. 5), in fact, show a relative vertical motion (between benchmarks #118 and #120) related to very recent creep. The southern fault, located about 2 km southeastwards between the AREA 1 and the AREA 2 (fig. 5), even though not showing evidence of deformation in the last decades, could have contributed in the past to the offset between the quarries located along the coast north of Augusta, explaining the different tectonic vertical mobility.

CONCLUSIONS

The altitude of the archaeological markers measured in six ancient quarries located in coastal sectors of southeastern Sicily have has been measured by an invar rod with respect to present mean sea level, and corrected for tide at the time of surveys. These data were compared with predicted sea level rise curves for the Holocene using a glacio-hydro-isostatic model (Lambeck & *alii*, 2011). The comparison with the curve for the southeastern Sicily coast yields a tectonic component of relative sea-level change related to regional uplift. Results show a good agreement between the estimated vertical rates of tectonic movements with the values known in literature for the site of Marzamemi, considered tectonically stable. On the contrary, discrepancies for the tectonically uplifted sites north of Augusta have been highlighted, where slight difference in the uplift rate between the two analysed areas resulted. Although this area suffers a general regional deformation, local inhomogeneities can be explained by the activity of two tectonic structures intercepting the coast.

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