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Millstone quarries along the Mediterranean coast: Chronology, morphological variability and relationships with past sea levels

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Abstract

The coast of the Mediterranean provide several remnants of ancient coastal quarries, which are now useful to study sea level change occurring during the last millennia. Millstones quarries were exploited with same quarrying techniques from rocks like beachrocks, sandstones or similar lithologies, were shaped to be suitable to grind olives, seeds and wheat, to produce oil and flour, or to break apart soft rocks.

In this study we integrated historical sources, aerial photography, field surveys and palaeo sea-level modelling to investigate a number of millstones quarries with the aim to asses the intervening sea level change that occurred since the quarries were abandoned.

We investigated on their chronology, spatial distribution and spatial relationship to the sea-level. Our results indicate that most of these were carved close to sea level between 1.45 ka and 0.25 ka cal BP, but mainly around 0.45 cal ka BP. Despite the uncertainties associated with the chronology in, we found good agreement between their lowest elevation (between 0.33 m and −0.06 m) and the paleo sea-levels, as predicted by the GIA models.

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Keywords

Mediterranean coastCoastal quarriesMillstonesRelative sea-level changesArchaeological sea-level markers

1. Introduction

Several archaeological sites located along the Mediterranean coast are today submerged due to the sea-level changes and vertical motion of the land occurring since the time they were built (Lambeck et al., 2004). Coastal structures found at these sites have been often used as sea-level markers to constrain relative sea-level variations since antiquity (Flemming, 1969, Schmiedt, 1975, Antonioli et al., 2007, Scicchitano et al., 2011, Auriemma and Solinas, 2009, Anzidei et al., 2011a, Anzidei et al., 2011b, Anzidei et al., 2014, Kolaiti and Mourtzas, 2016, Mourtzas et al., 2016).

A large range of archaeological, historical and iconographic sources provide evidence that millstones were designed both for grain grinding and olive pressing during a large temporal span.

Millstone are documented in southern Italy since around 2500 years BP (Amouretti, 1986, Amouretti and Brun, 1993, Brun, 1997); their sizes and shapes (see chapter 1.1) fit the carving systems used at those times, characterized by cylindrical or slightly truncated cone shape wheels that turn perpendicularly above a subjacent horizontal wheel of similar size placed above a masonry (Fig. 5).

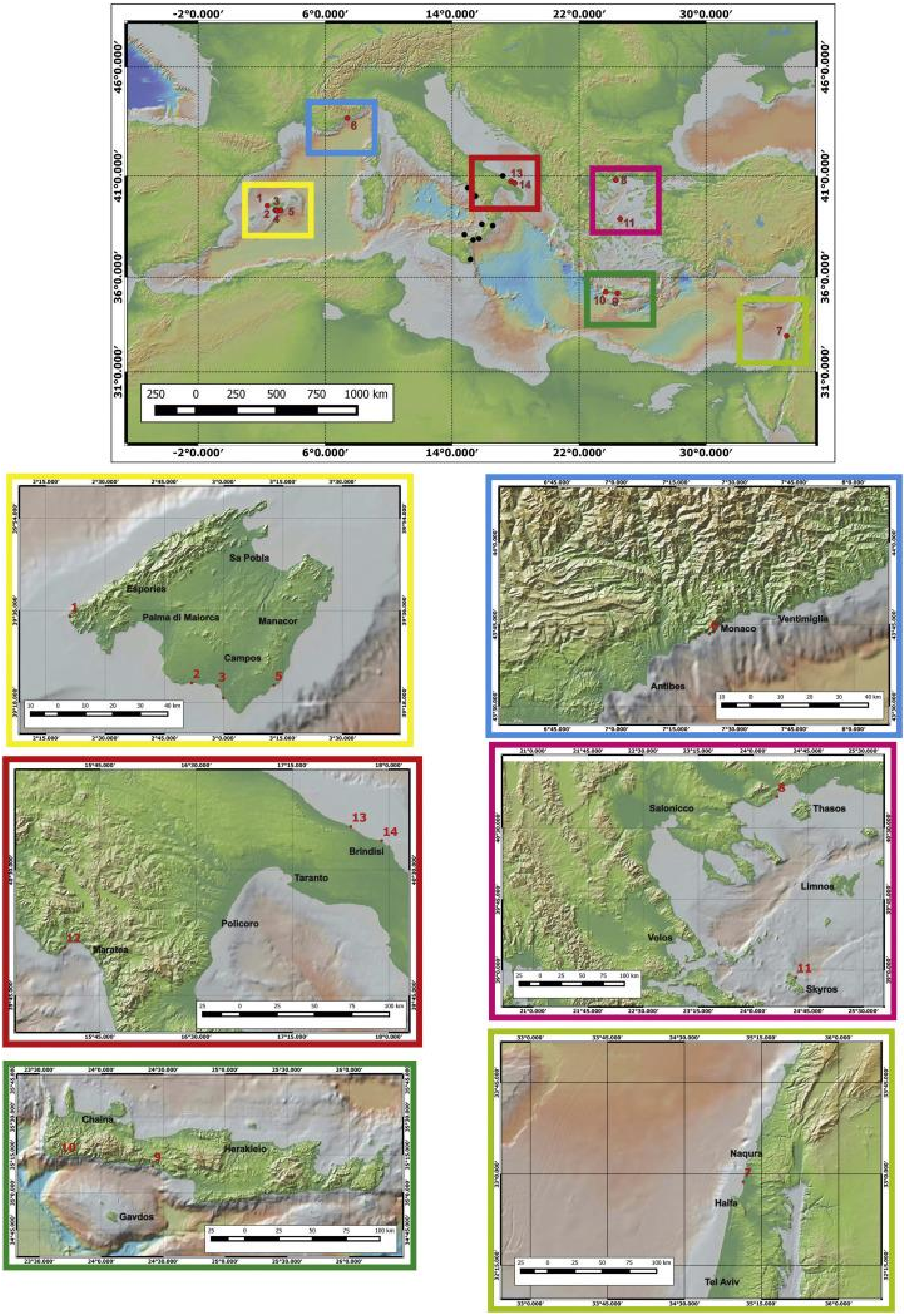
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Fig. 1

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Fig. 2

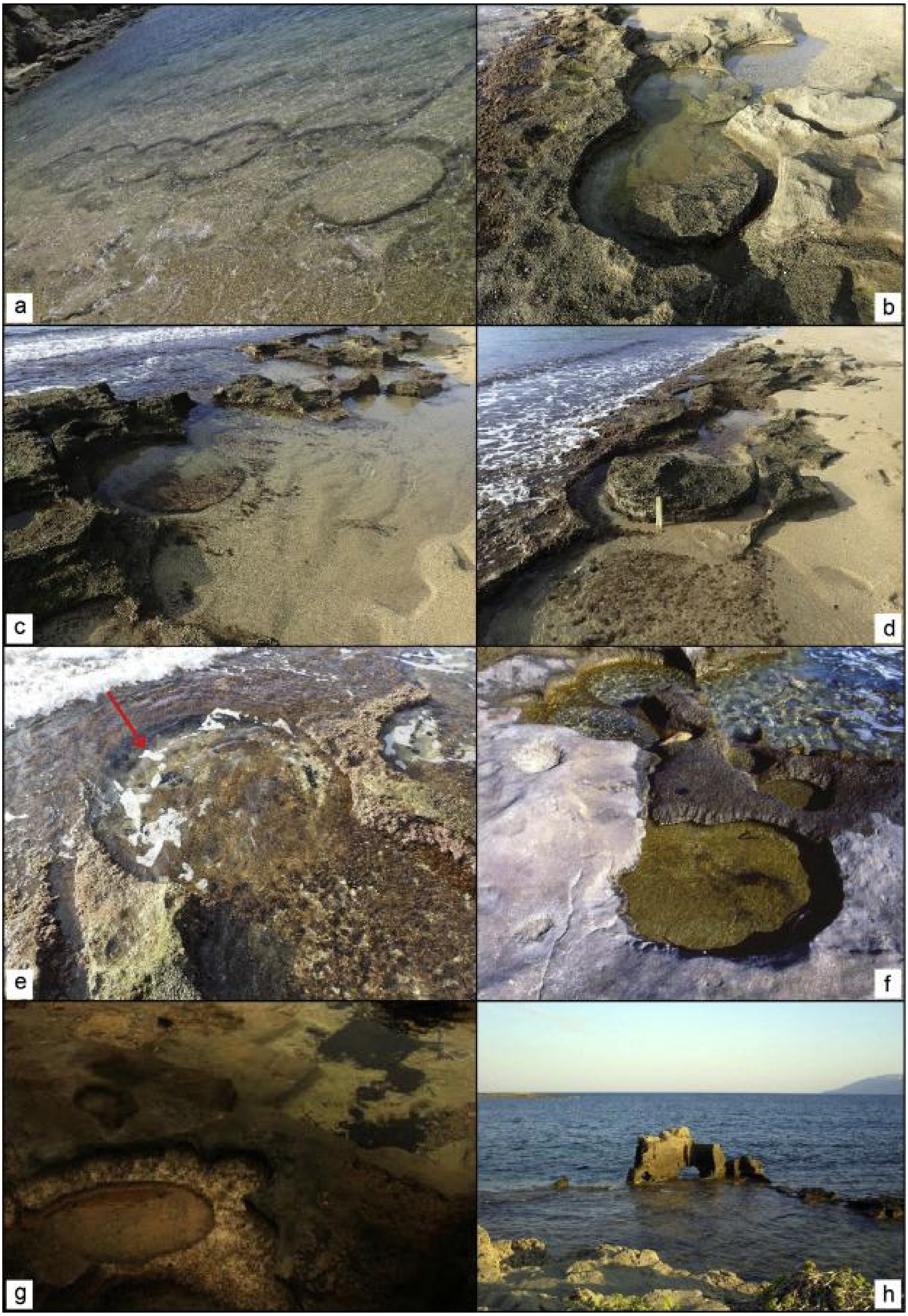

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Fig. 3


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Fig. 4

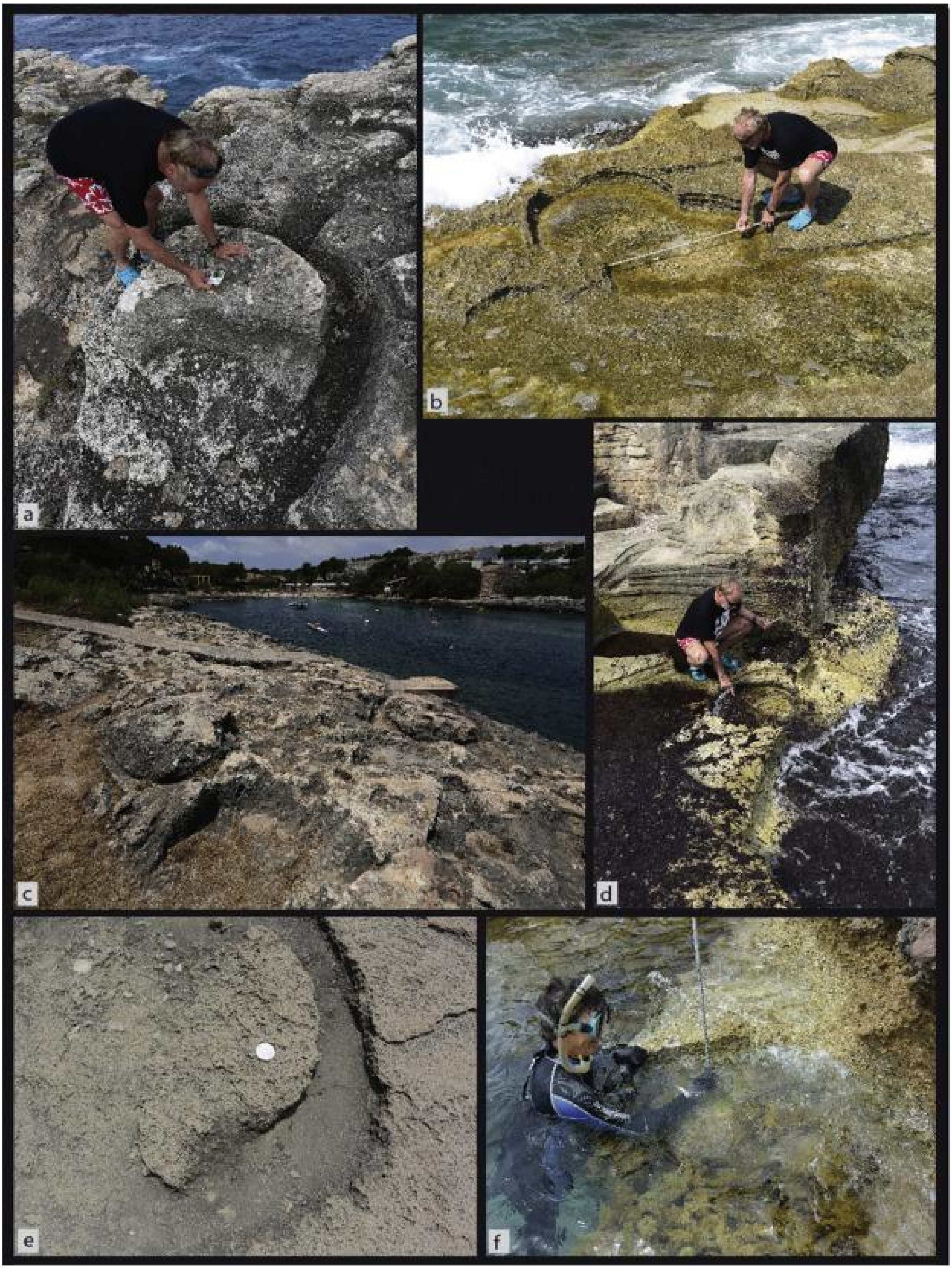

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Fig. 5

The use of millstones is reported since the beginning of the Hellenistic period but a large spread in the Mediterranean basin is evident from the Roman to the modern age. After the XIX century this traditional crusher system (the millstones) was progressively abandoned (Amouretti and Brun, 1993). According to literary archaeological sources coastal quarrying was one of the best logistic solution for the difficultyes (Please look at the English vocabulary difficulties not difficultyes) of heavy stone transport because, after extraction, the millstone could be directly transported on boats or barges almost exclusively through waterways (rivers and sea) Felici and Lanteri 2012.

Previous investigations focused on coastal millstone quarries and their use as sea-level markers along the Italian coasts (e.g., Lo Presti et al., 2014). In this study we extended investigations across the Mediterranean by studying 13 new coastal quarries located in Spain, France, Italy, Greece and Israel (Fig. 1, Fig. 2). The aim of this paper is to investigate the spatial distribution and chronological variability of these millstone quarries, analyzing their elevations above sea-level positions at the time they were used.

1.1. Millstone quarries: typology and chronology

Here we examine a series of coastal quarries used to extract cylindrical millstones with diameter >1 m, usually dating back to medieval and modern age (1.0–0.25 ka BP) and related to watermills/hydraulic mills, windmills, or animal or man-driven mills. In order to better specify the open question, we tried to clarify in this study the historical-archaeological documentation related to chronology and use of these artifacts.

A large range of archaeological, historical and iconographic sources provide evidence that millstones were designed for both grain grinding and olive pressing. Other and less important use was the milling of all kinds of seed oils (i.e. castor, sesame, in Egypt; walnut oil in France; Amouretti and Brun, 1993) and the breaking limestone and gypsum. The two main typologies of millstones are described below:

1.1.1. Flour millstones

During the Roman age in the Mediterranean two types of flour millstones are known: the Pompeian hourglass millstones and the double cylindrical flat various-size millstones. The second type specimens have diameters ranging between 0.25 and 0.40 m and were "rotary hand-mill", sometimes "adjustable" (*macine di tipo rotatorio manuale*, *regolabile*); the bigger diameters were between 0.45 and 0.8 m, and required big animals like horses or donkeys as power ("*macine a ingranaggio*"). Once millstone were connected to hydraulic wheels, it was possible to exploit the power of the water (hydraulic/water-mills, *macine per mulini ad acqua*). The most ancient reference to a watermill was found in an epigram attributed to the poet Antipatros of Thessaloniki (2.1 BP Ant. Pal. IX, 418), although other Latin sources describe these artifacts Vitruvius,, Plinius,, Wikander, 1979, Wikander, 1984). Large stones were used for these water mills, as testified by the millstones discovered in Athens (Parsons, 1936), Rome (Bell, 1994, Wilson, 2000, Humphrey et al., 2006), in France at Barbegal, Martresde-Veyre, Mesclans with mole in basalt, Les Laurons (1.8–1.7 ka BP), Marseille and La Calade (1.5 ka BP) (Benoit, 1940, Amouretti, 2002), and in Switzerland at Avenches (Castella, 1994). According to the available documentation, the millstones used in the Roman watermills were smaller than the examples extracted in the sites reported in this paper (see result section): they were ranging between 0.48 and 0.92 m of diameter and between 0.10 and 0.45 m of thickness; most of them were made of hard volcanic rocks.

The hydraulic mills with flat, cylindrical and horizontal coupled millstones were used in Europe only since Middle Ages, resulting in a great technological and cultural revolution. However, in the Eastern Mediterranean there are evidence of using them since the (1.8 ka BP, Frankel, 2007). This technology was in use without significant modification until the middle of 20th century or later (Ayalon E. personal communication 2016). Only the development of power mills' (operated by engines) and the lack of water, due to the alterations of the water courses, determined the end of the water mills in the 20th century. Millstones with diameter between 0.80 and 1.40 m are usually referred to the Middle ages while millstones with diameters between 1.50 and 1.75 m are dated back to XVII and XIX centuries (Belmont, 2011, Auriemma et al., 2014, Lo Presti et al., 2014). See also S1 for a detailed description of Oil millstones and quarrying technique.

2. Methods

The geographical variability of coastal millstone quarries was investigated combining bibliographic sources (Belmont, 2006), aerial photos as well as field surveys on 13 new sites throughout the Mediterranean (Fig. 1, Fig. 2).

The 13 new coastal millstone quarries surveyed in this study are presented in Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7 and Table 1, Table 2. We underline that sites from Greece (8–11) and the new sites in Italy (13–14) have been never investigated before. For the sites of Scario (Italy), Cap D'ail (France) and Akko (Israel), previous descriptions were available (Lo Presti et al., 2014, Belmont, 2006, Galili and Sharvit, 2001). The measurements of the current elevation of the millstones with respect to the current sea-level at the time of the surveys were performed by an invar rod as described inLambeck et al., 2004, Antonioli et al., 2007, Vacchi et al., 2012). All measurements were performed between 2014 and 2015. 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 IOC-sealevelmontoring.org). We have analyzed 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 tidal gauges (TG) of Palma de Mallorca, Marsiglia, Hadera, Otranto, Salerno, Brindisi, Kavala, Heraclion). We then used the estimated local msl values to correct the elevation of the significant parts of the millstone quarries with respect to the sea-level measurements during field surveys. The elevation of the lowest carvings of the millstone quarries were subsequently compared to the modern mean sea-level valid for the investigated area (following Lo Presti et al., 2014).

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Fig. 6

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Fig. 7

Table 1. Survey data: A) Site name and reference tide gauge station used to correct elevations of archaeological sea level indicators for local mean sea level., B) site coordinates; C) date and time of surveys; D) uncorrected altitude

of the archaeological indicators; E) tide value during surveys obtained from the nearby tidal stations. Sea level data retrieved from www.ioc-sealevelmonitoring.org and www.mareografico.it (Italian sites only); F) altitude after tidal correction has been applied; G) archaeological age. In parenthesis are the key references (see below); H) millstones size of the investigated sites.

A	B	C	D	E	F	G	H
Sites	**Coordinates**	**Date and time** **dd/mm/yy** **(GMT)**	**Altitude** **(cm)**	**Tide** **(cm)**	**Corrected altitude** **(cm)**	**Archeological age BP** **(2015)**	**millstones size (cm)** **a. millstone diameter** **b. hole of extraction diameter** **c. millstone**

							thicknes s
1 Sant'Elm Mallorca (TG Palma de Mallorca)	39° 34 53 31″ 02° 21 02 06″	11.06.15–15.15 (13:15)	−20 ± 5	−9	−11 ± 5	13th – 18th century (1) 465 ± 250	a. 95 b. 120 c. 25
2 Cala Pi Mallorca (TG Palma de Mallorca)	39° 2147 95″ 02° 51 51 26″	13.06.15–10.00	+10–15 m	–	No relationship with msl	16th – 18th century (1) 315 ± 100	a. 120 b. 200 c. 60/30
3 Campos Es Trenc Ses Covetes, Mallorca	39° 21 10 45″ 02° 58 20 84″	13.06.15–10.30	0 ± 5	−6	−6±5	16th – 18th century (1) 315 ± 100	a. 75 b. 95 c. 30

(TG Palma de Mallorca)							
4 Colonia Saint Jorda, Mallorca (TG Palma de Mallorca)	39° 18 51 30″ 2° 59 52 33″	13.06.15–11.30	+20 ± 5	+6	No relationship with msl	16th – 18th century (1) 315 ± 100	a. 75 b. 100 c. 25
5 Porto Pedro Mallorca (TG Palma de Mallorca	39° 21 22 74″ 03° 12 43 48″	13.06.15–14.00	+140 ± 5	–	No relationship with msl	5th – 15th century (1) 1300 ± 500	a. 100 b. 120 c. 35
6 Cap d'Ail Francia	43° 43 12 35″	30.04.15–14.00	+260 ± 5	–	No relationship with msl	750 ± 250 (1)	a. 100 b. 120

(TG Marseille)	07° 23 30 52″						c. 35
7 Akko Israel (TG Hadera)	32° 56′ 3.8″ 35° 04′ 19.6″	21.10.14–13.50 11.01.16–12.30	33 ± 5 27 ± 5	+21	−6±5	Post Persian (2) 1450-100 600 ± 600	a. 100 b. 120 c. 20-30
8 Nea Peramos, Nortern Greece (TG Kavala)	40°49′23.13″ 24°19′23.88″	26.10.15–09.0	−50 ± 5	+17	−33 ± 5	14th – 17th century (2) 450 ± 150	a. 55-160 b. 60-180 c. 15-30
9 Skyros, Northern Aegean, Greece –	38°55′30.41″ 24°34′55.14″		−25 ± 5	–	−25 ± 5	10th –14th century (2) 750 ± 250	a. 100 b. 120 c. 30

10 Damnoni, Crete, Greece (TG Heraclion)	35°10′26.70″ 24°24′58.40″	5.10.2014 09.30	−10 ± 5	+5	−15 ± 5	16th – 17th century (2) 350 ± 100	a. 150-170 b. 160-180 c. 30-40
11 Paleochora, Crete, Greece (TG Heraclion)	35°14′13,94″ 23°40′02,39″	3.10.2014 15.40	−15 ± 5	−9	−24 ± 5	16th–17th century (2) 350 ± 100	a. 25-120 b. 30-130 c. 20-30
12 Scario Italy (TG Salerno)	40 02 25 13 15 28 42 04	28.05.2011 12.30	−20 ± 5	+5	−15 ± 5	370 (3)	a. 130-160 b. 165-180 c. 30

13 Torre Santa Sabina Italy (TG Otranto)	40°45′26,96″ 17°42′14,38″	19.12.2015 10.00	−15 ± 5	+2	−13 ± 5	1450–250 600 ± 600	a. 85-105 b. 120-135 c. 15-25
14 Punta Penne, Brindisi, Italy (TG Otranto)	40°40′22,52″ 17°56′44,42″	19.12.2015 08.45	−10 ± 5; +30 ± 5	–	No relationship with msl	1450–250 600 ± 600	a. 75 b.not available, not in situ c. 25-95

References for the archaeological ages: 1 Belmont, A., (2006) *Atlas des carrières de meules de moulinsen Europe*, http://meuliere.ish-lyon.cnrs.fr/. Millstonequarries.eu consists of both an inventory of European millstone quarries and a source of related information. It is organised by the CNRS (UMR 5190, Laboratoire de Recherche Historique Rhóne-Alpes). The database can be consulted freely on-line and anybody with knowledge of unidentified sites is free to fill in an entry. 2 This paper. 3 Lo Presti et al., 2014. Because tidal stations are nearby the investigated sites, we can estimate a safe overall error in the elevation at ±5 cm (mostly depending on the level of preservation of the sea level indicator, corresponding to the deepest carved part of the millstone).

Table 2. Lithology; vertical tectonic: MIS 5.5 and late Holocene altitude, References for the studied sites.

Site	Lithology	Altitude MIS 5.5	Late Holocene	References
1 Sant Elm Mallorca	Quaternary Sandstone	3-5 m, stable.		Muhs et al., 2015 Hearty, 1987
2 Cala Pi Mallorca	Miocene Sandstone	3-5 m, stable.		Muhs et al., 2015 Hearty, 1987
3 Campos Es Trenc	Calcarenite MIS 5.5	3-5 m, stable.		Muhs et al., 2015 Hearty, 1987
4 Colonia Saint Jorda	Calcarenite MIS 5.5	3-5 m, stable.		Muhs et al., 2015 Hearty, 1987

5 Porto Pedro Mallorca	Sandstone MIS 5.5	3-5 m, stable.		Muhs et al., 2015 Hearty, 1987
6 Cap d'Ail Francia	Quaternary Breccias	18-20 m, quasi stable		Dubar et al., 2008
7 Israel Akko	Post Byzantine beach-rock	1-9 m stable		Galili et al., 2007
8 Nea Peramos, Nortern Greece	Upper Holocene beachrock	–	–	
9 Skyros, Northern Aegean, Greece	Pleistocene Sandstone	–	Relative sea level rise about 0.55 m during the last 450 years	Evelpidou et al., 2011 Present study

10 Damnoni, Crete, Greece	Beachrock dated 580 ± 55 yr BP	–	Relative sea level rise by 0.55 m during the last 400 years	Mourtzas et al., 2016 Neumeier et al., 2000
11 Paleochora, Crete, Greece	Beachrock dated 1044 ± 15 yr BP	–	Relative sea level rise by 0.55 m during the last 400 years	Mourtzas et al., 2016 Mouslopoulou et al., 2015
12 Scario	Conglomerate (Last Interglacial with *Strombus b)*	5 m, stable		Ferranti et al., 2006
13 Torre Santa Sabina	Calcarenite di Gravina formation - Lower Pleistocene Inferiore	7, stable		Mastronuzzi et al., 2011

14 Punta Penne, Brindisi	Calacarenite di Punta Penne (Middle -Upper Pleistocene)	7, stable	Mastronuzzi et al., 2011

For each site we assumed that quarry floors correspond to the lowest level of the millstone quarry with respect to the local msl, i.e. the deepest anthropic carved level of the rock outcrop as showed in Fig. 3e. Diameter and thickness of extraction imprints were also measured (Table 1, Table 2).

The uncertainties of our elevation measurements can be estimated at ±5 cm. (corresponding to the deepest carved part of the millstone), while tide correction at the time of measurements is applied using the available tidal stations located nearby the study area (se Table 1 and caption).

In order to evaluate the relationship between the quarry and the sea-level position at the time of excavation, we used the predicted paleo RSL for each site (Lambeck and Purcell, 2005, Lambeck et al., 2011).). Part of the measured millstone quarries submersion (about 0.13 m) has been related to the post-industrial (i.e. last 100 years) acceleration of sea-level rise (Lambeck et al., 2004), once that the recent eustatic value has been excluded in the analysis, the total RSL changes is reduced to 0 to −0.1 m at 0.4 ka BP and to −0.2–0.30 m at 1.0 BP.

In addition, we assessed the long-term coastal vertical displacement by measuring the elevation of the markers of the Last Interglacial highstand (MIS 5.5: Ferranti et al., 2006) and any possible recent vertical displacement using robust Holocene evidence of paleo RSL (Ferranti et al., 2006, Antonioli et al., 2007, Lambeck et al., 2011).

3. Data analysis

The elevations of the investigated millstone quarries with respect to the modern local msl are ranging between 3.0 m and −0.31 m. Millstones were carved into relatively soft rocks i.e. calcarenite, beachrocks, and sandstone (Table 2).

3.1. Sant Elm, Mallorca

This site is located on the western coast of Mallorca island (Fig. 1, Fig. 2, Fig. 5, Fig. 8, S2). The quarry lies on a small promontory gradually sloping to the sea. The excavation occurs between 6 and 2 m above msl. Here we measured about ten imprints of carved millstones. The lowest one is located a few centimeters below the current msl. The rock in which they are carved is particularly erodible (Quaternary sandstone). Imprints have a maximum diameter of 120 cm and 25 cm of thickness. Although they have been recently carved, are largely eroded. The chronological attribution refers to a period of activity of the quarry between the XIII - XVIII century (Belmont, 2006), (465 ± 250 BP), Table 1. The entire island of Mallorca is considered tectonically stable (Muhs et al., 2015; Hearty, 1987).

3.2. Cala Pi, Mallorca, Spain

This site shows some hundreds of millstones (imprints or not terminated) with different sizes and diameters ranging from 2 to 0.6 m. Lithology consists of Miocene sandstone, without evident correlation with sea-level being placed at the top of a cliff 15 m above current msl. The chronological attribution of this site refers to a period of activity of the quarry between the XVI - XVIII century (315 ± 250 BP) (Belmont, 2006) (Fig. 1, Fig. 2, Fig. 5, Fig. 8, S2, Table 1).

3.3. Campos Es Trenc Ses Covetes, Spain

This site contains extensive cuttings that can be related to millstone quarries. Here were found the imprint of a millstone with a diameter of 0.9 m, carved on sandstones of the last interglacial. The deepest traces of carving activity were found at −6 cm below msl. The chronological attribution of this site refers to a period of activity of the quarry between the XVI - XVIII century (315 ± 250 BP) (Belmont, 2006) (Fig. 1, Fig. 2, Fig. 5, S2, Table 1).

3.4. Colonia Saint Jorda, Spain

This site shows quarries with numerous cuts on a wide area. Millstones are carved on sandstone of the last interglacial up to a maximum depth of about −0.48 m and with diameters up to 1 m. The chronological attribution of this site refers to a period of activity of the quarry between the XVI - XVIII century (315 ± 250 BP) (Belmont, 2006). The outer dimensions of the excavation are 1 m and 0.35 m of thickness (Fig. 1, Fig. 2, Fig. 5, S2, Table 1).

3.5. Porto Pedro, Mallorca, Spain

This site is located within a channel connected with the sea, in which are cut some quarries and millstones (imprints and partially carved) at about 2.3 m asl. The part closest to the modern shoreline has been eroded. Lithology consists of a sandstone of the MIS 5.5. The chronological attribution of this site refers to a period of mining activities of the quarry between the V - XV century, (1300 ± 500 yrs) (Belmont, 2006) (Fig. 1, Fig. 2, Fig. 5, Fig. 8, S2, Table 1).

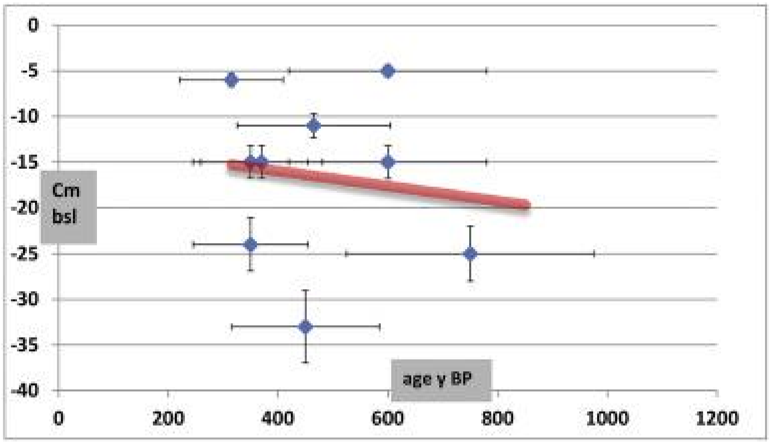

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Fig. 8

3.6. Cap d'Ail, France

The site is located between Nice and Monaco and dates to the medieval period (Belmont, 2006) 750 ± 250 BP, Table 1). About ten millstones showing 1.2 m of diameter and 0.35 m of thickness, between 2 and 4 asl were surveyed. The portion of the quarry closest to the modern shoreline shows evidence of marine erosion (Fig. 1, Fig. 2, Fig. 6, Fig. 8, S2). Lithology consists in well cemented Quaternary breccia. From a tectonic point of view, approximately 1 km away from this site has been observed a transgressive marine terrace reaching about 9 m asl. The depositional terrace cuts a metamorphic unit consisting in a marine conglomerate of approximately 1.5 m of thickness. A few hundred meters away, a massive limestone with Lithophaga spp. boreholes is outcropping at 7 m of elevation asl. We believe it represents the MIS 5.5 level and, based on its elevation, it is reasonable to hypothesize the tectonic stability of this area.

3.7. Akko, Israel

This site can be divided into a north and a south quarries, placed about 80 m apart. The northern quarry (ca 70 m long and 20 m wide) is split by a sewage pipe (Fig. 1, Fig. 2, Fig. 7, Fig. 8, S3). It includes circular depressions formed in the beachrock pertaining to the imprints of the millstones detached from the bedrock. Linear cuttings, stairs and channels, remnants of building stones are also present in this site. The quarry extends north-south, parallel to the coastlinebetween 0.24 m and −0.31 m of the Israel msl. Thirty six clearly circular incisions (1.2–1.4 m in diameter, 0.2 m deep) were also observed. These included 23 imprints and 13 millstones left in situ. Some of these are still integer while some are broken (Galili, and Sharvit, 2001).

The southern quarry (ca 5 m long and 3 m wide) is located on southeast side of a small islet, located some 10 m from the coastline. The imprints are at elevation of ca. 0.42 to 0.72 m above the Israel MSL. The southern quarry includes 4 scars of millstones, similar in size to the ones from the north quarry, but slightly thicker.

In the Akko north quarry, the round impressions and the unfinished stones indicate that the stones diameter was ca 0.8–1.0 m and they were ca 0.2–0.25 m thick. A first carving was performed marking a circle by a compass or a rope. Subsequently, a circular channel (0.2 m deep 0.13–0.2 m wide at the top, 0.06 m wide in its bottom) was cut in the beachrock. The channel was initially formed of two parallel cuts separated by a thin wall about 10 cm thick that was later removed by braking. Iron splits were then hammered into the channel in order to produce lateral pressure, which detached the stone from the bedrock. It was suggested that wooden splits and water may have also taken place in ancient quarries (Durkin and Lister, 1983). However, according to Dworakowska (1987) the use of this practice was never proven. Judging by the impressions, it seems that in the south quarry the stones were slightly thicker, ca 0.3 m thick.

The beachrock in the two Akko quarries is not fractured It is made of coarse, finely sorted, sand (mainly broken shells) and some fine quartz grains cemented by carbonate. The stones were probably used as millstones intended for grinding. The coarse and relatively hard, stone could have been chosen as a local substitute for the preferred basalt stone, which was commonly used for grinding stones in ancient Israel. The reason for this was probably because the basalt sources were distant and the beach rock was available and accessible and easier to get. The possibility that the round stones were used for other purposes (e.g. grave sills) cannot be ruled out. The quarry is located opposite a relatively deep underwater canyon, in a place where the abrasion platform is very narrow. Thus the access of water craft to the quarry enabled transportation of the extracted stones by sea.

Fragments of pottery shards dated to the Persian period (Getzov N. pers. Comm. 2015) were embedded in the beach rock close to the south quarry. The pottery suggests that the beach rock was consolidated after that period (after 2.4 ka BP) and that the stones were quarried at a later period.

Based on Rabinic sources in the Tosefta (*Tos. Shabat 1, 28*), Frankel suggested that water millstones (Large, round mill stones) probably began to appear in Israel during the Roman period as early as the first century AD (Frankel, 2003, Frankel, 2007). These millstones were common in Israel during the Byzantine, Crusader Mamluk and Ottoman periods (Ayalon E. Pers. Comm. January 2016). The millstone quarry may thus be post first century AD (Roman to late Ottoman periods: 2–0.1 ka BP. We assume the quarry activity between 1450 and 250 years BP.

3.8. Nea Peramos, Greece

The millstone quarry of Nea Peramos is located 2.5 km south of the village, along the coastline of the Northern Aegean Sea. Traces of millstone extraction are still observed in the beachrock formation developed on the coast, which consists of cemented coarse sandstone material with a high percentage of cobbles. It outcrops at elevation of +0.80 m on the modern msl and its seaward end is at a distance of about 12 m from the shore, with a maximum depth of its top and base at −0.85 m and −1.85 m, respectively. It is measured at about 260 millstone blocks have been carved out of monolithic beachrock slabs between the elevations −0.5 m and +0.5 m. The diameter of the carved rings and the in-situ left millstones ranges from 1.4 m to 1.6 m and their thickness from 0.15 m to 0.30 m; but also few smaller pieces of a diameter 0.55 m seems to have been extracted. A channel 0.1 m–0.15 m wide was carved around the millstone. The base of the deepest detached ring is located at −0.50 m and its top at −0.33 m.

Coastal quarries of circular sandstone millstones are found throughout the coast of Northern mainland Greece and date back from 15th century to 17th century (Papagelos, 1994, Melfos et al., 2014). The quarrying activity in Nea Peramos could be related with the nearby Byzantine town of Anaktoropolis that flourished between 10th century and 15th century. Quarrying most likely started in the Byzantine Times and continued into the Ottoman domination period (17th century), in a time interval of 450 ± 150 years BP (Fig. 1, Fig. 2, Fig. 4, Fig. 8, S3).

3.9. Skyros, Greece

The ancient sandstone quarry covers an area of about 5000 m^2. It is located at the cape of Pouria, in the NE part of the island, 3 km north of Skyros Chora. Together with blocks carved for building, millstone quarrying traces are also observed. The traces of the extracted millstones and all the coastal part of the quarrying area are today submerged and the quarry floor is at

−0.25 m. The diameter of the carved rings is about 1.0 m and their thickness is in the average 0.30 m. Based on the construction period of the castle and its repairs, the quarry can be dated to between the Middle Byzantine period and the Frankish-Venetian occupation (750 ± 250 yr BP), when repairs to the fortification of the Chora castle are mentioned (Karambinis, 2015). The submersion of the island that is attributed to a co-seismic subsiding episode of about 0.55 m slightly less than 850 years BP (Evelpidou et al., 2011), seems to have occurred at least 600 years later (Fig. 1, Fig. 2, Fig. 4, Fig. 8, S3).

3.10. Damnoni, Crete, Greece

The millstone quarry in Damnoni bay existed until 1990 and was then destroyed. It mainly developed on the central part of the coast at elevations between −0.15 m and +1.20 m, mostly in the younger, well cemented, beachrock formation dated at 580 ± 55 yr BP (Neumeier et al., 2000). About 55 to 60 millstone rings have been extracted from this beachrock. The millstone rings have diameters between 1.60 m and 1.80 m and a thickness of 0.30 m–0.40 m. A narrow channel about 0.10 m–0.15 m wide was carved around the millstone to be carved. The submersion of the seaward part of the quarry by 0.55 m occurred during the last 400 years, after 1604 when a large earthquake caused the subsidence of the entire coast of Crete by 0.70 m (Mourtzas et al., 2016) (Fig. 1, Fig. 2, Fig. 4, Fig. 8, S3).

3.11. Paleochora, Crete, Greece

The millstone quarry is located along the coast, about 1.5 km west of Paleochora, at an elevation between −0.24 m and +0.50 m. It develops in the well preserved beachrock formation, dated at 1044 ± 15 $_{14}$C (cal. age 704–452 yr BP) (Mouslopoulou et al., 2015). The beachrock is characterized by coarse sand and cobbles. It outcrops at the elevation +0.70

m on the modern beach and extends about 8 m away from the current shoreline. The maximum depth of the top and base of its seaward end are at 0.75 m and 1.15 m, respectively. More than 50 millstone rings were cut in this area, as deduced from the carved rings and the in-situ left millstones. Their diameter reaches 1.30 m, with a thickness of 0.30 m. A few millstones of small diameter of 0.30 m, were also found. A channel 0.10 m wide was carved around the millstones, to facilitate the extraction. The submersion of the seaward part of the quarry occurred during the last relative sea-level change of Crete by 0.55 m over the last 400 years (Mourtzas et al., 2016) (Fig. 1, Fig. 2, Fig. 4, Fig. 8, S3).

The dating of both Damnoni and Paleochora millstone quarries results indirectly from the dating of the workshops of western and central Crete. The earliest workshops are dated back to the 16th and 17th century. Few constructions were made at the beginning of Ottoman domination of the island, in the late 17th century (Vallianos, 1985, 1997).

3.12. Scario, Italy

The Scario site has a great scientific relevance for the presence of a prehistoric site called “Riparo del Molare” (Ronchitelli, 1993) while the research (1984–2001) of the prehistoric deposits allowed the discovery of a millstone quarry and important archaeological remains of the time of carving activities (Ronchitelli, 1993, Ronchitelli et al., 2010). Some millstones (broken or defective) as well as numerous rings indicating complete extractions are still preserved in Riparo Molare and also in different site of Scario coast (Lo Presti et al., 2014) for this site a precise dating at ~370 years BP was confirmed by radiocarbon analysis. We remark that this site lies in a tectonically stable area without vertical land movements (Ferranti et al., 2006) (Fig. 1, Fig. 2, Fig. 6).

3.13. Santa Sabina, Italy

The site of Torre Santa Sabina is placed near Carovigno, the ancient roman age Carbinia, at about 25 km north west of Brindisi, along the Traiana road, the latter was built along the Adriatic coast of Apulia. This area was continuously settled since the Bronze age (Auriemma et al., 2004, Auriemma et al., 2005). The general arrangement of the coast appear as gently sloping rocky coast cut by deep inlet with pocket beaches. It is shaped on the Calcarenite di Gravina formation of the Lower Pleistocene age (Ciaranfi et al., 1988), and is represented by calcarenites having different levels of cementation. The upper calcarenites units are buried and locally known as “cappellaccio”. This level is very well cemented since the over-consolidation due to the enrichment of $CaCO_3$.

A quarry, placed on the inlet directly southeast of the medieval tower, is reported to be in activity from the messapic age to the middle ages, (Auriemma et al., 2004, Auriemma et al., 2005, Mastronuzzi et al., 2017).

In this area, in correspondence to the isthmus connecting the peninsula to land, four millstones were recognized (Fig. 1, Fig. 2, Fig. 6, Fig. 8, S3). These are placed at about the modern msl, along the wave cut platform. They show typical size in diameter although they are less thick than those found in other localities (see Table 1, Table 2). Four more millstones blocks of about same size but largely eroded, are placed in another quarry area, placed at less than 150 m southeast.

3.14. Punta Penne Brindisi

Site 14 lies on calcarenitic rocks with layers rich in bioturbations. This lithological unit has been attributed to the Middle - Upper Pleistocene (Loiacono et al., 2002, Mastronuzzi et al., 2011) and constitutes the local gently sloping coast.

Here, three millstones and three rocky cylinders, likely corresponding to piled millstones, were found (Fig. 1, Fig. 2, Fig. 6, Fig. 8, S3). These are placed at the inner limit of a wave cut platform, extending about 20 m in the sea, at a depth not exceeding 0.50 m. Both millstones and cylinders are extracted from the bedrock. These are part of the temporary pebbles beach accumulated just in correspondence of the inner limit of the strip soil area and placed between −0.10 and + 0.30 m with respect to the local mean sea-level. Unfortunately, it was not possible to individuate the site from which they were carved. Millstone sizes are a little bit smaller in diameter with respect to other sites. For this site, we cannot determine any relationship between quarries and paleo sea-levels at the time of their extraction.

4. Prediction of the paleo sea-level

The ages of the investigated quarries span the period between 1.450 and 0.350 ka BP (Table 1, Table 2) with a mean of 0.455 ka BP. For the time 1 ka BP he GIA predicts at 1 ka BP a RSL at about −0.45 m for the Italian sites, at about −0.5 m for Mallorca, between −0.3 and −0.2 m for Greece and at the present msl in Israel (Table 3).

Table 3. Predicted sea-level altitude for the year 1000 and 400 in the Mediterranean Sea.

Sites	s.l. altitude (cm) Lambeck et al., 2011	s.l. altitude (cm) Lambeck et al., 2011 Italy at 0.4 ka BP	s.l. altitude in cm from Lambeck et al., 2004 Med sea, at 1 ka BP	s.l. altitude in cm from Lambeck et al., 2004 Med sea, at 0.4 ka BP

	Italy at 1 ka BP			
13–14 Puglia	−0.44	−0.25		
12 – Scario	−0.45	−0.25		
1–5 Mallorca			−0.6	−0.3
8–11 Greece			Between −0.3 and −0.4	Between −0.1 and −0.2
7 – Israel			0	0

5. Discussion

Dating ancient millstones quarries is not easy because quarrying activity lasted for centuries and datable material are rare or absent. Some quarries are an exception here of millstones, their chronological framework was established by historical documents by Belmont 2006, For Scario (Italy) the age (historical 370 yr BP) was dated to 1632–1657 BP (Lo Presti et al., 2014). Broadly, the age of millstone quarries presented in this paper spans between 1450 and 250 ka BP). The combined analysis of our new measurements, the chronological framework and the available GIA models (Lambeck et al., 2011), provide new insights into the relationships between the quarries and the paleo sea-levels of the Mediterranean at the time of millstone extraction. For the quarries, Auriemma and Solinas (2009), proposed a functional elevation at 0.30 m above high tide (corresponding to about 0.6 m above msl). Our results show significant correlations between millstone quarries excavation plans and the paleo msl at the time of their extraction, they fall close to the predicted sea levels (Table 1, Table 2). This implies that standard functional elevation previously proposed for other quarries cannot be applied to millstones quarries. The reason is that only for the former the upper and lower limiting values of sea-level at the time of quarrying activity can be roughly estimated. However in case of intensive demand for stones and limited raw material, it can be assumed that all the available stone resources were exploited up to the lowest level and even during low tides. This means that such coastal quarries may provide the uppermost limit of sea-level, and also the lowermost possible sea-level at the time of quarrying (Galili et al., 2015).

As regard to the timing of the quarrying activity, we found in literature as it is the case in Mallorca (this paper, Belmont, 2006 and references therein) or at Scario (Lo Presti et al., 2014), or in Greece (this paper), in the absence of precise historical data, we found a very broad chronological range (2–0.1 ka BP) for the sites 7 (Akko, Israel) and 13, 14 (Apulia Italy), Table 1. These findings raise an important consideration: there are many Greek and Roman age millstone quarries on Mediterranean, but these were not found at depths greater than −0.33 m on sea level, (Table 1). This means that in the central Mediterranean Sea, Greek and Roman millstone quarries (with a sea-level at about 1.2 m for 2 ka and 1.6 m for 2.35 ka cal BP m below the present, depending from local isostasy or tectonics) were gradually eroded in the last 2.4 ka by sea-level rise and coastal dynamics in the l.

Ucosich (2011) argued in the Messina Strait that millstones were extracted close to any tide level, and we completely agree with this observation.

Given that the Greek and the Roman millstones were smaller than the medieval ones, we assume that the sites 7, 13, 14, are younger than 1450 years BP (middle Byzantine period onwards). Following the lowering rates of calcarenites or beachrocks measured along the Mediterranean coasts (Furlani et al., 2009), the millstones found on the coasts of Israel and Apulia see Fig. 1 sites 13,14 (Apulia) site 7 (Israel) (that both show high lowering rates and reduced thickness see Fig. 6, Fig. 7) were carved at least 250 years ago, and therefore were not carved during the last century, but before.

Given the Akko (Israel, site 7, settlement, for example, the demand for building stones was high. The corresponding quarrying activity took place on the adjacent coast, which was the main source of building material (Flemming et al., 1978). Under such high demand of stones, we may assume that every source of stone was totally exploited. Thus the stone quarries near Akko can be used as a good marker for upper and lower limits of possible sea-level change at the time of quarrying. Today at low tides most of the stones and scars in the two reported quarries are exposed. Archaeological and geological investigations suggest that the coastal area of the western Galilee is tectonically stable (Galili et al., 2007, Sivan and Galili, 1999). In some of the studied sites we found agreement between the lowest part of the quarries and the paleo sea-level predicted by GIA models for the period 1.45 ka and 1 ka BP (Fig. 8 Table 3) (Lambeck and Purcell, 2005, Lambeck et al., 2011).

For the younger quarries (0.45–0.25 ka BP) we found a different sea-level situated between −0.33 m and −0.06 m. These values are in agreement with the predicted sea-levels, resulting from Lambeck et al. (2011) model for the time span of 400 years (Table 3), with the required GIA modifications for the Mediterranean Sea.

The elevation of the Akko quarries enabled quarrying stones during low tides, under sea-level conditions that are similar to the present ones. This may suggest that isostatic movements or tectonic changes exceeding 0.3 m (the local tidal range) did not occur in this region during the last two millennia.

In addition, our results provide new insights on vertical tectonics movements along the southwestern coast of France (Cap d'Ail, Site 6). Here, Dubar et al. (2008) report a MIS 5.5 deposit at about 20 m above msl. During our surveys, we measured the upper limit of *Lithophaga* spp. holes (near the millstones) at about 8 m above msl. This marker is a good indicator of paleo RSL and is often used to locate the elevation of past interglacial shorelines. Sites with MIS 5.5 shoreline placed between 5 and 10 m can be considered very close to the eustatic value (Ferranti et al., 2006, Kopp et al., 2009). Thus, is reasonable to assume a tectonic stability for this site in the last 125 Ka and surely in the last 2.5 Ka.

Finally, based on the shape, diameter and thickness, of the millstones described in this paper, these were mostly used to for grinding flour or producing oil, probably by using water mills during medieval and modern age. Because the chronological range is large it is possible to date precisely quarries only in a few cases.

6. Conclusions

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Field observations and interpretations of a set of millstone quarries located along the coast of the Mediterranean sea suggest that most of these were carved between 1.45 ka and 0.25 ka BP with a recurrence at 0.45 ka BP. Based on historical documents and chronological attribution for these sites, we hypothesize that millstones were carved at any elevation along the rocky coasts. But part of them were extracted close to sea-level at a functional elevation even at near 0 m. This implies that their extraction was performed without specific rules on functional elevation with respect to sea level.

- Quarrying techniques, type of rock chosen for their extraction and millstone dimensions seem to follow similar rules along the Mediterranean coasts during a time that span across the Byzantine period and the 18th century.

- In absence of further evidences, the lack of older millstone quarries for the Greek-Roman ages along the coastline and in the intertidal zone as well, can be reasonably explained as follows: i) they were extracted at higher elevations far from sea level, or ii) those located near sea level at the time of their extraction have been completely destroyed by the combined effect of sea-level rise and coastal erosion, being carved in beachrocks, sandstones or similar highly erodible lithology.

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We found a good agreement between the elevation of the lowest cuttings of the quarries (0.33 m and −0.06 m) and the predicted paleo sea-levels for the time range between 1.45 and 0.25 ka BP.

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In conclusion, the use of millstone coastal quarries as sea-level markers must be used with caution, evaluating from time to time the individual cases, given the uncertainties in the definition of the paleo RSL due to chronological attribution and functional elevation. The latter does not have similar rules around the Mediterranean, as for other coastal quarries: in some cases, millstones were extracted well above the paleo-msl, while in other cases at about at sea level, in the intertidal zone and even during low tides.

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Appendix A. Supplementary data

The following are the supplementary data related to this article:

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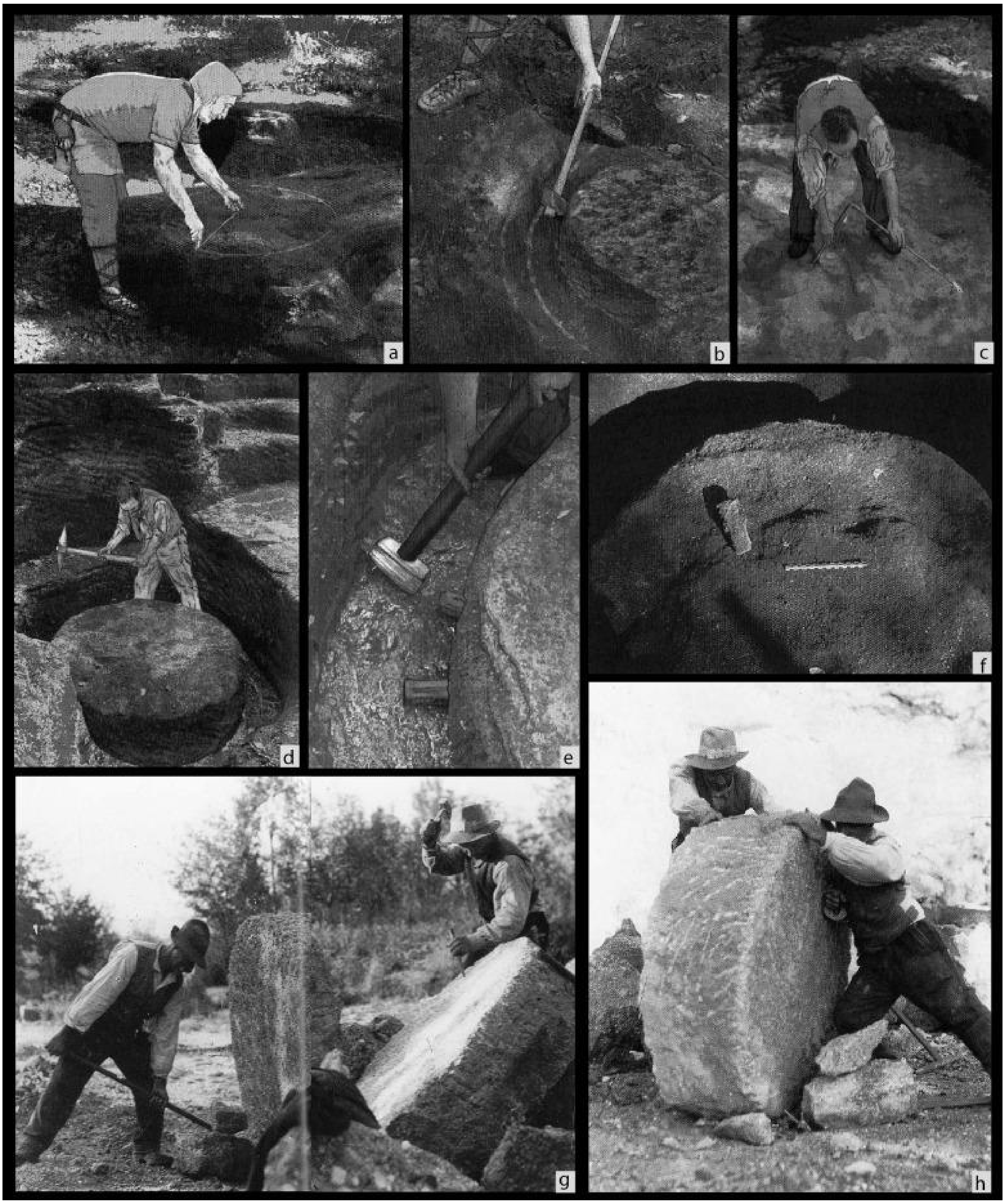
a
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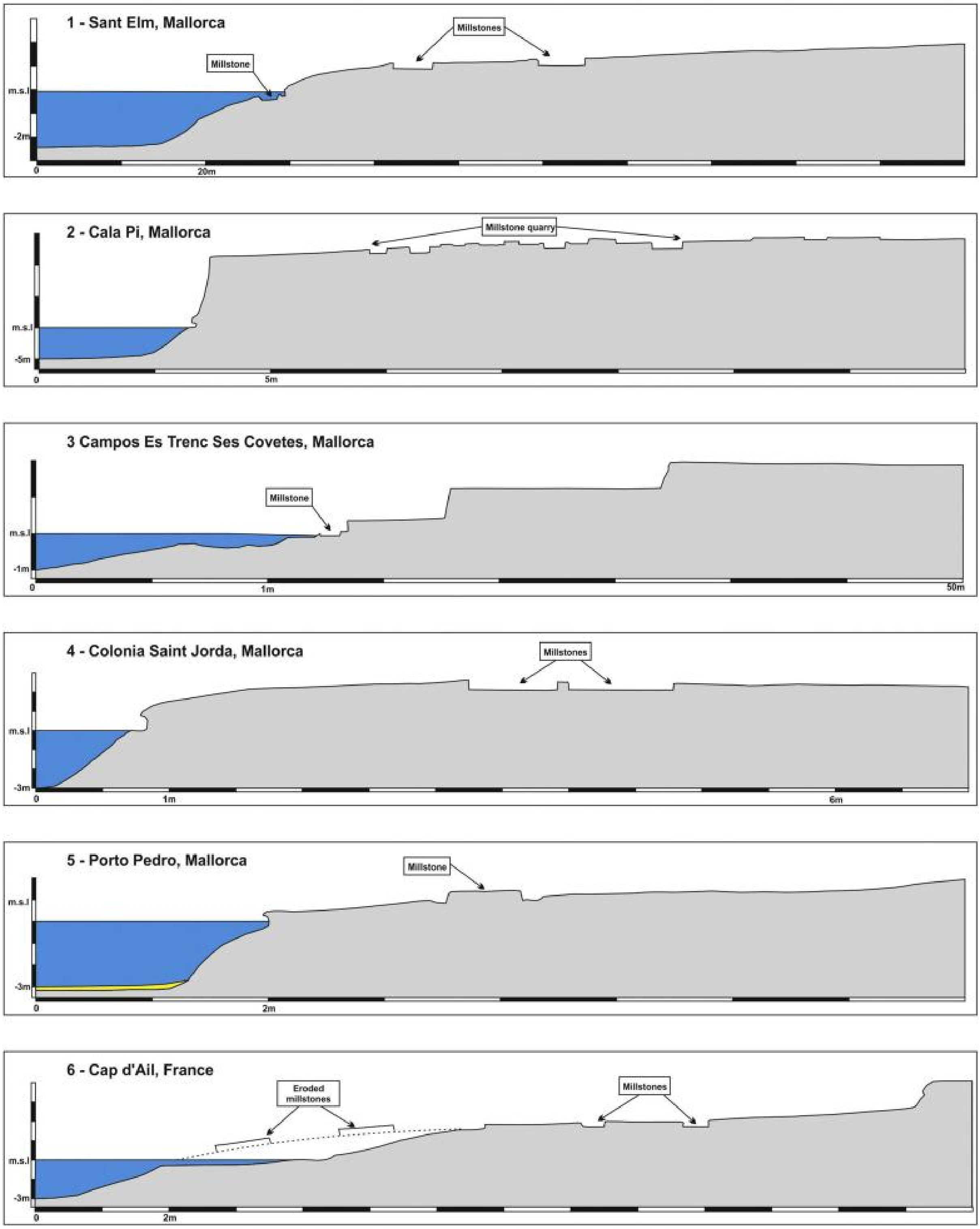
Supplementary data S1



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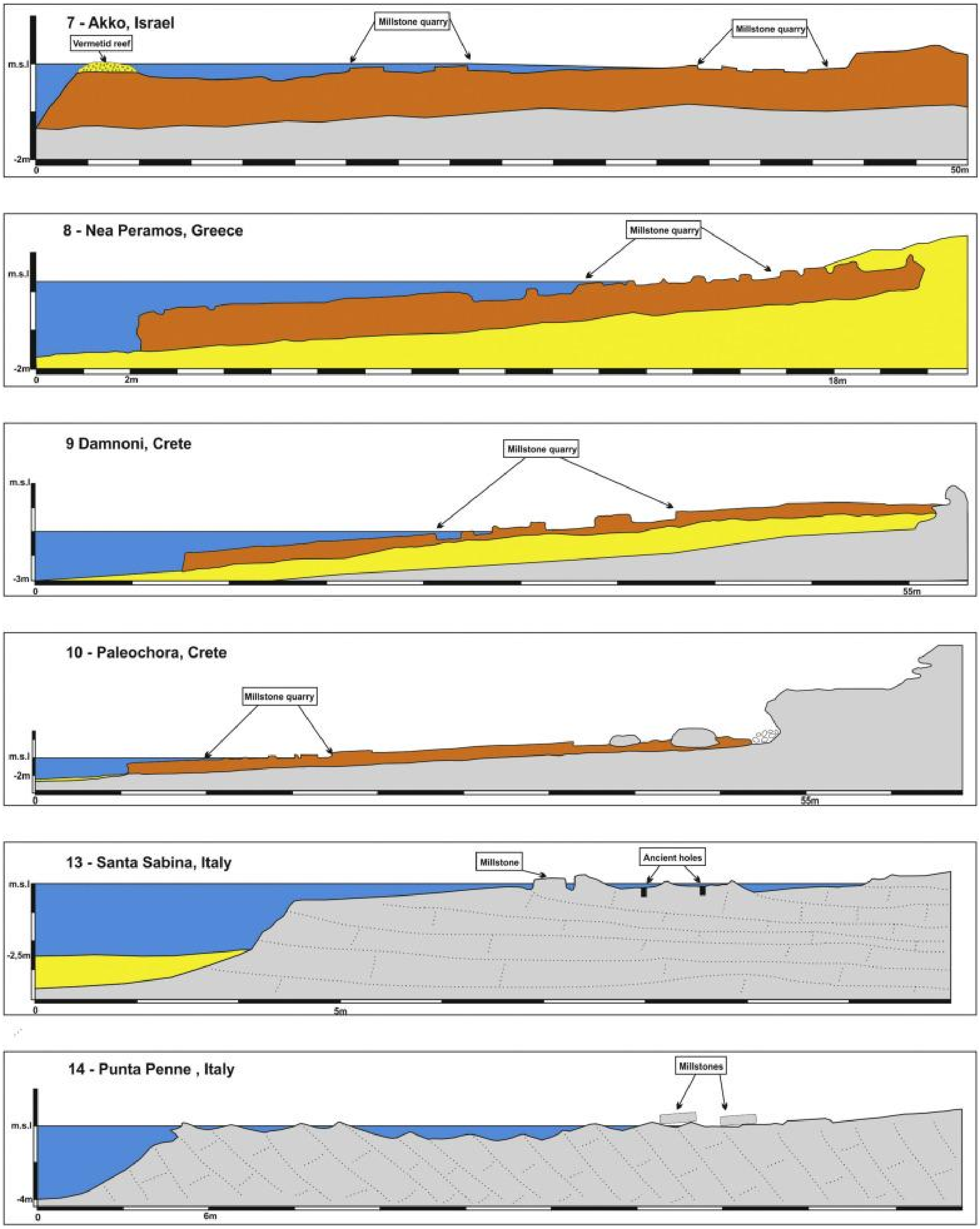

1. Download : Download high-res image (597KB)
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Supplementary data S3

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