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Article

New Estimation of the Post Little Ice Age Relative Sea Level Rise

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Abstract: The study area is located in NW Sardinia Island (Italy), Mediterranean Sea. Sardinia is considered stable since the late Pliocene with a negligible subsidence of about 0.01 mm/y. It is therefore normally used to reconstruct the Pleistocene and Holocene sea level curves. Our research focusses on the sea-facing city of Alghero that from 1353 to 1720 was under the Spanish government. During this time, the city was renovated and new buildings edified. Dimension stones were quarried all around Alghero both in the nearby inland and along the coast. Coastal quarries were considered the most suitable for both rock quality and the easiest way to transport the quarried material by boat. The quarried rocks are late Pleistocene dune and beach sandstones deposited from the 132 ka (Marine Isotopic Stage—MIS5) to about 65 ka (MIS4). Sandstones crop out from few cm to 3 m above the present sea level and underwent several consolidation processes related to loading and marine weathering. This latter favoured dissolution and circulation of calcium carbonate which cemented the rocks. It is reported that the Spanish were looking for these "marine" sandstones for their high geotechnical characteristics. Different rules were adopted through time for the size of the dimension stones and this has allowed us to establish a quarry exploitation chronology. For example, "40 × 60 × 20" cm was the size of the dimension stones used for the Alghero Cathedral dated at 1505–1593. Nowadays most of the coastal Spanish quarry floors are 30 centimetres below mean sea level (tidal range is 30 cm). Accordingly, we infer that relative sea level from 1830 AD (and of the Little Ice Age) rose in about 200 years to the present level at the rate of about 1.4 mm/y. Considering that relative sea level rise during the Medieval warm period was of 0.6 mm/y over a period of about 400 years, we may deduce that human influence was strong enough to lead to a relative sea-level rise faster and in shorter time.

Keywords: Alghero; Sardinia; Spanish Quarry; dimension stones; late Quaternary; luminescence

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1. Introduction

Sea level rise is one of the main effects of the currently occurring climate changes. It is worldwide accepted that not only natural events have driven these processes, but humans have also strongly contributed to them.

The Holocene is the current geological Epoch. It follows a main glacial interstadial (Marine Isotopic Stage—MIS2) having its lowstand between 26.5 and 19 ka [1]. During this cold period, sea level regressed and reached about 120 m below the present. The new transgression was very fast and in about 10 ka sea level rose about 110 m [2]. About 6.8 ka the Holocene reached the Climate Optimum and mean temperature was just little higher (1–2 °C [3]) or similar to the present [4,5], and sea-level rise decreased up to few mm per year reaching the today level at about 2.5 ka in a period defined as the Warm Roman Time [6]. After this time, high frequency, centennial scale, and warm/cold climate fluctuations occurred. These fluctuations, however, strongly influenced humans' activities. It is well known that during the Dark Age cold period (450–900 AD) one of the largest human migrations triggered by catastrophes mostly related to miserable climatic conditions occurred [7]. In the following Medieval Warm Period (MWP) (900–1300 AD) Vikings landed in Greenland, sailed through the NW passage and grapes were grown as far north as England [8]; that is, about 500 km north of present. This implies that temperature was 1–2 °C higher than present [9]. Consequently, also sea level was 12–21 cm higher [10]. This warm time was followed by a relative cold period known as Little Ice Age. The new modern relative warm period started at about 1850 and is continuing now. Because of the strong emission of CO_2 due to industrial activities and related atmospheric pollution, it is not simple to discriminate which are normal from induced effects on this new climate warming.

The aim of this paper is to point out the relative sea level fluctuations that occurred during 1350–1750 AD analysing the underwater quarries present all around the city of Alghero (Sardinia, Italy) that were exploited during this time interval. This time is coincident with the so-called Little Ice Age. We claim that the comparison of the emerged data with those relative to previous warming times (i.e., Medieval) may differentiate the amount of human contribution on climate changes.

The Little Ice Age

The term Little Ice Age (LIA) is used to describe a cold epoch in Europe spanning from about 1300 to 1850 AD [9,11]. During the LIA, temperature (in the Northern Hemisphere) dropped at least 1 °C and climate conditions deteriorated, increasing glaciations [12]. Historical evidence clearly describes the Little Ice Age. The Baltic Sea froze over ("1621 AD. The cold was very intense for the whole month, and a part of the Baltic Sea was covered with a thick ice sheet", [13]), as did many of the rivers and lakes in Europe. Pack ice expanded far south into the Atlantic making shipping to Iceland and Greenland impossible for months on end [14]."Winters were bitterly cold and summers were often cool and wet. These conditions led to widespread crop failure, famine, and population decline. The tree line and snowline dropped and glaciers advanced, overrunning towns and farms in the process. There were increased levels of social unrest as large portions of the population were reduced to starvation and poverty" [15].

In polar and high mountain areas glaciers advanced and achieved their maximum postglacial positions during this period [16].

In Italy, for instance, climate changes that occurred during the LIA may be analysed looking at paintings and historical documents of Venice where the most severe winters are described (i.e., [13]) and painted (Veronese in the 16th Century and Canaletto and Bellotto in the 18th Century, who provided a view of the frozen Venice lagoon [17,18]).

2. The Study Area

Sardinia (Italy) is one of the biggest islands of the Mediterranean Sea (Figure 1A). The study area, Alghero, is located in NW Sardinia (Figure 1B).

Our research focusses on the city of Alghero that from 1353 to 1720 was under the Spanish kingdom, becoming one of the most important harbours of the Mediterranean. As a consequence, the city growth and defence walls and buildings were edified. Dimension stones used for these buildings were quarried all around Alghero both in the nearby inland (Cuguttu area (CU); St. Agostine area (ST)) and along the coast (Massacà road) (Figure 2A). Coastal quarries were considered the most suitable for both rock quality and being the easiest way to transport the quarried material by boat into the city harbour. Most of these quarries are today underwater and could be dated using archaeological evidence (Figure 2B).

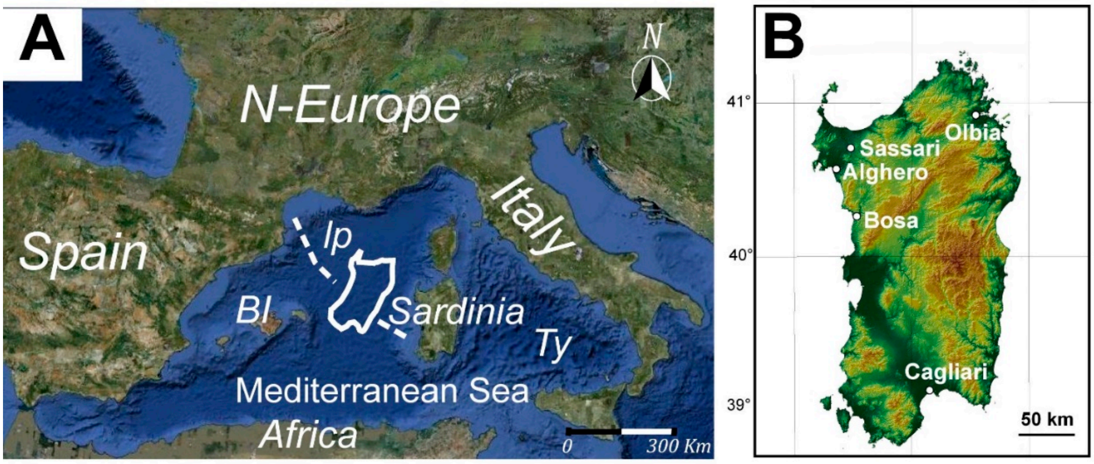

Figure 1. Sardinia. (**A**) Satellite view of the Mediterranean region where Sardinia occupies a central position. Dashed line indicates the Sardinia anticlockwise rotation of the island occurred that in the Neogene time; (**B**) Digital terrain model of Sardinia; in the map are reported the main cities. Alghero is on the north-west coast. BI = Balearic Islands; lp = Liguro–Provençal Basin; Ty = Tyrrhenian Sea.

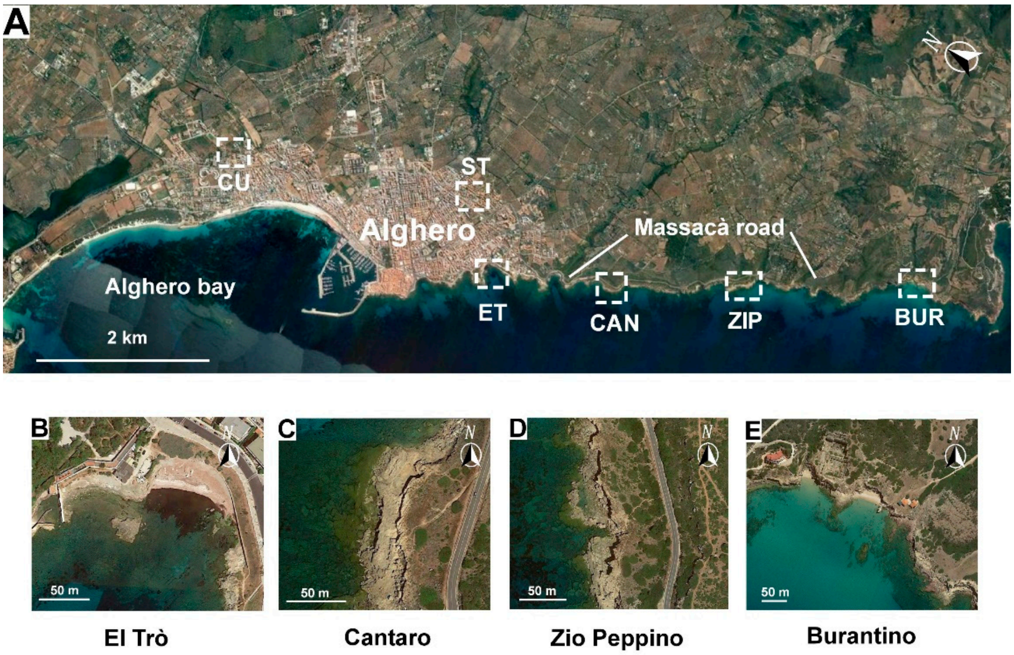

Figure 2. (**A**) Alghero and location of the main quarries. Inland quarries: CU = Cugutto, ST = St. Agustine (these quarries today have almost totally disappeared because of the city expansion). Coastal quarries: (**B**) ET = El Trò, (**C**) CAN = Cantaro, (**D**) ZIP = Zio Peppino, (**E**) Bur = Burantino.

2.1. Alghero Spanish Domination

The city of Alghero was founded in the second half of the 12th Century by the Genoa Doria family. It however experienced a strong influence from both Pisa and Genoa marine republics, which were engaged in the fight against the persistent Saracen pirate attacks to the island, and both were involved in the government of the city until 1353 AD when it was conquered by the Kingdom of Aragon. Aragon-Catalan citizens repopulated Alghero moving from Catalonia with their families thanks to the favourable immigration lows. These people were mostly from Barcelona, Valencia, Tarragona and Majorca [19]. They retained the hallmark features of the Catalan-Aragon time, still visible in the architecture of churches, buildings, system of fortifications, and language [20,21]. In 1720 AD, the city passed under the Savoy Kingdom.

2.2. Geographical Setting

The Mediterranean Sea is microtidal with an average tidal range of 35 cm [22]. The present-day NW coast of the island around Alghero is characterized by high steep cliffs often bounding small embayments where sandy or gravelly pocket beaches occur. The base of the cliffs may host tidal notches and incipient intertidal *Lithophyllum byssoides* bioconstructions or large wave cut platforms [23]. The island has a typical Mediterranean climate characterized by temperate a rainy autumn and spring, a not very humid winter and hot dry summer, with a sea-surface temperature between 12 and 25 °C. The NW-W blowing wind (Mistral) dominates along the west coast and triggers a longshore current flowing the same broad direction [24].

2.3. Present Climate

Alghero is characterized by a typical Mediterranean climate, warm and temperate with more rainfall in the winter than in the summer. According to Köppen and Geiger the climate is classified as Csa [25,26]. The average annual temperature is 16.3 °C in Alghero. The average annual rainfall is 584 mm. The maximum high tide recorded is 0.5 m and a minimum height –0.1 m (referenced to Mean Lower Low Water (MLLW)).

2.4. Geological Setting

Sardinia represents a segment of the South-European plate that reached its present position during the Oligocene–early Miocene after an anticlockwise rotation as a consequence of the opening of the Liguro–Provençal Basin (Figure 1A). The island was affected by intense tectonic and volcanic activity that ended in the late Pleistocene (ca. 140 ka) related to the eastern opening of the Tyrrhenian Basin [27–29]. Presently, it is considered stable micro-continent only affected by a general subsidence of about 0.01–0.02 mm/yr [30] or slight tectonic activity [31]. Mesozoic bedrocks overlain by Quaternary strata characterize the study area. The first are mostly Triassic quartz-rich sandstones and conglomerates, and limestones/dolostones. Rare are the Oligo-Miocene volcanics, more widespread the Plio-Pleistocene basalts (Figure 3).

The Middle Pleistocene–Holocene Sardinian stratigraphy is the result of sea level fluctuations controlled by Milankovitch cycles [32]. It has been recently reviewed by [33] and grouped into eight major lithostratigraphic units mainly represented by repetition of shallow marine deposits (highstand deposits), alluvial systems (falling stage deposits) and coastal dunes (lowstand-regressive deposits) spanning in time from about 300 ka (MIS8) to present (MIS1) (Figure 4).

Recent absolute dating of the late Quaternary deposits cropping out close to Alghero constrained most of them to the last 132 ka [23,33–36]. The last interglacial and following substadials deposits (132–75 ka) are composed of well-cemented shoreface to beach face sandstones overlain by cross-bedded sandstones (aeolianites) (Figure 4). The following glacial deposits are composed of silty reddish palaeososls or colluvia. These are overlain by well-developed cross-bedded moderately cemented sandstone interpreted as transgressive dunes (Figure 4).

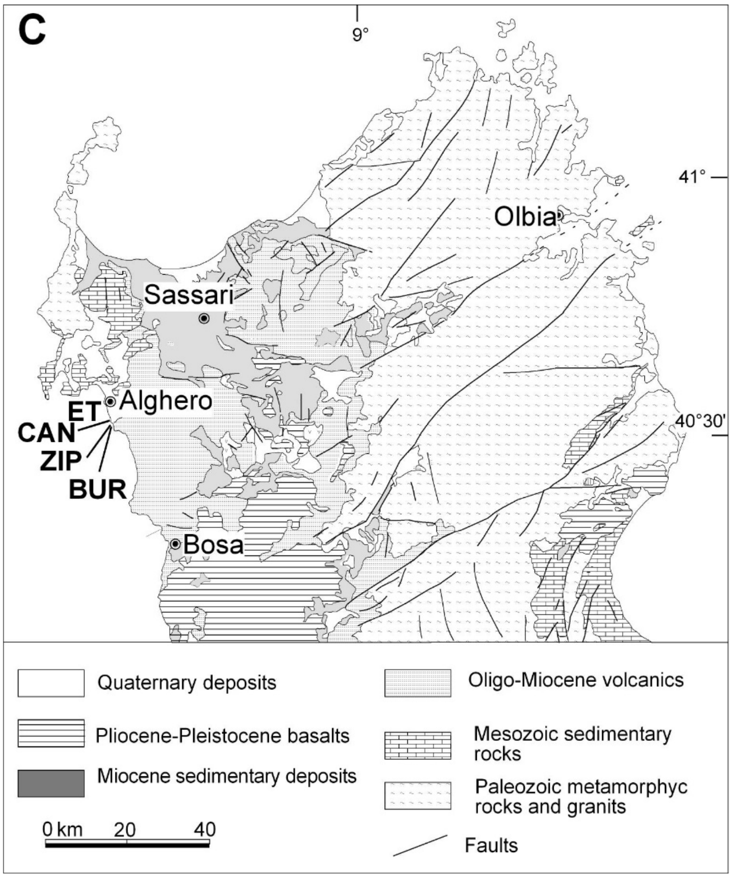

Figure 3. Schematic geological map of Sardinia (modified from [27]).

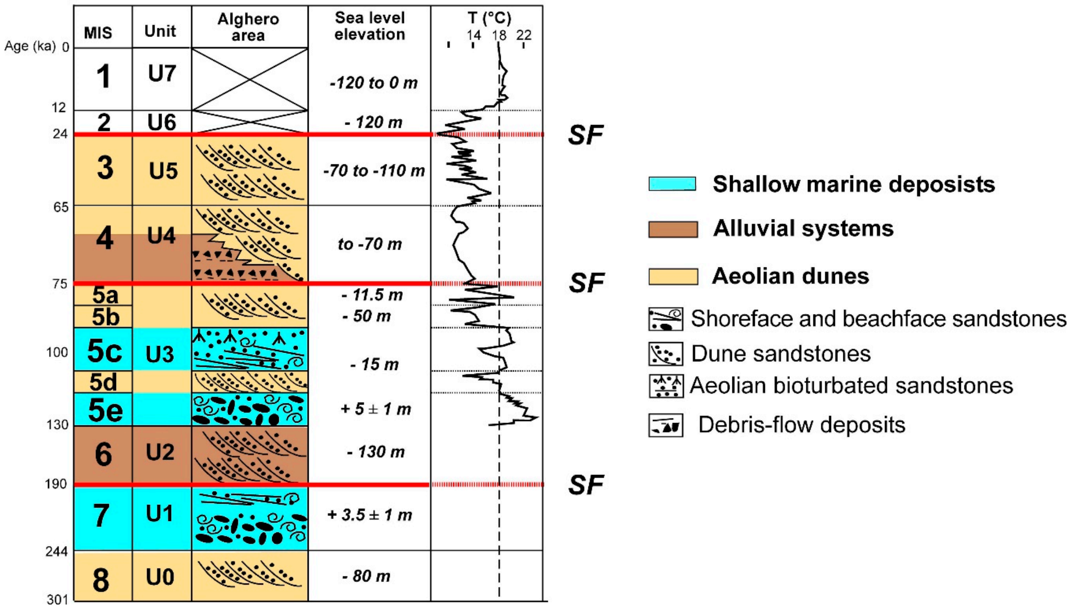

Figure 4. Stratigraphy of the mid-late Quaternary stratigraphic units (U0–U1) revised for this work cropping out in the studied area (modified after [6,35]). Units cover the last 300 ka. In the right columns are reported the estimated sea level elevations and temperatures from Marine Isotopic Stage 5 (MIS5) to MIS1 as defined and revised by [33]. *SF* = sea level fall. Sea level elevation has to be considered as Relative Sea Level as estimated for Sardinia. In the right column is the average sea-temperature of the West Mediterranean basin (from Martrat et al. [37]).

3. Material and Methods

A detailed analysis of the lithofacies characterizing the studied quarries and review of the stratigraphy has been conducted in order to define which rocks were quarried and used by the Spanish during the 15th to 17th Centuries. Quarries have been studied to define the size, the sedimentary structures and composition of the quarried dimension stones. These have been compared with those used in the main dated buildings of Alghero. A quarry exploitation chronology has been so far defined. Most of the coastal quarries are submerged, the seal level flooding the quarry plane has been measured using both rulers and optical level (error of about 10% [38]).

In order for the quarry floors to act as relative sea level markers, the following assumptions have been made: (i) that the quarry floor was worked down to the lowest possible level prior to abandonment; (ii) that the "abandonment level" was above the lowest elevation of the material (i.e., that the quarry was abandoned prior to the exhaustion of the material); (iii) that no subsequent later reworking occurred; (iv) that the "abandonment level" was 10 to 20 cm above (mean low water during spring time) sea level at the time of abandonment so as to facilitate dry working/loading of boats; (v) that ~0.5 to 1 cm of tectonic subsidence from the time of abandonment is to be included in calculations (i.e., if the quarry was abandoned in the 13th Century—oldest possible, although unlikely—this gives ~700 years, but if abandoned in the mid 16th Century, this gives ~470 years at 0.01 to 0.02 mm); and (vi) that there has been negligible glacio-isostatic adjustment from ~0.2 to 0.3 mm/yr (according to the model proposed by [39]—VM2 Earth model in ICE5G), accounting for unloading and hydro-isostatic effects.

4. Results

4.1. Stratigraphy and Main Sedimentological Characters of the Studied Area

The late Quaternary succession is well exposed along more than 5 km continuous rocky cliff present south of the Alghero city with just five of the eight defined units.

The oldest late Quaternary deposits (Unit 0 = U0) crop out in scattered isolated places along the southern Alghero coast. They consist of well-sorted, high angle planar cross-bedded, medium grained sandstones. They have been luminescence (Optically Stimulated Luminescence (OSL)) dated at 275 ± 25 ka. They are interpreted as lowstand dune systems formed during the glacial MIS8 stage [36]. These deposits were never quarried.

MIS7 deposits (Unit 1 = U1) do not crop out in the studied area, but just north of Alghero (Le Bombarde), [33] and are therefore not considered.

In the sheltered area of Cala Burantino Bay (Figures 2E and 5), a few kilometres south of Alghero, 2 m thick, well sorted, high angle laminated parallel or trough cross-bedded coarse-grained sandstones crop out. They represent the regressive dune system referred to MIS6 (Unit 2 = U2). They have OSL dated at 150 ± 10 ka [34,36] (Figure 5A).

Unit 3 (U3) deposits crop out quasi-continuously along the southern coast of Alghero presenting a high facies variability.

At Cala Burantino Bay site (Figures 2E and 5) Unit 3 consists of carbonate deposits developed on a conglomerate lag made of large pebbles and cobbles (Figure 5A). These are overlain by coarse-grained sandstones organized in dm-thick strata with sub-horizontal or low-angle cross stratification gently dipping seaward (Figure 5B). The unit ends with cross-bedded highly bioturbated, well-cemented sandstones (Figure 5C). U3 is interpreted as a prograding sandy beach system; the uppermost sandstones represent coastal dunes. It is OSL dated at the interval 113 ± 8–97 ± 6 ka, thus referred to MIS5 [33]. The well-cemented sandstones were, at least in part, quarried during Aragon-Catalan time (Figure 5D), whereas the uppermost cross-bedded during the 20th Century (Figure 2E).

On a wider embayment of El Trò bay (Figures 2B and 6A) Unit 3 is composed of 0.6 m of highly bioturbated medium to fine grained massive sandstone, passing to parallel low angle cross-bedded medium to coarse sandstone with well-rounded, poorly stratified coarse-grained (pebbles and cobbles) conglomerates interlayered (Figure 6B,C). Well-stratified and cemented, plane laminated, seaward inclined medium to coarse-grained sandstone beds cap the succession (Figure 6C,D). Sandstones in places alternate with 0.3–0.5 m thick well rounded, openwork, landward-imbricated coarse-grained conglomerates (pebbles and cobbles) (Figure 6C,D). The uppermost sandstones surface is highly bioturbated by several deer footprints (*Premegaceros cazzioti* [40]) (Figure 6D). Unit 3 has been Luminescence (K feldspar, post infrared luminescence (pIR IRSL)) dated between 131 ± 8 and 97 ± 8 ka [33]. Thus, it is referred to MIS5.

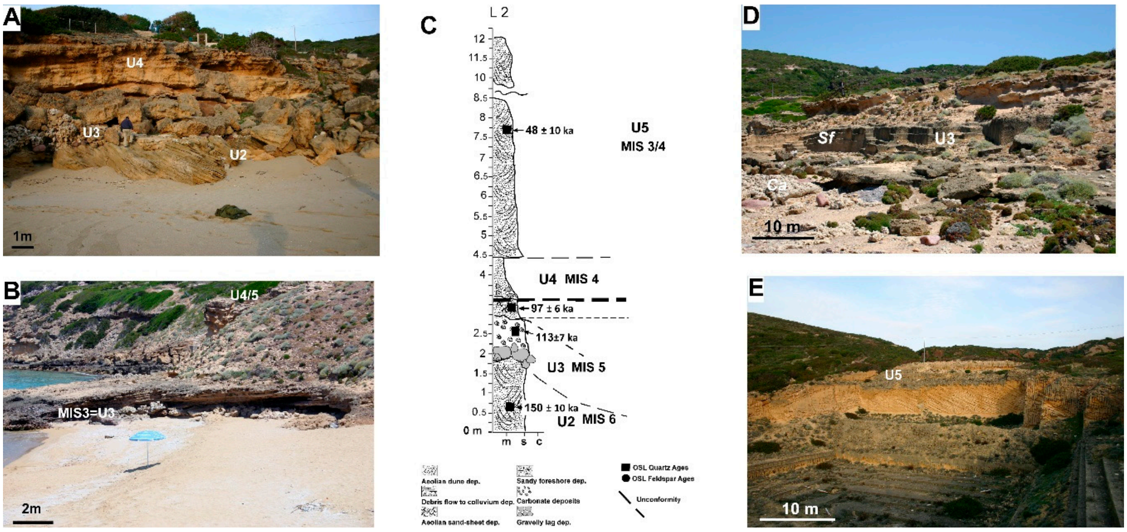

Figure 5. Burantino area. (**A**) Outcropping sedimentary units. (**B**) Full view of the prograding beach system associated to Unit 3 (U3) and referred to MIS5. Note the similarity with the modern beach. Sun umbrella for scale (about 2m high). (**C**) Synthetic log of the sedimentary succession of Burantino Bay. The 0 value is the present mean water sea level. Luminescence ages are made quartz grains (Optical Stimulating Luminescence (OSL)). More details on dating method are found in [33,34,36]). (**D**) The 16th–17th Century quarry. Quarried material derived from U3, mostly well-cemented sandy foreshore (*Sf*) resting on carbonate deposits. (**E**) The 20th Century quarry. Quarried material derived from Unit 5 (U5) cross-bedded, poorly cemented sandstones.

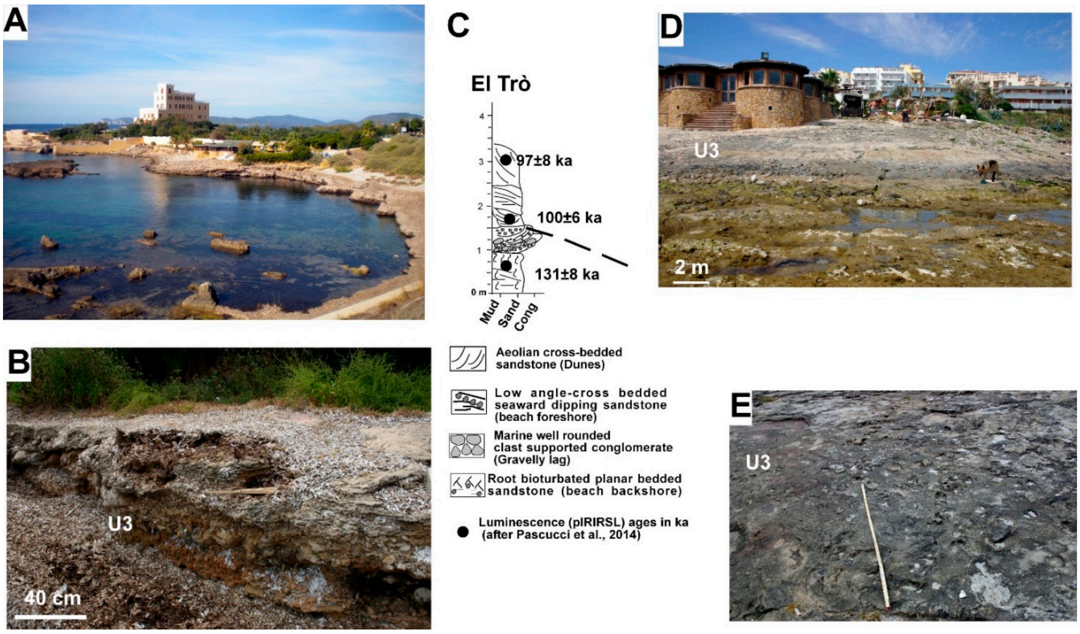

Figure 6. El Trò area. (**A**) Panoramic view of the quarry. Note that the quarry floor is completely underwater. (**B**) Lower part of U3: highly bioturbated medium to fine grained massive sandstone,

passing to parallel low angle cross-bedded medium to coarse sandstone with well-rounded, poorly stratified coarse-grained (pebbles and cobbles) conglomerates interlayered. (**C**) Synthetic log of the sedimentary succession of El Trò Bay, where 0 value is the present mean water sea level. Luminescence ages are made on feldspar grains (post infrared luminescence (pIR IRSL)). More detail on dating methods are in [33,34]. (**D**) Well-stratified and cemented, plane laminated, seaward inclined medium to coarse-grained sandstone. (**E**) Highly bioturbated, by several deer footprints (*Premegaceros cazzioti*), sandstone surface (foreshore).

The succession represents a regressive high-energy reflective mixed sand and gravel beach system (sensu [41]) formed during the last interglacial highstand (MIS5e) [33]. It was intensively quarried during the Aragon-Catalan time (Figure 7).

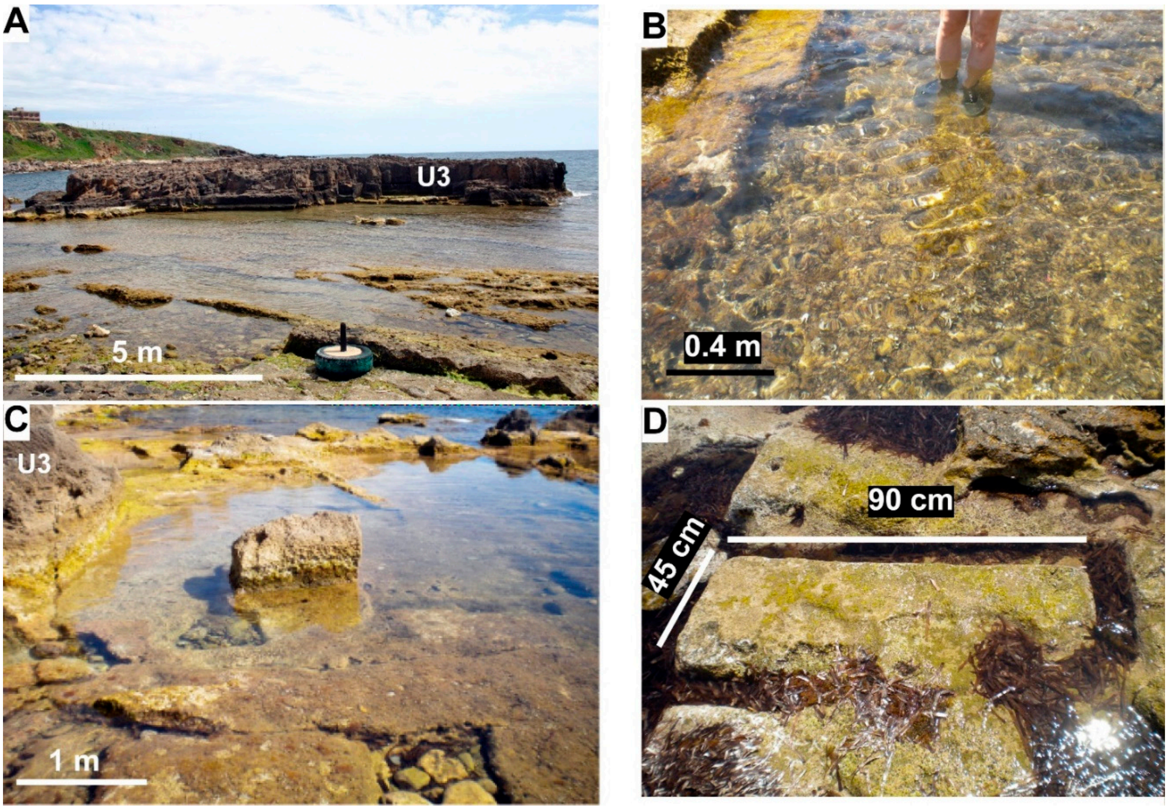

Figure 7. El Trò quarry. (**A**) The main underwater quarry floor. (**B**) Detail of the underwater quarry floor. It is about 30 cm underwater during low tide in spring time. Blocks are 30 cm high and fully underwater. (**C**) Remnant of a quarried block. It is about 80 × 45 × 30 cm. (**D**) Close view of a quarried block. Note the perpendicular grooves made with the help of a pickaxe (picaza).

Unit 4 (U4) crops out quasi-continuously along the southern Alghero coast. It is characterized by reddish silty, poorly sorted, angular cobbly–pebbly, matrix supported conglomerates laterally passing to planar cross- or trough cross-bedded pale yellowish well stratified medium to coarse-grained sandstones. Conglomerates fill channels up to 2 m deep and 7 m wide (Figure 8A). The pebbles mainly occur as lags at the base of the channels; in places they may be absent or totally formed by *Glycymeris glycimeris* shells (Figure 8B).

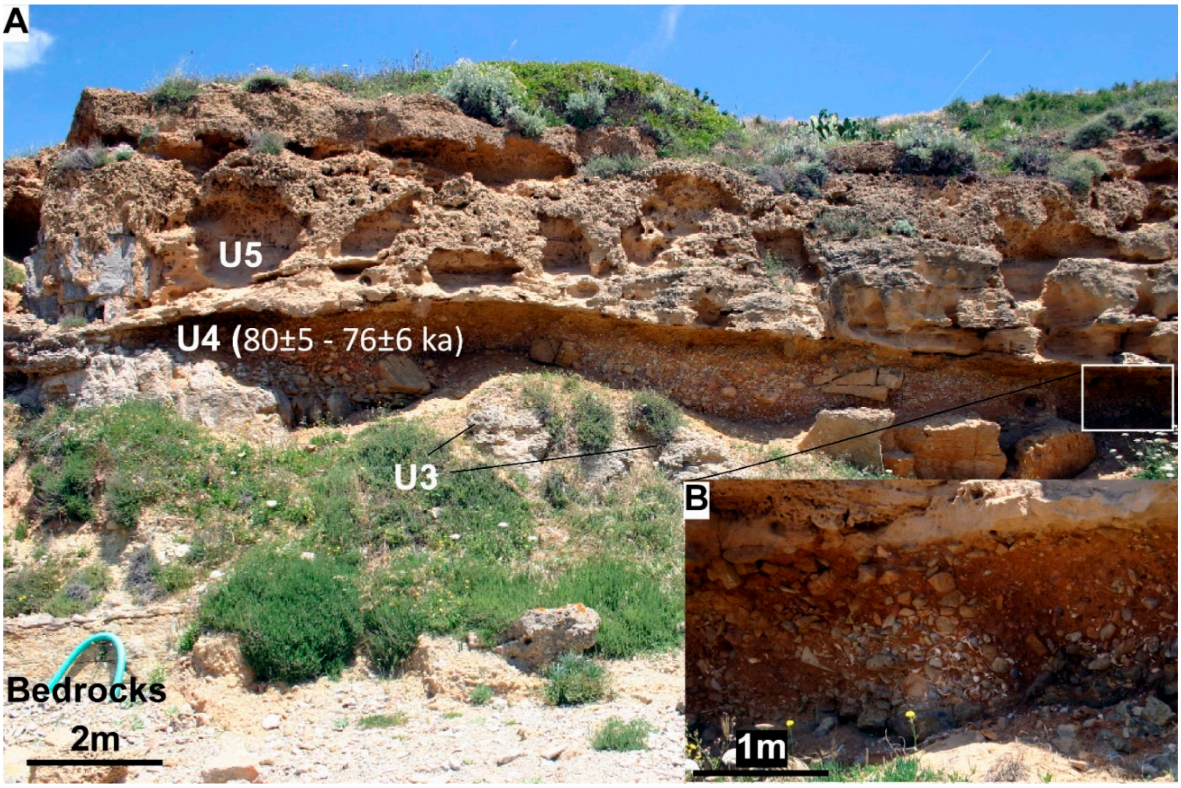

Figure 8. Detail of conglomerate Unit 4 deposits close to the El Trò area. (**A**) They are made of reddish silty, poorly sorted, angular cobbly–pebbly, matrix supported conglomerates. Conglomerates fill channels up to 2 m deep and 7 m wide. (**B**) *Glycymeris glycimeris* shells. Luminescence ages are made of quartz grains (Optical Stimulating Luminescence (OSL) [33]).

Clast conglomerates derive from the local bedrock; the sandy fraction derives either from the erosion of older sandy deposits or from marine bioclastic sand deposited on an exposed shelf and blown inland. Unit 4 has an OSL quartz age spanning from 80 ± 5 ka to 69 ± 4 ka [33]. Thus, it is referred to the latest stages of interglacial MIS5 and to glacial MIS4. Conglomerates are interpreted as a colluvial gravity flow formed during the sea level fall associated to the passage MIS5–MI4. Sandstones are interpreted as falling stage dunes. Only dunes have been extensively quarried during Aragon-Catalan time in the Zio Peppino quarry (Figures 2E and 9)

Unit 5 (U5) drapes most of the oldest units. It is characterized by planar cross- or locally trough cross-bedded pale yellowish well stratified medium to coarse-grained sandstones (Figure 10). The sand grains mostly consist of marine bioclasts (red algae, molluscs, echinoids, benthic foraminifera, and bryozoans) and in minor amounts of quartz and feldspar. Foresets dip 15°–30° generally toward SE or S. Occasionally, root traces, bones of terrestrial vertebrates, such as deer (*Praemegaceros cazioti*), and terrestrial gastropods occur. Unit 5 has an OSL quartz age between 51 ± 2 ka and 48 ± 4 ka and is thus referred to the MIS3 [33,34]. Deposits of these units are interpreted as coastal dune systems developed during relative sea level lowstand. They have been intensively quarried only in the 18th Century in the inland quarries of Alghero (Cuguttu and St. Agustine, Figure 2A) and in recent times (20th Century) in the Burantino area (Figure 5E).

Most of the quarried sandstones underwent several consolidation processes related to loading and marine weathering. This last favoured dissolution and circulation of calcium carbonate (derived from the abundant bioclastic grains forming sandstones) which cemented the rocks. The best-cemented sandstones are those present at the base of the succession, mostly shoreface to beachface deposits and dunes of MIS5, mostly interglacial (MIS5e) and interstadial (MIS5c) [33–35].

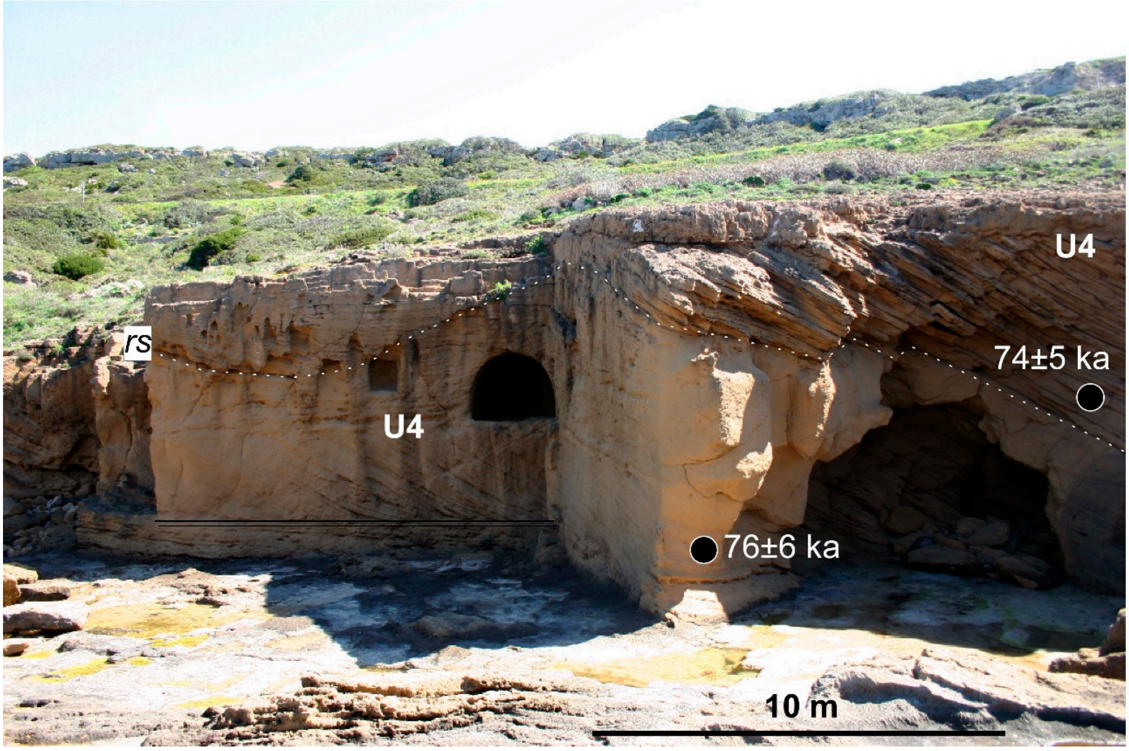

Figure 9. The sandstone Unit 4 deposits at the Zio Peppino quarry. Luminescence ages are made of quartz grains (OSL [32]). rs = reactivation surface separating sandstones with different cementation degree.

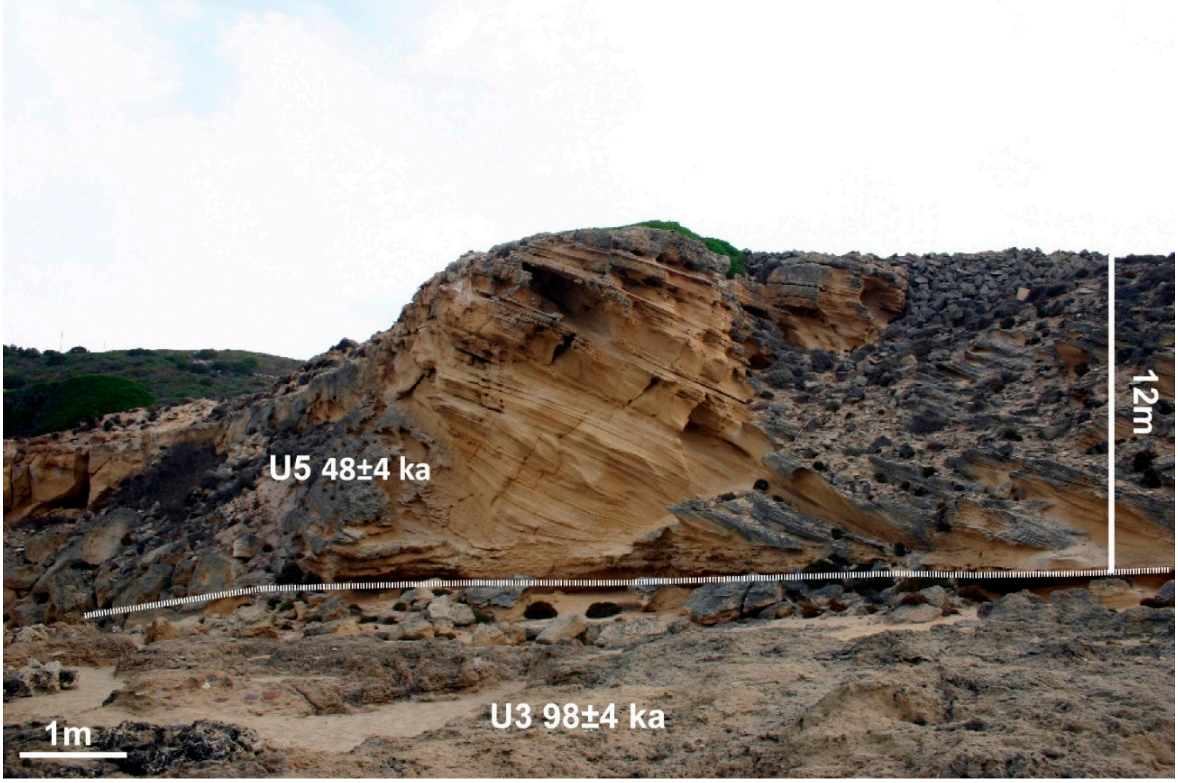

Figure 10. Burantino area. Planar cross-bedded pale yellowish well stratified medium to coarse-grained sandstones of Unit 5. Luminescence ages are made of quartz grains (OSL [34]).

4.2. Archaeology

4.2.1. Alghero Quarries

Quarry activity is well documented in the Alghero historical archives [21,42,43]:

1. 13th–16th Centuries—quarries close to the City (El Trò) up to the Cantaro spring (1 km south of Alghero) (Figure 2B,C) and, later, to Zio Peppino (3 km south) (Figure 2D);
2. 17th–19th Centuries—little activity along the coast up to Burantino (5 km south) (Figure 2E). Beginning of the exploitation of the inland quarries of Cuguttu of St. Augustine (Figure 2A);
3. 19th–20th Centuries—re-exploitation of Cantaro and Burantino quarries (Figure 2C,E);
4. 19th Century—Miniera di Calabona and re-use of Zio Peppino quarry (Figure 2E);
5. 20th Century—Zio Peppino quarry (Figure 2E).

Most of the quarried material was delivered by boat at the Alghero harbour. However, working people also used the coastal road named the "strada del massacà" (road of massacà) from the local name given to the sandstones (Figure 2A).

Sandstones were extracted by way of a stepped quarries. The exploitation was made downward from a fixed point down to about 20 cm above the sea-level [43] (Figures 11 and 12) and following the natural stratification where this was horizontal (Figure 11B).

The rock was carved with a chisel from the top to bottom according to the depth of a standard block (Figures 7, 11 and 12). Two perpendicular grooves were made with the help of a pickaxe (picaza), according to the required width and the length (Figures 7D and 12). Special iron wedges (or pieces of wood) were introduced into the shaped block to cause it cracks (Figure 12B). Finally, wooden sticks were used (perpal or parpal) to extract the sandstone block so delimited. Blocks appeared rough-hewn (Figure 7C) and it was necessary for the shaping, levelling and smoothing of each surface. This was the task of the arrancadors de pedra (quarry man and stonemason) who dimensioned the blocks directly in the quarry, according to the measures established by the customer. Blocks were measured in palms (palmi) and varied from

- 90 (to 80) × 40 (to 50) cm → (5 × 2 + 1/2 palmi—palms) during the 14th to the first half of 16th Centuries (i.e., Palazzo Machin, Cathedral, St. Barbara Church Figure 13);
- 50 × 20 (to 35) cm → (2+ 1/2 × 1 + 1/2 palmi—palms, Figure 11C) during the second half of 16th to 18th Centuries (i.e., Palazzo del Pou Salit, Figure 14A,B).
- 20 (to 18) × 40 (to 60) during the last part of 18th to 19th Centuries (i.e., Theatre, Figure 14C–E).

However, it is not clear how long a Catalan palm (or the local Alghero palm) was. We have estimated an average measure of 20 cm according to [42]. What clearly emerges is that the dimensions (whichever was the used palm) of the quarried blocks decreased through time. This is confirmed by the 17th Century rate table (Tarifa de traballadors de cada offici) [42,44] made for the inland quarries of St. Agostine and Cugutto (Figure 2A) between 1653 and 1658 AD. Still, in 1658 the new rate and dimension are fixed for the quarried block with the introduction of the "buit" (Figure 11C). This implies that most of the marine quarries were no longer active from the second half of the 17th Century.

A brief description of the three major quarries of El Trò, Cantaro and Zio Peppino is given below. These quarries have most of the 14th–16th quarry floor underwater. Several small quarries are present all along the Alghero–Bosa road (old "via del Massacà"). However, most of these could be considered, at least in part, the enlargement of the three major quarries.

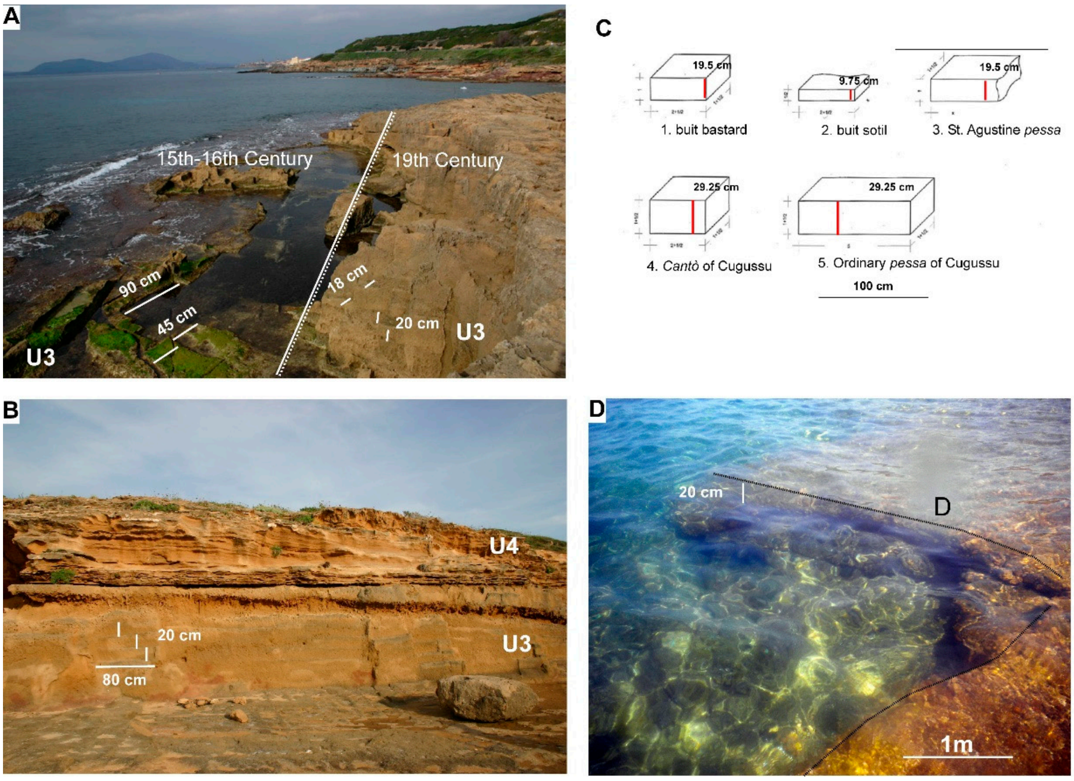

Figure 11. Cantaro quarry. (**A**) Sea side of the quarry. Note the different block size between the quarry floor active during 15th and 16th Centuries and the wall reactivated in the 19th Century. (**B**) 17th Century more inland side of the quarry. Note that the blocks' dimensions change according to the new rate table (Tarifa de traballadors de cada office) and the introduction of the "buit" as reference dimension stone. (**C**) Dimension stones quarried at Alghero during the second half of 17th Century (from Tariffa de traballadores da cada Offici visible c/o the Historical Archive of Alghero, 1658, file 853/26). Forms are as follows (from [42]): 1. the buits bastarts (rough-hewn dimension stones), had to be two and half palms long, a palm and half wide and a palm thick; 2. the buits sotils (thin dimension stones), had a thickness of half palm, a length of two and half palms and a variable width, depending on the requests of the customer; 3. las pessas de St. Agustì (the pieces of St. Augustine) had a height of a palm and half, a thickness of a palm and the width depending on the request of the customer "la larghezza a gusto di chi la domanderà"; 4. los cantos de Cugusso (the dimension stones of Cuguttu) measured a palm and half in height, two and half palms in length and were about a half palm wide; 5. la pessa ordinaria de Cugusso (the ordinary pieces of Cuguttu) measured five palms in length and was identical in the other dimensions stones of Cuguttu (de altaria e amplaria com lo cantò pedra de Cugusso). (**D**) Submerged quarry floor with a curved part used for boat anchoring. The still visible step was most probably used to facilitate boat loading. The dock (**D**) is 20 cm below the present low tide sea level and about 20 cm high.

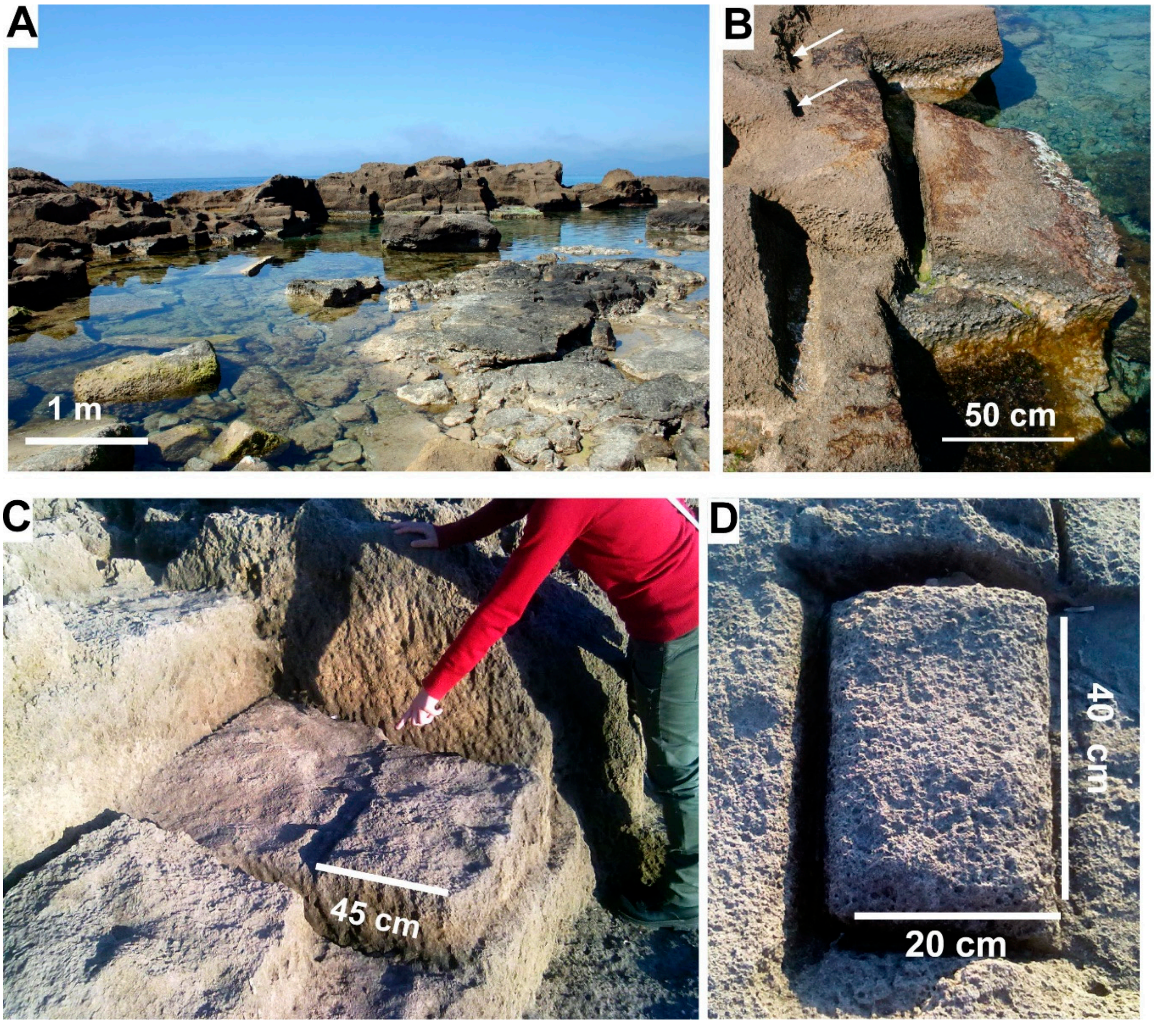

Figure 12. Zio Peppino quarry. (**A**) Underwater quarry plane. Note that blocks were carved from the top to the bottom according to the depth of a standard block. (**B**) Sing of the iron (or wood) wedges introduced to crack the sandstone blocks. (**C**) Perpendicular grooves made on sandstones with the help of a pickaxe (picaza). (**D**) Detail view of a squared block.

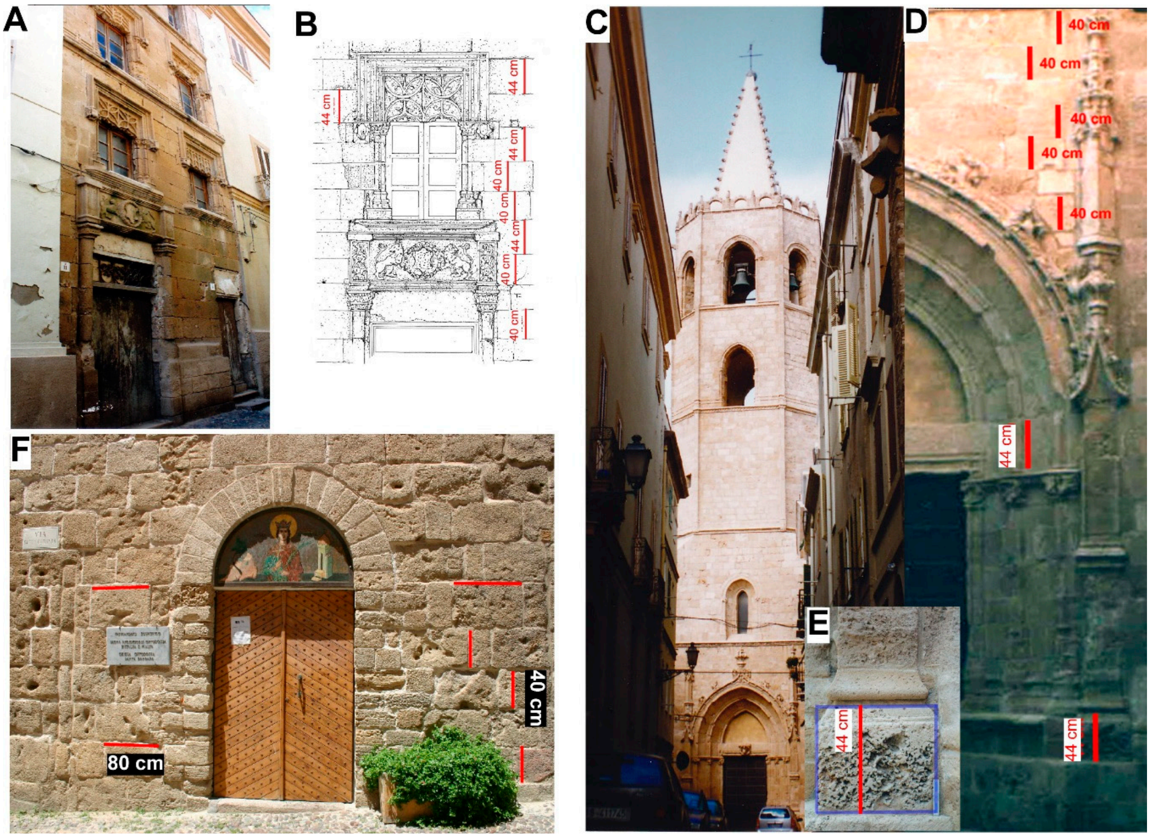

Figure 13. Alghero buildings of the 14th to the first half of 16th Centuries. (**A**) Façade of the Palazzo Machin, (**B**) Sketch of the façade of the Palazzo Machin enhancing di-dimension of used blocks. (**C**) Bell tower of the Alghero Cathedral. (**D**) Dimension of blocks used for the Bell tower and their size. (**E**) Detail of a block used for the left entrance pillar of the Bell Tower. (**F**) Dimension stones of the St. Barbara Church.

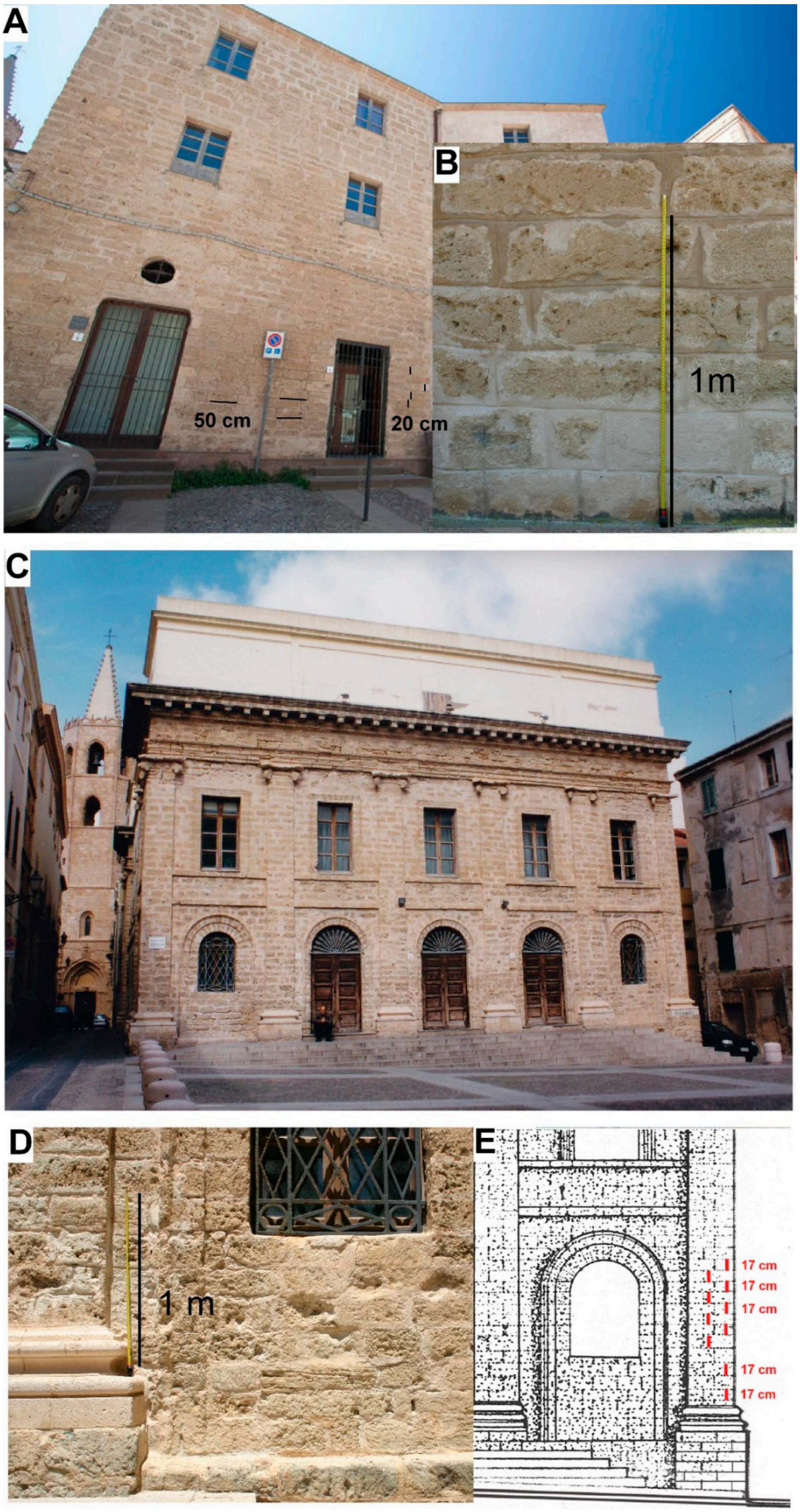

Figure 14. (**A**) Alghero buildings of the 16th to 18th Centuries—the Palazzo del Pou Salit. (**B**) Detail of blocks used for the building. (**C**) Alghero buildings of the 18th to 19th Centuries—the City Theatre. (**D**) Detail of the dimension stones used for the Theatre. (**E**) Sketch of the façade of the Theatre enhancing di-dimension of used blocks.

4.2.2. El Trò Quarry

The El Trò is located at the southern tip of the city of Alghero on the small homonymous embayment (Figure 2). The quarry occupies almost a half-hectare of the north side of the bay. The quarried sandstones belong to the lower middle part of Unit 3; that is, to beachface deposits of the last interglacial (MIS5e). Remnants of quarried block are clearly visible on the quarry floor. Their dimensions are about 80 × 45 × 30 cm (Figure 7). The quarry floor is today submerged and used by tourists as a natural swimming pool. The average water depth, during low tide in springtime, is 20 cm (Figure 7B).

4.2.3. The Cantaro Quarry

The quarry is located 1 km south of the city on the Alghero–Bosa road (Figure 2). It occupies almost a half-hectare on the west side of the road. The exploited sandstones belong to the uppermost part of Unit 3; that is, to the aeolian sandstones capping the marine last interglacial (MIS5e) deposits (Figure 11B). Sandstones are highly cemented and just traces of cross-beds are visible. Remnants of quarried blocks are still clearly visible on both the floor and wall of the quarry. On the seaside and floor part of the quarry block dimensions are about 90 × 45 × 30 cm (Figure 11A) whereas those on the wall are constantly 18–20 cm high and wide with variable length between 50 to 90 cm (Figure 11). This difference in block size confirms what was reported by [45,46]: that the Cantaro quarry was abandoned in the second half of the 16th Century and re-exploited in the 19th Century (Figure 11A). The seaside quarry floor is today submerged forming a wave cut platform. On this platform a dock for boat loading is still visible (Figure 11D). The average water depth, during low tide in springtime, is between 20 to 30 cm (Figure 11A,D). In the inland side, the 19th Century quarry floor is about 20 cm above the present mean low tide sea level.

4.2.4. Zio Peppino Quarry

The quarry is located 3 km south of the city on the Alghero–Bosa road and the exploited area was of about a half-hectare (Figures 2, 12A and 15). The quarried sandstones are characterized by well-developed high angle cross-beds forming metre-thick sedimentary bodies. A major reactivation surface divides sandstones with different cementation degrees (Figure 9). Both sandstones are referred to the glacial MIS4 [33]. Similar to other quarries, the largest blocks (90 × 45 × 30 cm, Figure 12B) occupy the lowermost part whereas those smaller (40 × 20 × 20) occupy the uppermost part (Figure 12D).

The left side of the quarry is flooded only during major storms (Figure 15A), whereas the right part (north side) is permanently submerged (Figures 12A and 15B). The maximum water high during springtime low tide is 20–30 cm.

The quarry area during the early years of the 20th Century was used for mining purposes [47]. This has, at least in part, altered the original quarry plane. However, this part of the quarry documents how the quarry plane should have been during the Spanish exploitation; that is, about 20 cm above the present mean low tide sea level to facilitate dry working and boat loading. The dock (D) is still visible (Figure 15A).

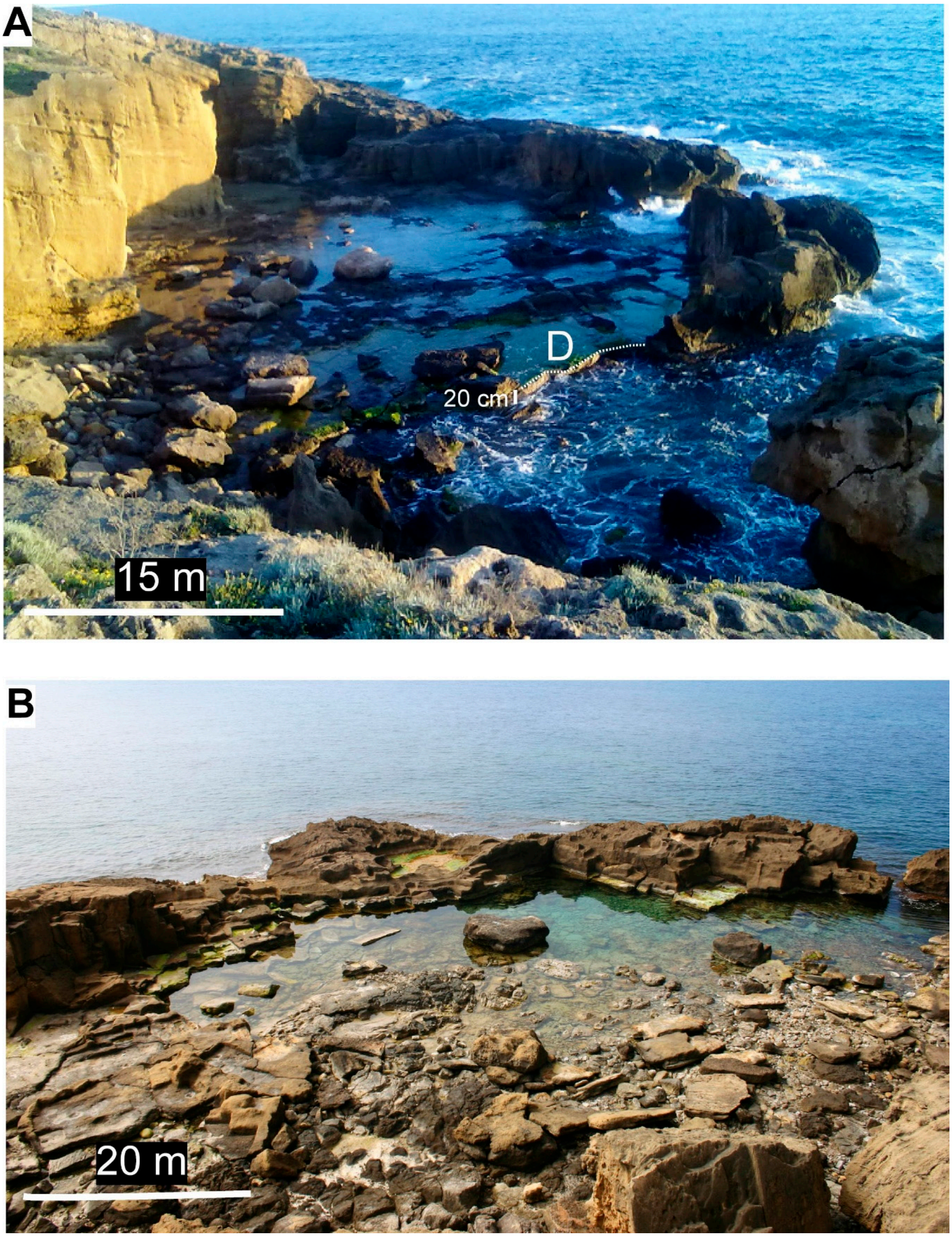

Figure 15. Zio Peppino quarry general view. (**A**) Left side of the quarry flooded during major storms. With D indicated the 19th Century dock 20 cm above the present mean sea level. (**B**) The right part (north side) permanently submerged. The maximum water high during springtime low tide is 30 cm.

5. Discussion

The Little Ice Age (LIA) is considered a time of modest cooling of the Northern Hemisphere, with temperatures dropping by about 0.6 °C during the 15th–19th centuries [48–51]. Grove [52] claimed that during the LIA the coldest temperatures occurred during the interval of 1400 to 1700 AD, with greatest cooling over the extratropical Northern Hemisphere continents. The patterns of temperature change imply dynamical responses of climate to natural radiative forcing changes involving El Niño and the North Atlantic Oscillation–Arctic Oscillation.

LIA post-dates the Medieval Solar Maximum, and encompasses up to four solar minima sun spot activity: Wolf (1275–1300 BP), Sporer (1460 and 1550 AD), Maunder (1645–1715 AD) and Dalton (1790 and 1830 AD) [53], and precedes the 'contemporary' (namely, late 20th century Solar Maximum) [54,55] occurring during the so-called Anthropocene [56,57].

There are widespread reports of famine, disease, and increased child mortality in Europe during the 17th–19th Centuries related, at least in part, to colder temperatures and altered weather conditions [12].

The Aragon-Catalan city of Alghero reached its maximum splendour during 1400–1700 AD; that is, during the Little Ice Age [52]. At the end of the 15th century, Alghero was one of the major Sardinian centres and one of the most important military strategic points of the western Mediterranean. The city increased in population (reaching about 5000 people) and from the 1500–1600 AD (16th–17th Century) important military, religious and civil buildings were made in gothic Catalan architecture style [44]. Building were made using exposed block implying the use of well-shaped and squared dimension stones [42]. Because of the similarity with other used dimension stones (i.e., Balearic island, Figure 1A), Catalan architect, the picapedrers, found suitable the exploitation of the local late Quaternary sandstones cropping out along the Alghero–Bosa road [58]. These sandstones were easy to quarry and carve and, if perfectly squared, suitable for the exposed facades of religious and civil buildings. Of this time, for example, there are the Palau Machin palace (first half of the 16th century, Figure 13A,B), the base of the Cathedral bell tower (mid-16th century–before 1577 AD, Figure 13C,D) and St. Barbara Church (1501–1600 AD, Figure 13E). Used dimension stones were normally 80 (to 94) × 40 (to 45) × 30 cm (Figure 13).

Budruni [19] reports that in the 16th Century the Cantaro Quarry was exploited for the dimension stones used for the Cathedral (1586–1591 AD) and re-exploited in the 1654 AD to build the pillars of the pronaos and the St. Croce church (one of the very few buildings of worship that completely disappeared from the architectural panorama of the old City of Alghero).

Since the 18th Century, coastal quarries were almost completely abandoned [42]. Buildings were mostly plastered and cavity mortar become regularly used. Dimension stones, both sandstones and limestone (occasionally volcanics) were draft, half-worked and of poor quality.

The few buildings with exposed stones and stretches of wall from the 18th Century are made of sandstone blocks with a regular height of about 20 cm and width from 55 cm to 90 cm (Palazzo del Pou Salit, Figure 14A,B) and the city wall (Figure 16). Dimension stones of the 19th Century buildings have height reduced to about 17 cm (i.e., façade of the Civic Theatre, second half of the 19th Century, Figure 14C,D).

It appears clear that the dimensions of the quarried blocks decreased with time. This allow us to reconstruct times during which the submerged quarries of El Trò, Cantaro and Zio Peppino were active. The unquarried underwater blocks constantly experience dimensions compatible with a 15th–16th Centuries activity. Thus, we state that these quarries were exploited in these centuries when relative sea level had to be lower than today. It is impossible, in fact, that quarrymen worked the blocks underwater. This is also confirmed by boat docks of the 20th Century today 20 cm above the present mean low tide sea level (Figure 15A) and by the same feature, today submerged, at the Cantaro quarry (Figure 11D).

Sedimentary structures still visible in the used dimension stones also account for the age of the used quarries. Aeolianite sedimentary structures are almost always visible in 18th Century buildings (Cugutto quarries) (Figure 16A), whereas dimension stones used in 15th to 17th centuries lack sedimentary structures indicating that their origin was from the well-cemented sandstones (MIS5 marine and aeolian deposits) that occupy the lowermost part of the quarries.

Nowadays, the 15th to 17th Centuries quarries are always submerged during low tide having a water average height of 35 cm. The abandonment of the quarries could also be related to the relative sea level rise that has as result the flooding of most of the marine quarry floor.

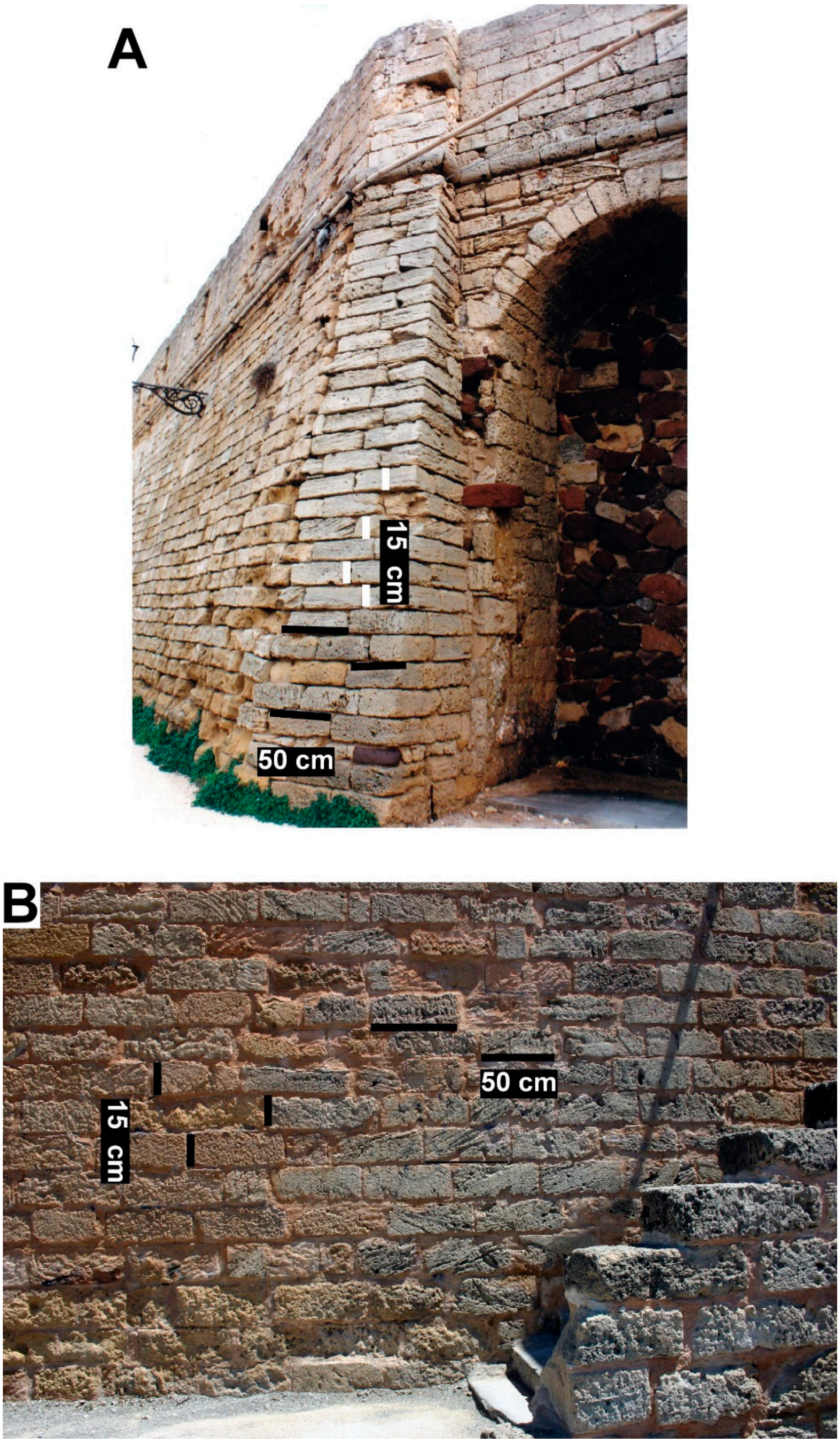

Figure 16. (**A**) 18th Century City wall of Alghero. Note the cross-beds preserved in the sandstone blocks. They indicate blocks were not quarried from the coastal quarries where exploited sandstone was well-cemented and often bioturbated, avoiding any sedimentary structures. (**B**) Detail of the dimension stones used for the renovation of the City wall (bastion) during 20th Century. Note how blocks are highly weathered because of poor geotechnical quality.

The south of the Alghero coast is tectonically stable as indicated by the numerous last interglacial sea level markers present [59]. Tidal notches, erosive and depositional features and *Lithophaga lithophaga* boreholes are constantly at a position confirming that subsidence and/or uplift in the area are negligible (0.01–0.02 mm/y, [30]) and that sea level about 125 ka was 5 m above the present [34]. This tends to exclude tectonic subsidence responsible for the quarry flooding. Quarries most probably were abandoned because no more good quality sandstones were available. This hypothesis could be confirmed looking at the 20th Century quarry of Burantino, where the lack of quality of the sandstones appears evident (Figures 5E and 16B). Quarrymen found it more suitable to exploit the inland sandstones reducing block dimensions.

6. Conclusions

Today, most of the 15th–17th Century coastal Spanish quarries of the Alghero area are at least 20 cm below the minimum tide sea level, and 50 cm below the high tide (average 35 cm). They were active during 1350–1650 AD (first half of the Little Ice Age) and abandoned during last part of 17th Century. The exploiting activity necessary occurred 10 to 20 cm above sea level to allow boat loading and almost dry working conditions. Today, this can be observed in the quarry floor used to load the boats carrying the material mined form the Cala Bona mine (Figure 15A). Exploitation activity moved inland toward the Cugutto and St. Agustine areas (Figure 2) in the last part of the 17th and 18th Centuries; that is, during the final part of the LIA (1645–1715 AD, [60]). This could be related 1) to quarry flooding, and 2) to the end of the exploited material. During this part of LIA (coincident with the Maunder minimum), sea level was at its minimum [61]. Thus, it seems unlikely to relate the moving to quarry floor flooding. It was most probably due to the necessity to find new places where to exploit good quality material, which had almost ended in the coastal sites. Extreme weather conditions that occurred during the 17th to first half of the 19th Centuries in the Mediterranean Sea area [18] may have played a role as well to force the abandonment of the quarries. Severe superstorms characterized the Mediterranean Sea between 1700–1900 AD. These were associated with an increase in cyclone occurrences in the Mediterranean, if compared to present-day [62,63]. Storms may have prevented the exploitation of the coastal quarries. It is worth noting that when the Cantaro quarry was reactivated in the 19th Century a sort of wall protecting the new quarry from the sea-wave action was left (Figure 2).

The estimated minimum relative sea level (RSL) reached during the LIA was about 35 cm below the present. This is obtained measuring the high of the present day sea level on the submerged quarry floor. This estimation of RSL is in good agreement with what was derived from proxy data on salt-marsh sediments and assemblages of foraminifera for the LIA [61]. Moreover, data of the submerged quarries of the Alghero area allow the conclusion that the rate of relative sea-level rise occurred during the last 200 years; that is, since 1809–1821 AD [60]. Several authors consider this time interval the beginning of the 19th Century sea-level rise [6,53,61,64]. The estimated rate, considering the measuring error, a subsidence between 0.01 and 0.02 mm/ym [30] and a glacio-isostatic adjustment between 0.3 and 0.4 [65], should be between 1.4 and 0.99 mm/y. This value is lower than that derived from proxy data (2.1mm/y, [61]), and two/three times higher than that estimated for the sea level rise occurred during the Warm Medieval Time over a period of about 400 years (0.6 mm/y, [61]). This may confirm once more that sea-level rise during the 19th–20th Centuries was strongly influenced by humans' activities that increased the speed and reduced the time of natural ongoing processes.

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