Flood control at Lipari Harbour

Evidences of rapid late-Holocene submergence of the eastern coast of Lipari Island (Italy)

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Abstract *– The discovery of submerged structures, in 2008, during archaeological works in the port of Lipari highlights a series of natural and anthropological factors on the struggle of the inhabitants of Lipari against the sinking of their old wharf. The actual excavations (2008-2013) radically changed the image of romantic coves with beaches for hauling boats in favor of a mighty structure connected to the port, also suggesting a review of the urban part of the Roman city: Lipari, for centuries a strategic center for the dominion of the southern part of the Tyrrhenian Sea, began to loose its importance, probably because of the sinking of the port, started around the* 2^{nd}*-*1^{st} *centuries BC and definitely canceled in the* 3^{rd}*-*4^{th} *century AD. The markers of this vertical deformation are remnants of Roman constructions, Middle Age buildings and morphological indicators of the sea level (i.e. marine notches, abrasion surfaces). Some among these indicators are time-constrained and provide an estimation of the rate of vertical displacement, while some others can only be considered as clues of submergence, but do not provide any velocities. Although the mechanism of the deformation is still unclear, we suggest, together with volcano related processes, the substantial incidence of regional tectonics. In particular, the activity of the NW-SE crustal-scale fault system affecting the whole volcanic arc and NE Sicily can account for the observed deformation.*

Inhalt *– Die Entdeckung versunkener Anlagen bei archäologischen Arbeiten 2008 im Hafen von Lipari unterstreicht eine Reihe natürlicher und anthropologischer Faktoren im Kampf der Liparesen gegen das Sinken ihres alten Kais. Die derzeitigen Grabungen von 2008 bis 2013 haben das Bild romantischer Buchten mit Sandstrand zum Aufziehen der Boote radikal verändert zugunsten eines mächtigen, mit dem Hafen verbundenen Bauwerks und eine neue Sicht des urbanen Teils der römischen Stadt nahegelegt: Lipari, über Jahrhunderte ein strategisches Zentrum für die Beherrschung des südlichen Tyrrhenischen Meeres, begann an Bedeutng zu verlieren, vermutlich wegen des Sinkens des Hafens, das um das 2./1. Jh. v. Chr. einsetzte und im 3.-4. Jh. n. Chr. endgültig aufhörte. Reste römischer Anlagen, mittelalterliche Gebäude und morphologische Indikatoren des Meeresspiegels (z.B. marine Auskehlungen, Abschliffflächen) sind Anzeichen dieser vertikalen Verformung. Manche dieser Erscheinungen sind zeitgebunden und ermöglichen eine Schätzung des Umfangs der senkrechten Versetzung, während andere nur als Hinweise auf eine Senkung angesehen werden können, aber nichts über deren Geschwindigkeit aussagen. Obwohl der Mechanismus der Senkung noch unklar ist, denken wir neben vulkanischen Prozessen an erhebliche Wirkung regionaler Tektonik. Vor allem kann die Tätigkeit der nordwest-südostlichen Plattenverschiebung, die den ganzen vulkanischen Bogen und Nordost-Sizilien betrifft, für die beobachtete Verformung verantwortlich sein.*

1. Introduction

The Aeolian archipelago is located on the south-eastern corner of the Tyrrhenian sea and, due to the peculiarity of its volcanics and to the evaluation and mitigation of hazard, in the last three decades has raised the attention of the scientific community. More than the volcanological aspects, the very fact that these islands formed more than 200 ka ago[1], that volcanism is still active and that are bordered by the sea, yield to consider them as an ideal natural laboratory able to register all the long-term changes in the level of the sea during the late Quaternary up to present-day. Indeed, those islands having volcanics erupted in the last 1-2 ka, therefore with massive and not very altered products, are also able to evidence vertical movements (uplift or subsidence) of shore-lines, also on a short-term time scale. The sub-aerial volcanic activity on the island of Lipari, located in the central portion of the Aeolian arc, started ~220 ka, with the last eruption that occurred in 580 AD. Its western coastlines were studied by several authors (e.g. Lucchi 2000; Calanchi et al. 2002; Lucchi et al. 2004), who found a general long-term uplift (0.34 mm/yr) evidenced by three levels of raised shorelines.

Conversely, in literature the eastern side of the island was not accurately studied and investigated. Only Calanchi et al. (2002) noticed that the southern area of the harbor of the town of Lipari was affected by a rapid and localized submergence, estimating a rate of subsidence of 10 mm/yr in the last century.

Although this was only an esteem, as not calculated with a reasonable detail, it is worth to note as the morphology of the human buildings along the coast-line of the harbor of Lipari has macroscopically and drastically changed at least in the last 4-5 decades, with several quays overbuilt on older ones to overcome to the oncoming apparent rising of the level of the sea.

In the present work, in the frame of a wider field survey of the coastlines of the island of Lipari, the attention was focused on the vicinity of this town, going from M. Rosa at north toward the southern area of Lipari harbor. Investigations were performed both on rocky coasts and on human construction built near the shoreline sea-level. This study allowed us to constrain the late-Holocene short-term vertical movements of the area of Lipari Town, establishing the time span and the main locus of the displacement and accurate rates of displacement for each site of surveying. The here presented data can provide important hints on the complex Aeolian volcanic framework and on the southeastern Tyrrhenian area and can have important consequences in terms of hazard and urbanization of the area of Lipari town adjacent to the sea.

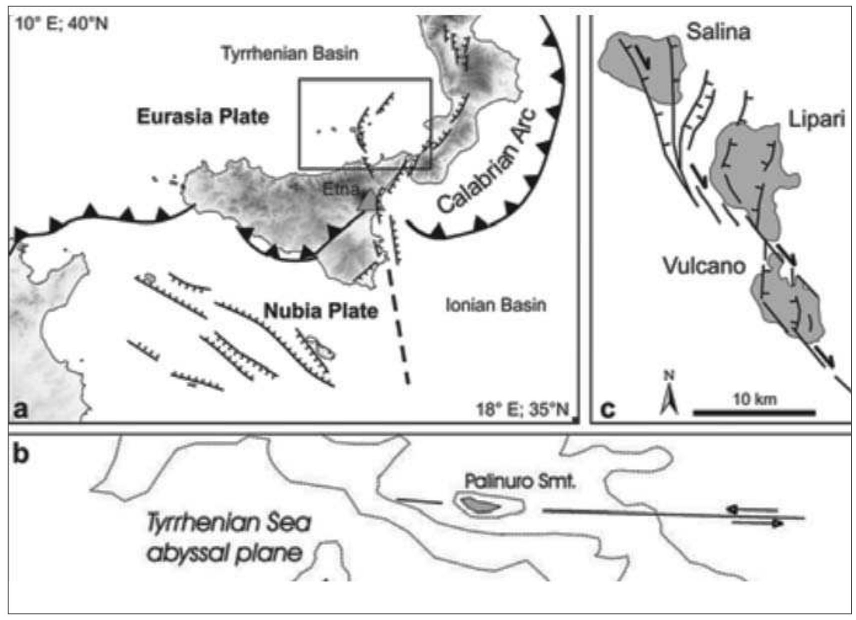

Fig.1: Location and structural sketch maps of southern Italy (a); southern Thyrrhenian Sea and Aeolian archipelago (b); central islands of the archipelago (c); The star indicate the main recent earthquake in the area; numbers refer to Late Pleistocene (i.e. 125 ka) uplift rate (values are in mm/yr from Lucchi et al., 2000).

2. Aeolian archipelago and Lipari island: a background

The Aeolian archipelago is located at the southeastern border of the Tyrrhenian Sea (Fig. 1), between the Marsili oceanic basin and the Calabrian Arc, an orogenic belt affected by Late Quaternary extensional tectonics (cf. Boccaletti et al. 1984; Tortorici et al. 1995). The seven islands of the archipelago represent the emerged portions of an extended arc-shaped submarine volcanic complex rising from 1-1.5 km b.s.l. and emplaced on a 15-20 km-thick continental crust (Ventura 2013). The magmatism in this area started at about 1.3 Ma and, based on its geochemical features and occurrence of a NW-dipping Benioff zone under the arc (Gasparini et al. 1982), is interpreted as consequence of the active subduction of the Ionian domain beneath the Calabrian arc (Barberi et al. 1973; Keller 1980; Ellam et al. 1989; Francalanci et al. 2004). Another interpretation ascribes the Aeolian volcanism to the thermal uplift linked to the opening of Tyrrhenian Sea in a post-subduction extensional tectonic regime (Wang et al. 1989; Crisci et al. 1991; Esperança et al. 1992).

From a structural/volcanological point of view, the Aeolian archipelago can be divided into three main sectors (Fig. 1):

1) western sector (Alicudi and Filicudi islands), dominated by a NW-SE oriented tectonic alignment (Santo 2000; De Astis et al. 2003; Peccerillo et al. 2004);
2) central sector (Salina, Lipari and Vulcano islands), aligned along a NNW-SSE crustal-scale tectonic system (Mazzuoli et al. 1995; Ventura et al. 1999; Ventura 2013);
3) eastern sector (Panarea and Stromboli islands), characterized by mainly NE-SW oriented tectonic lineaments.

2.1 Volcanological evolution

Lipari island is located in the central sector of the magmatic arc, and it represents the emerged portion of a broader submerged volcanic edifice. The sub-aerial volcanic activity started ~220 ka, while the last eruption occurred during historical time (Forni et al. 2013).

Several subdivisions of Lipari volcanism are present in the literature. We follow the one proposed by Lucchi et al. (2004; 2010), which individuates five principal volcanic epochs each characterized by different eruptive styles, products and separated by main erosional episodes. The first eruptive epoch embraces the oldest products, constituted by scoriaceous deposits, lava flows and subordinate hydromagmatic pyroclastics (see also Pichler 1980; Crisci et al. 1991; De Rosa et al. 2003), emitted from several centers along the-western sector of the island (Fig. 2) and, on a minor extent, in the central-eastern sector of Lipari (Monterosa and Timpone Croci). Radiometric revealed ages from 223±0.9 ka to 127±9.5 ka (Gillot 1987; Crisci et al. 1991); however, a more recent K/Ar dating gave an age of 102 ± 2 ka for M.

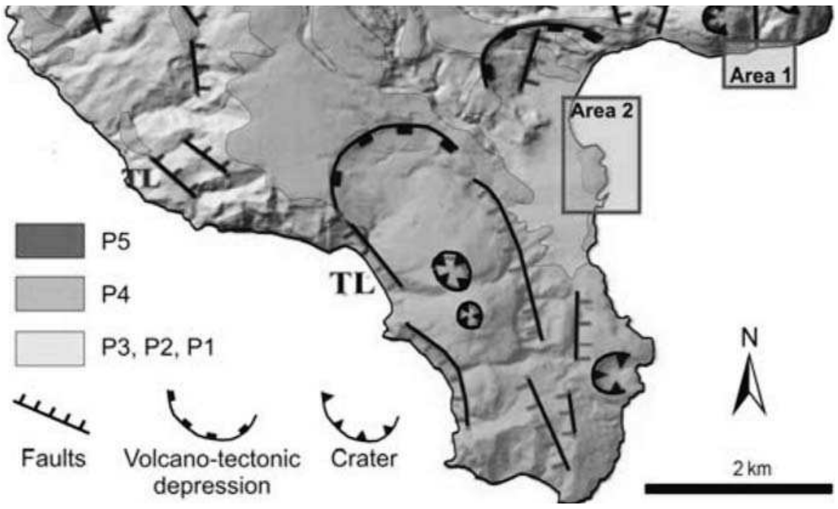

Fig. 2: Simplified geological and structural map of Lipari Island. Red boxes indicate the area were the evidences of recent submergence have been found.

Rosa. (De Rosa et al. 2003). The second epoch is characterized by the emission of lavas and hydromagmatic pyroclastics mainly from M. S. Angelo and M. Chirica eruptive centers (Fig. 2); these products are dated to 127±8 ka (Crisci et al. 1991). The third epoch is characterized by the emplacement of wide and thick lava flows and hydromagmatic pyroclastics belonging to the final phases of activity of M. S. Angelo and M. Chirica (Fig. 2). The latest lava flows are dated to 92±10 ka (Crisci et al. 1991). The fourth epoch includes pumiceous hydromagmatic pyroclastics associated to the emplacement of volcanic domes (M. Guardia and M. Giardina) in the southern sector of the island (Fig. 2). The pyroclastic succession emplaced in the chronological interval between 70 ka, and 13±0.2 ka, age of the 'tuff layer' at the top of the succession. The products of the last epoch, ranging in age from 11.4 ± 1.8 ka to historical times (Bigazzi – Bonadonna 1973), crop out along a N-S trending belt that extends in the eastern part of the island. During this phase, the activity moved northwards generating some volcanic centers (Gabellotto, Forgia Vecchia, M. Pilato), from which obsidian lava flows and pyroclastics were erupted (Fig. 2). Finally, the renewal of the activity is dated at 10 ka and the recorded eruptions occurred during medieval time (776 AD: Keller 2002; 1220 AD: Tanguy et al. 2003).

2.2 Tectonic framework

The island of Lipari, together with those of Salina and Vulcano, forms a NNW-SSE alignment, oriented orthogonally to the Aeolian volcanic arc (Fig. 1). The development of these volcanic islands is linked to an active crustal discontinuity (Barberi et al. 1994; Ventura 1994; Mazzuoli et al. 1995), corresponding to the NNW-SSE-trending dextral strike-slip fault system named Tindari-Letojanni (TL) inferred from geological, seismological and geodetic studies (Ghisetti 1979; Lanzafame et al. 1997; Pondrelli et al. 2004; Billi et al. 2006; Argnani et al. 2007). The horizontal movements along the strike-slip system are accommodated by N-S to NE-SW trending normal faults, where pure extension occurs (Frazzetta et al. 1982; Mazzuoli et al. 1995). On Lipari two main sets of faults can be identified (Figs. 1-2). The first one is developed in the western and central portions of the island and is constituted by a NNW-SSE to NW-SE trending structural alignment, including several oblique-slip faults with a right-lateral component of motion showing an overall right-hand en echelon arrangement (Mazzuoli et al. 1995). The second set of faults trends N-S to NE-SW and is considered as purely extensional (Mazzuoli et al. 1995). This set develops in the central-eastern part of Lipari and is characterized by normal fault segments defining large depressions filled by lacustrine and/or pyroclastic deposits and lava flows, and by the occurrence of different volcano-tectonic features, such as collapses, grabens and eruptive fissures (Mazzuoli et al. 1995). Although the clear structural evidence on Lipari and also on Volcano islands, this area partially lacks the seismicity associated to the TL system. Most of the seismicity is concentrated in the "Gulf of Patti" area where the focal solutions, both right-lateral and extensional, are coherent with TL system geometry (Neri et al. 2005; Billi et al. 2006; Presti et al. 2013). The major recorded earthquake occurred on April 15, 1978 (ML = 5.5) along the alignment of TL, some kilometers southward from Vulcano island (Del Pezzo et al. 1984; Neri et al. 1991).

3. Markers of vertical deformation

A marker of vertical deformation is here defined as an object (construction, landform, fossil, etc.) able to provide a definite value of the elevation (relative to the sea-level) at a given time of the past. The comparison of the paleo-elevation with the present-day elevation allows to calculate the vertical deformation and, if a marker is dated, also the rate of this deformation. The elevation of the markers is estimated, when possible, with direct measurement referring to the present-day sea level. Thereafter all the measurements are corrected considering the tide-level and the atmospheric pressure at the time of the survey (Auriemma et al. 2009). The tide level is evaluated consulting the meteorological reports when available (http://www.mareografico.it/ and www.wun-

derground.com) or by means of a predictive model (TideWizard 1.3.2 software; Smartcom Software) when the direct measurement was not available. Moreover, it is well known that the sea level has not been constant through time. In particular the sea level constantly rose through the Holocene at variable rate. The values of elevation for the measured markers, each in dependence of its age, have been corrected considering the sea level variation in the area during the past. For this purposes we adopted the model of Lambeck et al. (2011) which have been specifically performed for Italy and already comprises the eustatic, and glacio-hydro-isostatic components. We mainly focused our investigations in the eastern side of the island, where archaeological sites, buildings and civil construction are located, in order to temporally constrain the markers and therefore to provide a reliable deformation rate. Also other indicators of paleo-elevation occur in this area (e.g. typical coastal landforms), but they only provide a qualitative information. The studied portion of coastline extends from the southern wall of M. Rosa toward the southern termination of the Lipari harbor, named Marina Corta (Fig. 2). We present the survey sites and the markers divided into two groups according with their location: Pignataro di Fuori (Area 1 in Fig. 2) and Lipari town and harbour (Area 2 in Fig. 2).

3.1 Area 1: Pignataro di Fuori

The area of Pignataro di Fuori is located on the southern flank of M. Rosa (Fig. 2), at the northern termination of the gulf of Lipari. Here, the remnants of Roman habitations (1^{st}-2^{nd} century BC) and overbuildings of the late Middle Age (17^{th}-18^{th} centuries) were firstly noticed by Bernabò Brea (1978). These constructions are visible along a narrow beach carved into the products of M. Rosa. Archaeological remains are often very useful for the reconstruction of the ancient coastlines and may represent reliable indicators of sea level changes (Antonioli et al. 1998; Antonioli et al. 2007; Scicchitano et al. 2008; 2011; Auriemma et al. 2009; Anzidei et al. 2011a; 2011b; 2013). We carried out both surface and submarine surveys along the beach of Pignataro di Fuori, providing the evidence for three constructions along the coastline. In the western side of the beach, two wall remains of a Roman-age building of the 1^{st}-2^{nd} centuries (Site 1-a) were overbuilt in the late Middle Age (17^{th}-18^{th} centuries) (Bernabò Brea 1978). In a photograph taken in August 1966 (Bernabò Brea 1966) the floor is still visible in the corner between the two walls (Fig. 3a). At the present time the construction shows many changes but some features can be taken as reference even though some portions partially collapsed and the floor is covered by present shoreline deposits (Fig. 3a). A new picture was taken to have the same perspective of the old one and then they were both scaled together. The reference line in Fig. 3a is now located at 1.22 \\m a.s.l. (field measure) while it was higher in 1966, suggesting that the site subsided. However, a precise measurement is not possible because we have no information about tide level and atmospheric pressure at the moment the 1966 picture was taken.

The remains of another construction occur at the intertidal level in the central part of the beach Site 1 (Fig. 3b). Another wall, part of the same construction, is partially submerged. Since 1966 the construction remains were intensely eroded and dismantles, as shown by the comparison between present-day and 1966 photographs in Fig. 3b. The construction was interpreted by Bernabò Brea (1978) as an old cistern belonging to a wide complex of houses that in the 17^{th}-18^{th} centuries constituted the "Lazzaretto" (i.e. a place where pestilent was deported from the nearby town of Lipari). Because of its function, the cistern was most probably buried (Giustolisi 2001), while it is presently (and already in 1966) exposed and the base is partially covered by shore deposits. The provided features indicate an intense erosion of the area caused by marine action and ascribable to a submergence process. It is not possible to establish the exact elevation of the reference line at the time the picture was taken and it is not possible to calculate its velocity. Just opposite a submerged wall was also examined (Site 1-d; Fig. 4). This wall shows evidence of two different constructive styles: three basal layers of massive and squared off basaltic blocks over-built by a chaotic mixture of cemented beachstones. The basal structure is associated to the foundations of an ancient Roman building dated to 1^{st}-2^{nd} centuries AD (Bernabò Brea 1978), and its base is now located at 1.53 m b.s.l.; the superstructure is instead related to the architecture of the nearby late-Middle age cistern. This wall was certainly built up above the sea level by the Romans and was already submerged in 1966. This is an evidence of the submergence and it started before 1966. At the western side of the Pignataro di Fuori beach, a marine abrasion notch and an abrasion surface are discovered along the submerged shore (Site 1-e; Fig. 5). These landforms are indicative of a paleo-sea stillstand. The notch is a curvilinear landform carved into pyroclastic deposits of M. Rosa (Fig. 5a) and the submerged abrasion surface is located at 30 m of distance, facing the notch (Fig. 5b-c). The inflexion point of the notch is at 0.90 m b.s.l., whilst the average depth of the surface is at 1.30 m b.s.l. These recent morphologies are distinctly drowned but they cannot be dated to provide a subsidence rate. Although the formation of a marine notch is normally associated with limestones (Pirazzoli 1986) they have been also encountered on volcanics (Firth et al. 1996; Kershaw et al. 2001; Ramírez-Herrera et al. 2004; De Guidi et al. 2009). The formation of notches requires a steadiness of the sea level over a relatively long period of time, probably in the order of thousands of years considering the lithology. This implies that for a certain period during Holocene the area uplifted at the same rate of the sea level rise

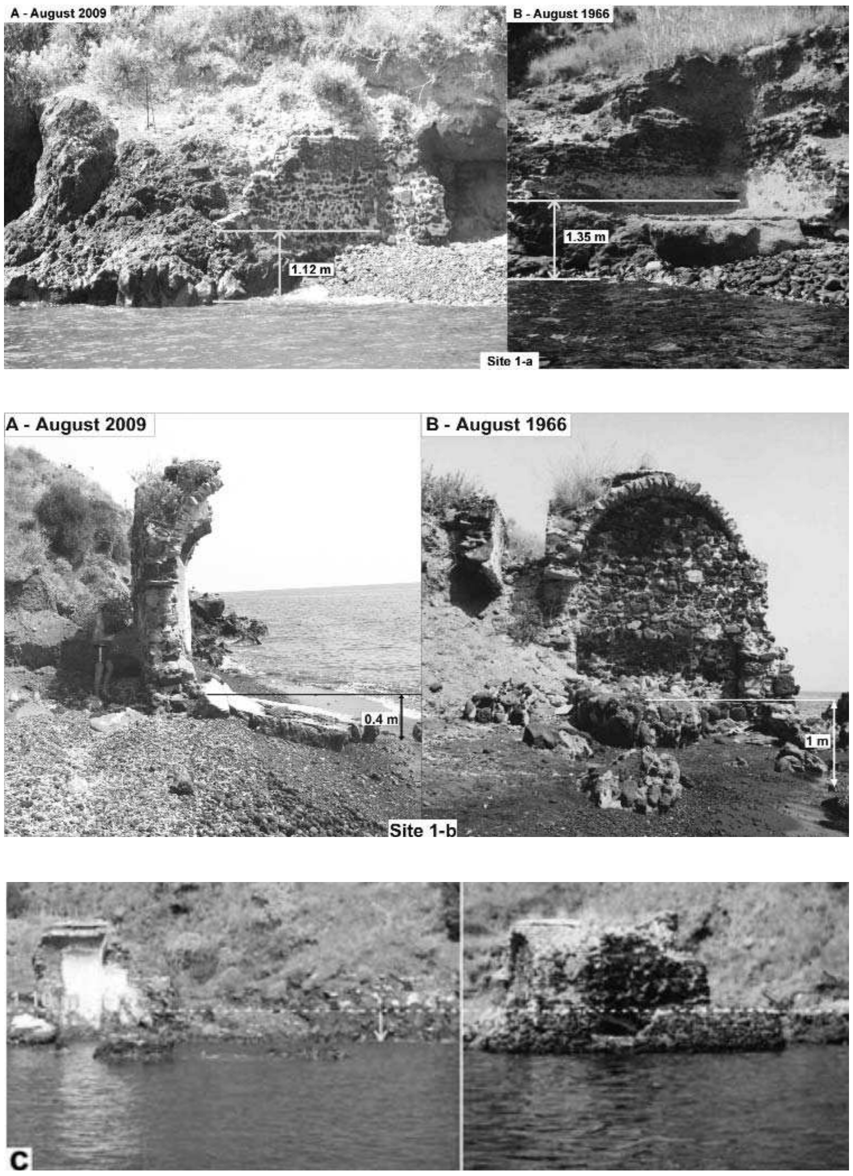

Fig. 3: Comparison between August 2009 (left) and August 1966 (right) photographs (sites 1-a, 1-b and 1-c in Table1). The new photographs were taken to have the same perspective of the old one and then they were both scaled together The red arrows indicate some common recognizable features; the yellow dashed line indicate the height for the reference points measured in the field (see Table 1). Clear evidences of subsidence in all the sites are the shore deposits partly covering previously exposed features and the wave erosion affecting the structures due to the progressive relative sea-level rise.

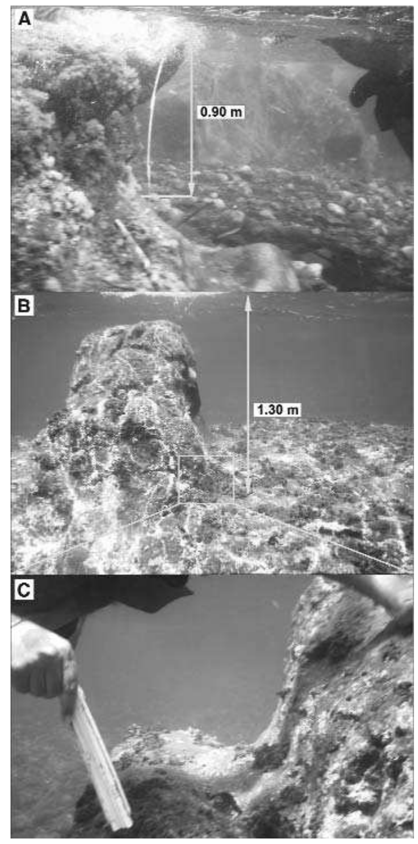

Fig. 5: Markers of site 1-e; a) the inflection point of the submerged marine notch is at 0.9 m b.s.l. (uncorrected values); b) submerged abrasion surface at 1.30 m b.s.l.; c) particular of the columnar structure indicating the paleo-sea level.

(allowing the formation of the notch), and at a certain moment the uplift prevailed and the notch remained suspended before the subsidence would start. Such high uplift is plausible because during Holocene the volcano was in its last phase of remarkable activity (Cortese et al. 1986; Gioncada et al. 2003; cf. 2.1).

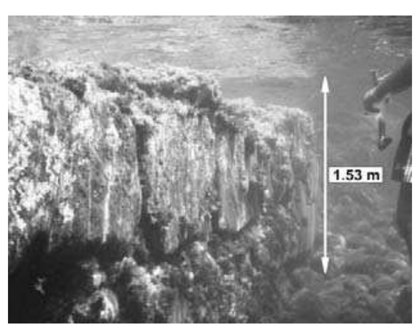

Fig. 4: Submerged Roman wall grounded at 1.53 m b.s.l. (site 1-d). located in the western corner of the little beach of "Pignataro di Fuori".

3.2 Area 2: Lipari town and harbor

Some of the markers of the submergence in the study area are situated in the surroundings of the harbor of the town of Lipari (Fig. 6). Because of their role, port areas are strictly connected with the coastline and are able to provide indications about relative sea level changes over time (Marriner et al. 2007; Auriemma et al. 2009). An evidence of submergence is found in front of the commercial harbor of Marina Lunga (Site 2-a; Fig. 6). Here, the *Soprintendenza del Mare – Regione Sicilia* noticed, in August 2008, clues of Roman rests. A submarine survey of this archaeological site was performed with the support of the *Soprintendenza* and the *Capitaneria di Porto* of Lipari and revealed remnants of constructions. They consist of an alignment of *in situ* basements of Roman columns placed above a sub-horizontal floor constituted by cemented beach stones of the 2^{nd}-1^{st} centuries BC, which is sustained by an in situ artificial (Fig. 7b) build-

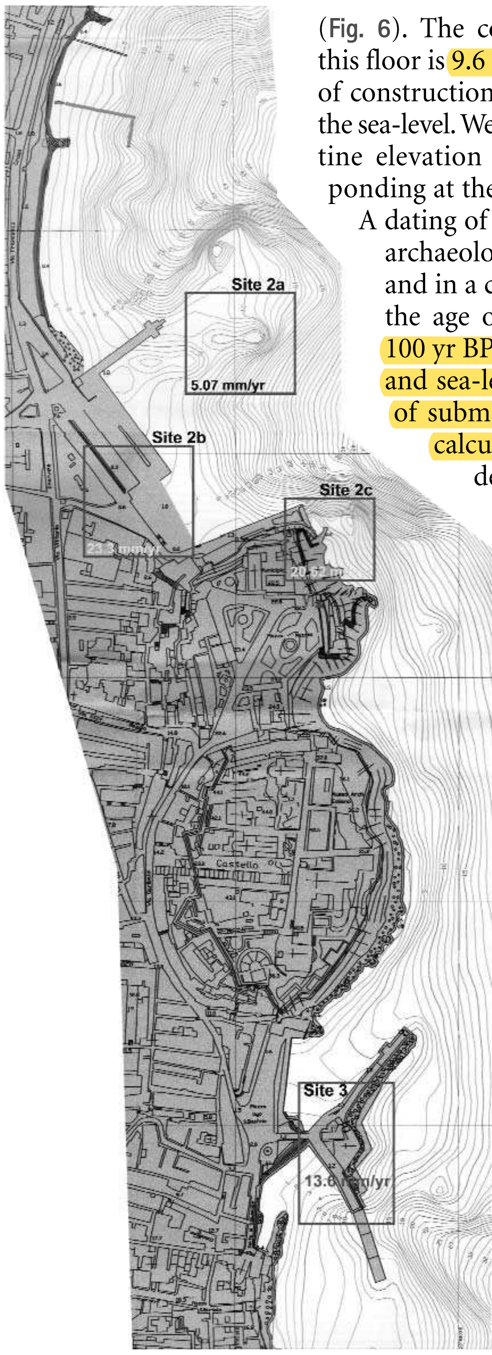

Fig. 6: Bathymetric map of Lipari area and location of the surveyed sites (Area 2 in Fig. 2).

(Fig. 6). The corrected present-day depth of this floor is 9.6 m b.s.l. and, given the typology of construction, this certainly was not built at the sea-level. We can reasonably consider a pristine elevation of about 2.0 m a.s.l. corresponding at the height of the underlying wall. A dating of the building is possible trough archaeological finds on the Roman floor, and in a conservative way we considered the age of 2nd-1st centuries BC (2100 ± 100 yr BP). Taking into account the tidal and sea-level eustatic corrections, a rate of submergence of 4.8 ± 0.3 mm/yr is calculated (Table 1). Important evidence were found also in the emerged portion of Lipari's coastline. During time, several quays have been overbuilt on older ones to overcome the oncoming apparent rise sea level; so the present-day quay of Marina Lunga was rebuilt in 1975-76, and large parts of the old quay was sinking in front of the modern pier (Bernabò Brea 1978). A photograph of this quay, taken before 1975 (the year the new quay was built) and after 1950 (the year given by the types of motorboats), shows that the edge of the quay was emerged (at least 60 cm), while it is now at the intertidal level (Fig. 8). In fact, periodically during the high tide, the old quay is flooded by the water passing through an aperture in the new quay. Considering the present-day elevation of the old quay edge and assuming a functional height of 0.6 ± 0.1 we can reasonably estimate a submergence rate of 12.8 ± 5.1 mm/yr (Table 1). In the site 2-c, located in the southern area of the harbor of Marina Lunga (Fig. 6), close to the Town Hall, the marker is constituted by a partially submerged quay with six bollards (Fig. 9). A photograph of the site taken in the 1930s-1940s shows the difference with the present (Fig. 9a-b). In the old picture is visible the quay in the southern corner of Marina Lunga standing at about 30 cm above the sea level and the bollards were emerged (Fig. 9a). Conversely, at present the bollards, erected over a platform constituted of three steps, are partially submerged; the top of this platform is located around the present sea level (Fig. 9c). The uncertainties related to the date of the photograph and to the exact elevation of the markers at that time, lower the reliability of the calculation of the submergence rate. However we could make an estimation, at least for the quay, resulting in a rate of 6.8 ± 3.2 mm/yr (Table 1).

Fig. 7: Submerged Roman floor and basal portion of the columns at 9.7 m b.s.l. (site 2-a); ultimate 3-D resolution, 2015.

ing constructed probably during the extension of the city. A line of bases of columns placed above of those of the 2nd-3rd sec. AD show how people tryed to fight with the sinking of this area (Tisseyre 2010; Tusa 2010).
A detailed bathymetric survey (1:2000 scale) performed by the local government of Lipari for the construction of the new harbor clearly shows that this archaeological site lies on a rocky platform

Age (yr)	Elevation (m)	Rate (mm/yr)
0	0	0.00
500	0.317	0.63
1000	0.675	0.68
1500	1.075	0.72
2000	1.541	0.77
2500	2.065	0.83
3000	2.684	0.89
3500	3.434	0.98
4000	4.254	1.06
4500	5.14	1.14
5000	6.109	1.22
5500	7.134	1.30
6000	8.22	1.37

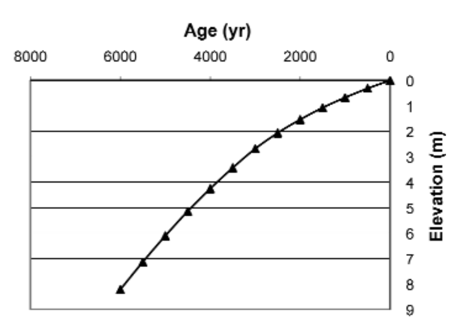

Table 1: Reference eustatic curve.

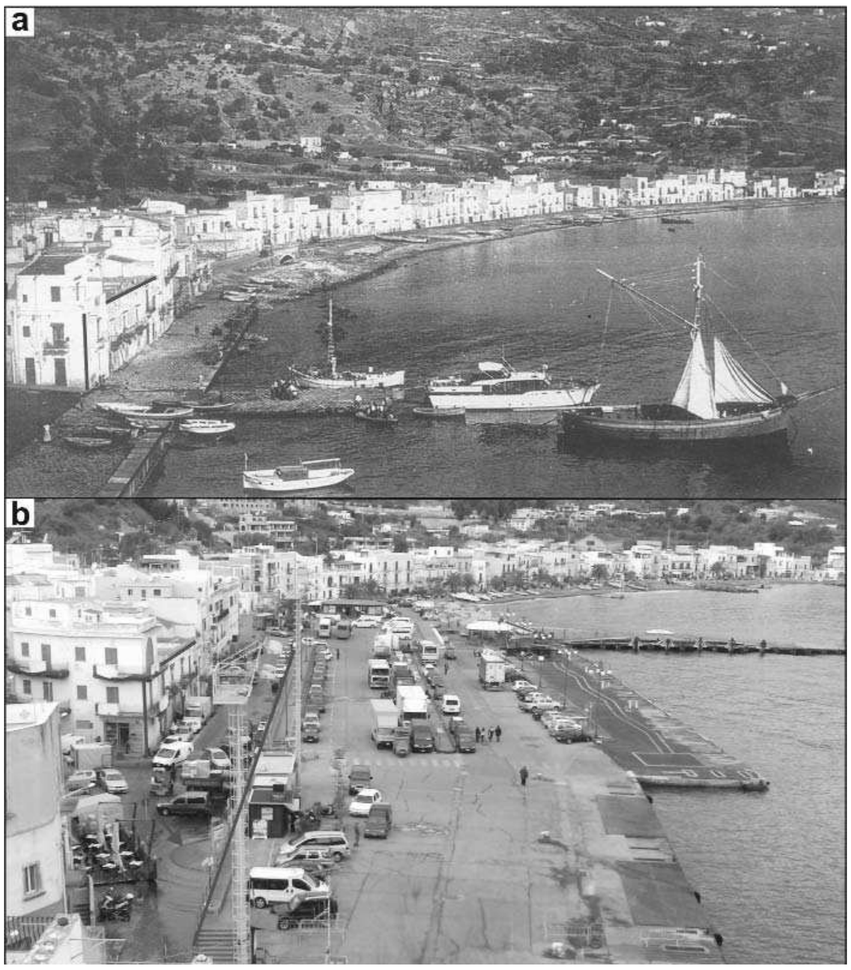

Fig. 8: View of Marina Lunga (site 2-b); how it was before the building of the new quay (a) and how it appears at present (b). The red lines indicate the common recognizable features and the arrow the sea flooding the street.

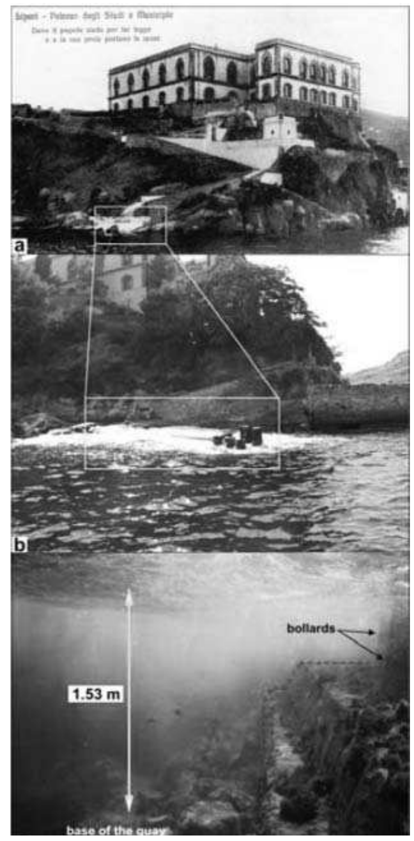

Fig. 9: View of site 2-c; how it was in the 30s (a) and how it appears at present (b); note how the quay and the bollards where emerged (note the dangling rope) while today are partially submerged. c) Submarine photograph of the platform with three steps constituting the base of the pier (see text for further explanation).

In the harbor of Marina Corta (Site 2d; Fig. 6) the little church of Maria SS. Della Neve – Anime del Purgatorio (16th century) and the adjacent buildings have been examined. By comparing old and new photographs of the little church (Fig. 10b) results make clear how the church drastically changed, at least in the last 100 years. The old photograph from August 13, 1913 (De Pasquale 1995) shows that the bottom of the main door was at about 6.70 m a.s.l. whilst now is at 5.48 m a.s.l. (Fig. 10a); moreover the basement of the building, used in the past for warehouses, is now partially submerged. (Fig. 10b). Taking into account the corrections and the uncertainties we can estimate a rate of subsidence of 12.2 ± 1.7 mm/yr (Table 1). A subsidence rate of 10 mm/yr for this marker was estimated also by Calanchi et al. (2002). Moreover the picture shows that the left door of the ground level was bricked up, suggesting that the submergence was already active at that time. In the same area and opposite to the Anime del Purgatorio church is located the S. Giuseppe church (18th century). The comparison between old (beginning of the 20th century) and 12 new photographs show clues of active submergence (Fig. 10a). The main door of the church is presently at 9.09 m a.s.l. while it was at about 10.5 m. Taking into account the corrections and the uncertainities we can estimate a rate of subsidence of 12.8 ± 2.2 mm/yr (Table 1). Moreover, a further comparison of this last sites with a painting of the 18th century painter Jakob Philipp Hackert from 1778 reveals the impressive lowering of this whole area (Fig. 11).

4. Discussion

All the collected markers in the eastern coast of Lipari evidence that a submergence trend occurred, at least in the last century and is active at present. The vertical deformation process is clear, even though a precise estimation of the velocity of the submergence was generally impossible. In particular, the markers of Pignataro di Fuori, Area 1 (sites 1-a, 1-b and 1-c) allow only a qualitative estimation of the submergence. The submergence rates calculated in the area of Lipari range from 4.8 ± 0.3 to 12.8 ± 2.2 mm/yr, although with different degree of uncertainty. Thus some considerations on the timing and the magnitude of the submergence trend can be made. Some markers indicate that the submergence has been active during the last 40 years (sites 1-a, 1-b and 1-c),

Fig.10: a) View of S. Giuseppe church (site 2-e); how it was at the beginning of the XX century and how it appears at present. b) View of the church Anime del Purgatorio (site 2-d); how it was in August, 1913 and how it appears at present; in the inset note the ground floor partially submerged. Both pairs of pictures are taken from the same perspective and the scaled together. The red lines indicate the common recognizable features and the dashed yellow lines refer to the preset-day average sea level.

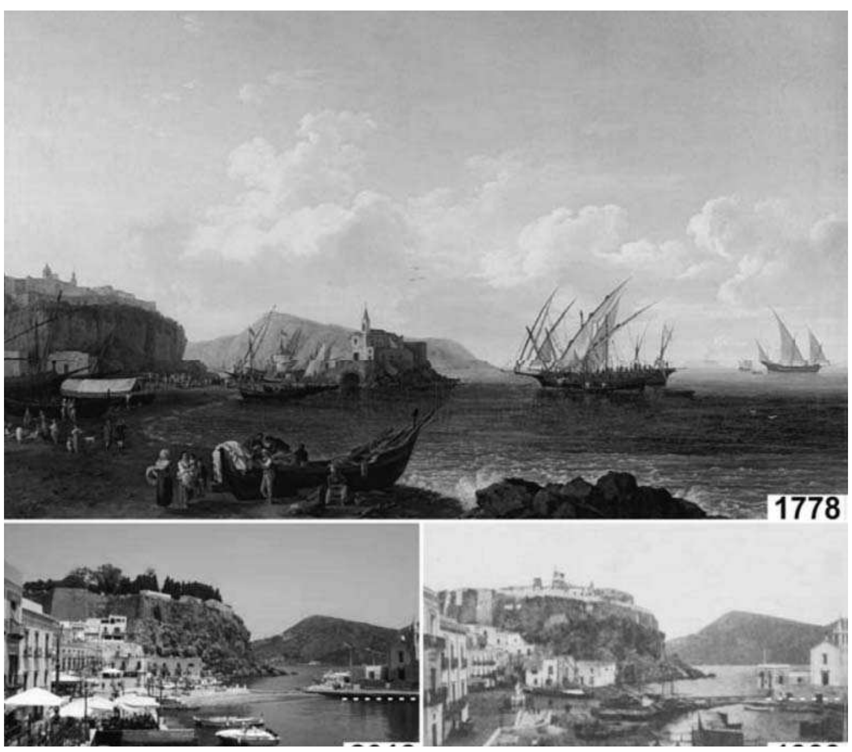

Fig. 11: Three views of Marina Corta area from the south. Note the church perched over a rocky islet and the wide beach in the painting by J.P. Hackert from 1778 of the view of Lipari and Stromboli (oil on canvas, 116 × 168 cm, State Museum Zarskoje Selo near St. Petersburg). The islet is today completely drowned (see also Fig. 11b) and the beach was partially present on the picture taken in 1900 while today it is absent. The pictures at the bottom are taken with the same perspective and scaled together; the yellow line refers to the preset-day average sea level.

and probably the last two centuries (site 2-d and 2-e). Even taking into account the errors that each value of rate carries with it, there is a certain variability that could be ascribed to lateral variations of the subsidence, although the investigated area is restricted.

Leveling and GPS surveys on Vulcano and Lipari islands carried out for 1976-1996 and 1996-2006 period respectively (Obrizzo 1998; Bonaccorso 2002; Mattia et al. 2008) have shown that both islands are affected by submergence. GPS permanent stations indicate that the rates are greater moving from Vulcano to Lipari (i.e. from South to North) where the highest values are registered (up to 20 mm/yr) and in the same order of magnitude of the values presented in this study.

Rapidly vertical ground movements, positive (Table 1) or negative, are very common on active volcanoes and several process are able to explain their origin. We now discuss the various possible causes and mechanisms.

The central portion of the Aeolian archipelago is dominated by a NW-SE right-lateral fault system, with some minor associated N-S and NE-SW extensional structures, responsible of the shallow seismicity of the area (cf. chapter 2.2). The deformation associated to this system is considered by many authors the main cause of the recent subsidence at Vulcano-Lipari islands, in particular, most of it would be ascribable to the 1978 seismic crisis (Bonaccorso 2002; Calanchi et al. 2002). In another hypothesis, Mattia et al. (2008), coupling the subsidence with the observed compression between Vulcano and Lipari, suggest a local thrust loading mechanism.

Alternatively the subsidence could be related to morphological processes such as ground compaction phenomena. Ground compaction can be excluded because it is usually a very local phenomenon and the markers of submergence on Lipari lie on a rock ground.

A submergence directly related to an eruption can be partially excluded. The most recent volcanic episodes in the area are those of M.

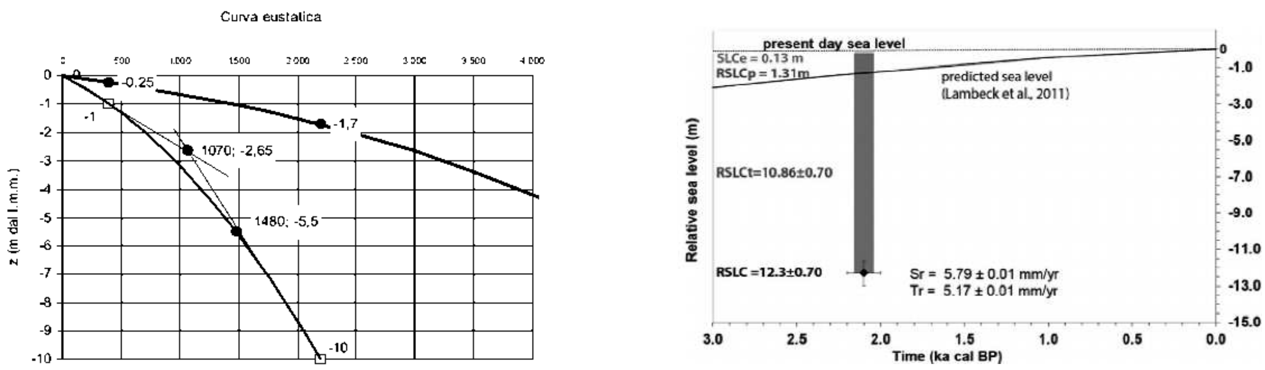

Fig.12: Estimated eustatic sea-level change of the Italian coastlines for the past 7000 years. Corrected eustatic curve and new dating evidences after industrial coring in the modern harbor of Sottomonastero.

Pilato, NE Lipari, dated AD 776 and 1220. Since the mechanism of degassing or pressure change are substantially simultaneous to an eruption, those episodes are too far in the time to account for the more recent subsidence. However we cannot definitively exclude some volcanic implications.

Finally, the deformation on tectonic structure is plausible even though such high velocities are not very common; the mechanism alternates long period of accumulation of elastic energy with sudden episodes of coseismic displacement. The only structure that could eventually account for the observed submergence is the main TL system. The vertical deformation would be accommodated on the N-S and NE-SW structures and the shortening between Vulcano and Lipari is accommodated on the NW-SE right-lateral segments (Fig. 1c).

5. Conclusive remarks

The detailed survey on several archaeological and geological markers on the eastern coast of Lipari has shown clear evidence of a submergence trend characterized by variable velocities of deformation (from 4.8 ± 0.3 to 12.8 ± 2.2 mm/yr). Such process acted from the last century and is active at present but we cannot definitively constrain temporally its beginning.

In the literature various interpretations try to explain the subsidence at the Aeolian islands and in particular at the Vulcano-Lipari system, and the most plausible hypothesis are linked to volcanic and tectonic mechanisms. In our opinion it is not correct to ascribe the observed subsidence to a single process which constant rate, even though variable in space. Steady deformations are uncommon for volcanic areas where, conversely, the variability in space and time is high and velocities are up to 100 mm/yr (Lajoie 1986). Rather we can assert that the combination (alternation and superimposition) of active processes occurred, either volcanic or tectonics, resulting, over the last century, in a general submergence of the eastern coast of Lipari.

Archaeological note

Dr. Philippe Tisseyre

The detailed survey on several archaeological and geological sites on the eastern coast of Lipari has shown a general and rapid vertical downward movement of the area between M. Rosa and the harbor of Marina Corta (southern part of the town of Lipari) and in the area of Pignataro di Fuori, on the southern coast of M. Rosa, very variable rates of subsidence of some Roman and Middle Age buildings (2.2-19.9 mm/a). However these values are lower than those found in the area of the town of Lipari (5.07-23.3 mm/a). These data allows us to locate the main locus of the subsidence in an area comprising the harbor of the town and the foreland gulf-sea. The rapid submergence of the eastern portion of the town could be temporally located in the last 100 years and it is very rapid, as testified by the occurrence of a submerged marine notch (0.9 m b.s.l.) and traces of the intertidal areas are still visible on the columns with mussel's perforation of *lithodomus lithophagus*, and gas hole on the base of various columns.

It is possible to conclude that the fast rising water caused a submersion of the area, perceptible from antiquity. The struggle of the population resulted in the establishment of a breakwater created by groups of column base fragments, and certainly other actions (walls, etc.). Archaeological stratigraphic studies allow us to date the coverage of the site and therefore its abandonment in the 3rd century AD (http://www.consorziouno.it/Notizie/Archivio/2015/As_Lipari ResocontoScavi.html). The base of columns show that they have never been used (absence of lead clamping), and consequently never been integrated, as we had thought at first, in "a temple" or a "commercial portico". Further on and at a superior depth (-4 m.slm) the remains of another breakwater wall oriented SE-S, not well identified, were observed placed on sterile clay-pyroclastic sedimentation, dated to the early Middle Ages (6th-8th cent. AD) according to the corrected eustatic curve and new corings during the construction of the new harbor (Cucinotta 2013; Gionfra 2014) (Fig. 12). The recent proposal of a "Lighthouse" dating 3 AD (Anzidei 2015) can't be accepted because of the evidence of an archaeological stratigraphic mistake. The new corings into the bay have done -18.5 m for the katolimenic level (Cucinotta 2013) so, also according to the corrected curve, including Anzidei 2015 (but not for his final opinion) we should therefore think that the structures visible at a depth of -15/-20 meters, spotted since 2008 (Tisseyre 2010) further forward compared to the current site and corresponding to the reading by the subbottom profiler, can be the remains of the *Melingunis Lipara* harbor, the rich Lipari of the Greek era, the main producer of the Mediterranean alum, and central protagonist in the conquest of the Mediterranean during the wars of conquest of Magna Graecia against Etruscans and Romans (Diodorus of Sicily V 9, 4-5; Pausanias, Graeciae Descriptio X 11, 3-4).

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[1] 1 ka ago = 1000 years BP, Ma = million years BP.

References

Abbreviations:

BV = Bulletin of Volcanology

JGR = Journal of Geophysical Research

JVGR = Journal of Volcanology and Geothermal Research

QuInt = Quaternary International

Antonioli, F. – Leoni, G. 1998: Siti archeologici e loro utilizzazione quali indicatori per lo studio delle variazioni recenti del livello del mare. Il Quaternario 11, 122-139.

Antonioli, F. – Anzidei, M. – Lambeck, K. et al. 2007: Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. Quaternary Science Reviews 26(19), 2463-2486.

Anzidei, M. – Antonioli, F. – Benini, A. et al. 2011a: Sea level change and vertical land movements since the last two millennia along the coasts of southwestern Turkey and Israel. *QuInt* 232(1), 13-20.

Anzidei, M. – Antonioli, F. – Lambeck, K. et al. 2011b: New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. *QuInt* 232(1), 5-12.

Anzidei, M. – Antonioli, F. – Benini, A. et al. 2013: Evidence of vertical tectonic uplift at Briatico (Calabria, Italy) inferred from Roman age maritime archaeological indicators. *QuInt* 288, 158-167.

Anzidei, M. 2015: https://www.researchgate.net/publication/282624220_New_insights_on_the_subsidence_of_Lipari_island_Aeolian_islands_southern_Italy_from_the_submerged_Roman_age_pier_at_Marina_Lunga.

Apuani, T. – Corazzato, C. – Cancelli, A. et al. 2005: Stability of a collapsing volcano (Stromboli, Italy): Limit equilibrium analysis and numerical modeling. *JVGR* 144, 191-210.

Argnani, A. – Serpelloni, E. – Bonazzi, C. 2007: Pattern of deformation around the central Aeolian Islands: evidence from multichannel seismics and GPS data. Terra Nova 19(5), 317-323.

Arrighi, S. – Tanguy, J–C. – Rosi, M. 2006: Eruptions of the last 2200 years at Vulcano and Vulcanello (Aeolian Islands, Italy) dated by high-accuracy archeomagnetism. Physics of the Earth and Planetary Interiors 159, 225-233.

Auriemma, R. – Solinas, E. 2009: Archaeological remains as sea level change markers: A review. *QuInt* 206(1), 134-146.

Barberi, F. – Gasparini, P. – Innocenti, F. et al. 1973: Volcanism of the Southern Tyrrhenian Sea and its geodynamics implications. *JGR* 78, 5221-5232.

Barberi, F. – Gandino, A. – Gioncada, A. et al. 1994: The deep structure of the Eolian arc (Filicudi-Panarea-Vulcano sector) in light of gravity, magnetic and volcanological data. *JVGR* 61, 189-206.

Bernabò Brea, L. 1978: Alcune considerazioni sul carico di ceramiche dell'età del Bronzo di Pignataro di fuori e sugli antichi scali marittimi dell'isola di Lipari. Sicilia Archeologica 36, 36- 42.

Bernabò Brea, L. 1966: Archivio Fotografico del Museo Eoliano, Lipari; Archive numbers: 12176, 12178, 12191.

Berrino, G. 1998: Detection of vertical ground movements by sea-level changes in Neapolitan volcanoes. Tectonophysics 294, 323-332.

Bigazzi, G. – Bonadonna, F. 1973: Fission Track Dating of the Obsidian of Lipari Island (Italy). Nature 242, 322-323.

Billi, A. – Barberi, G. – Faccenna, C. et al. 2006: Tectonics and seismicity of the Tindari Fault System, southern Italy: Crustal deformations at the transition between ongoing contractional and extensional domains located above the edge of a subducting slab. Tectonics, 25(2), TC2006. DOI:10.1029/2004TC001763.

Boccaletti, M. – Nicolich, R. – Tortorici, L. 1984: The Calabrian arc and the Ionian sea in the dynamic evolution of the central Mediterranean. Marine Geology 55, 219-245.

Bonaccorso, A. 2002: Ground deformation of the southern sector of the Aeolian islands volcanic arc from geodetic data. Tectonophysics 351(3), 181-192.doi: 10.1016/S0040-1951(02)00163-4.

Calanchi, N. – Lucchi, F. – Pirazzoli, P.A. et al. 2002: Late Quaternary relative sea-level changes and vertical movements at Lipari (Aeolian Islands). Journal of Quaternary Science 17(5-6), 459-467. DOI:10.1002/jqs.721.

Chiocci, F.L. – Romagnoli, C. 2004: Terrazzi deposizionali sommersi nelle Isole Eolie. Mem. Descr. Carta Geologica d'Italia 58, 81-114.

Cortese, M. – Frazzetta, G. – La Volpe, L. 1986: Volcanic History of Lipari (Aeolian Islands, Italy) during the last 10,000 years. *JVGR* 27, 117-133.

Crisci, G.M. – De Rosa, R. – Esperança, S. et al. 1991: Temporal evolution of a three component system: the Island of Lipari (Aeolian Arc, southern Italy). *BV* 53, 207-221.

Cucinotta, C. 2013: Relazione geologico-tecnica, in: Sutera, A. – Bernado, G., Ripristino delle condizioni di stabilità della banchina punta Scaliddi e porzione della banchina commerciale in loc. Sottomonastero nell'ambito della portualità principale dell'isola di Lipari, 2-110.

Davì, M. – De Rosa, R. – Barca, D. 2009: A LA-ICP-MS study of minerals in the Rocche Rosse magmatic enclaves: Evidence of a mafic input triggering the latest silicic eruption of Lipari Island (Aeolian Arc, Italy). *JVGR* 182, 45-56.

Davì, M. – De Rosa, R. – Holtz, F. 2010: Mafic enclaves in the rhyolitic products of Lipari historical eruptions: relationships with the coeval Vulcano magmas (Aeolian Islands, Italy). *BV* 72(8), 991-1008.

De Astis, G. – Ventura, G. – Vilardo, G. 2003: Geodynamic significance of the Aeolian volcanism (Southern Tyrrhenian Sea, Italy) in light of structural, seismological, and geochemical data. Tectonics, 22(4). DOI: 10.1029/2003TC001506.

De Guidi, G. – Monaco, C. 2009: Late Holocene vertical deformation along the coast of Pantelleria Island (Sicily Channel, Italy). *QuInt* 206(1-2), 158-165. DOI:10.1016 /j.quaint.2008.08.002.

De Pasquale, R. 1995: Eolie racconto per immagini (Lipari).

De Rosa, R. – Guillo, H. – Mazzuoli, R. et al. 2003: New unspiked K-Ar ages of volcanic rocks of the central and western sector of the Aeolian Islands: reconstruction of the volcanic ages. *JVGR* 120, 161-178.

Del Pezzo, E. – Maresca, R. – Martini, M. et al. 1984: Seismicity of the Aeolian Islands, Southern Italy. Annales de Géophysique 2, 173-180.

Ellam, R.M. – Hawkesworth, C.J. – Menzies, M.A. et al. 1989: The volcanism of Southern Italy: Role of subduction and relationship between potassic and sodic alkaline magmatism. *JGR* 94, 4589-4601.

Esperança, S. – Crisci, G.M. – De Rosa, R. et al. 1992: The role of the crust in the magmatic evolution of the island of Lipari. Contribution to Mineralogy and Petrology 11, 450-462.

Esposito, A. – Anzidei, M. – Atzori, S. et al. 2010: Modeling ground deformations of Panarea volcano hydrothermal/geothermal system (Aeolian Islands, Italy) from GPS data. *BV* 72(5), 609-621. DOI:10.1007 /s00445-010-0346-y.

Ferri, M. – Grimaldi, M. – Luongo, G. 1988: Vertical ground deformation on Vulcano, Aeolian Islands, southern Italy: observations and interpretations 1976-1986. *JVGR* 35, 141-150.

Firth, C. – Stewart, I. – McGuire, W. J. et al. 1996: Coastal elevation changes in eastern Sicily: implications for volcano instability at Mount Etna. Geological Society, London, Special Publications 110(1), 153-167.

Frazzetta, G. – Lanzafame, G. – Villari, L. 1982: Deformazioni e tettonica attiva a Lipari e Vulcano (Eolie). Mem. Soc. Geol. It. 24, 293-297.

Gamberi, F. 2001: Volcanic facies associations in a modern volcaniclastic apron (Lipari and Vulcano offshore, Aeolian Island Arc). *BV* 63, 264-273. DOI:10.1007/ s004450100143.

Gamberi, F. – Marani, M.P. 1997: Detailed bathymetric mapping of the Eastern offshore of Lipari Island (Tyrrhenian Sea): insight into the dark side of an arc volcano. Marine Geophysical Researches 19, 363-377.

Gasparini, G. – Iannaccone, G. – Scandone, P. et al. 1982: Seismotectonics of the Calabrian Arc. Tectonophysics 84, 267-286.

Ghisetti, F. 1979: Relazioni tra strutture e fasi trascorrenti e distensive lungo i sistemi Messina-Fiumefreddo, Tindari-Letojanni e Alia-Malvagna (Sicilia nordorientale): Uno studio microtettonico. Geologica Romana 18, 23-58.

Gillot, P.Y. 1987: Histoire volcanique des Iles Eoliennes: arc insulaire ou complexe orogenique annulaire, Doc. & Trav. IGAL Paris 11, 49-56.

Gioncada, A. – Mazzuoli, R. – Bisson, M. et al. 2003: Petrology of volcanic products younger than 42 ka on the Lipari-Vulcano complex (Aeolian Islands, Italy): an example of volcanism controlled by tectonics. *JVGR* 122(3-4), 191-220. DOI:10.1016/ S0377-0273(02)00502-4

Gionfra, L. 2014: Indagine geofisiche nel Porto di Lipari, Marzo 2014, relazione al Comune di Lipari, Soprintendenza del Mare 2014.

Giustolisi, V. (Ed.) 2001: Alla ricerca di Lipari bizantina. Centro di documentazione e ricerca per la Sicilia antica Paolo Orsi.

Keller, J. 1980: The Island of Salina. Rendiconti della Società Italiana di Mineralogia e Petrologia 36, 489-524.

Keller, J. 2002: Lipari's fiery past: dating the medieval pumice eruption of Monte Pelato, in: Internat. Conference UNESCO-Regione Siciliana, Lipari.

Keller, J. – Morche, W. 1993: Exceptional explosivity of Upper Quaternary andesitic volcanism of Salina, Aeolian Islands: dynamics of fall, surge and blast event. IAVCEI General Assembly, Canberra, Abstracts Volume 57.

Kershaw, S. – Guo, L. 2001: Marine notches in coastal cliffs: indicators of relative sea-level change, Perachora Peninsula, central Greece. Marine Geology 179(3), 213-228.

Lajoie, K.R. 1986: Coastal tectonics. Active tectonics 95-124.

Lambeck, K. – Antonioli, F. – Anzidei, M. et al. 2011: Sea level change along the Italian coast during the Holocene and projections for the future. *QuInt* 232(1), 250-257.

Lanzafame, G. – Bousquet, J–C. 1997: The Maltese escarpment and its extension from Mt. Etna to Aeolian Islands (Sicily): importance and evolution of a lithosphere discontinuity. Acta Vulcanologica 9, 113-120.

Lima, A. – De Vivo, B. – Spera, F.J. et al. 2009: Thermodynamic model for uplift and deflation episodes (bradyseism) associated with magmatic-hydrothermal activity at the Campi Flegrei (Italy). Earth-Science Reviews 97 (1-4), 44-58.

Lucchi, F. 2000: Late Quaternary volcanic activity evolution and vertical mobility of the Aeolian Islands. Plinius 23, 101-107.

Lucchi, F. – Tranne, C.A. – Calanchi, N. – Romagnoli, C. et al. 2001: Antiche linee di riva tardo-Quaternarie sull'isola di Lipari (Isole Eolie) e mobilità verticale dell'apparato vulcanico. Bollettino della Società Geologica Italiana 120(2/3), 161-185.

Lucchi, F. – Tranne, C.A. – Calanchi, N. – Pirazzoli, P. et al. 2004: Late-Quaternary ancient shorelines at Lipari (Aeolian Islands): stratigraphical constraints to reconstruct geological evolution and vertical movements. *QuInt* 115/116, 105-115.

Lucchi, F. – Tranne, C.A. – Calanchi, N. – Rossi, P.L. 2004: Geological cartography in volcanic areas: the case of Lipari late-Quaternary volcanism (Aeolian islands), in: G. Pasquar – C. Venturini, Mapping Geology in Italy, ROMA, APAT Serv. Geol. It., 137-146.

Lucchi, F. – Tranne, C.A. – Rossi, P.L. 2010: Stratigraphic approach to geological mapping of the late Quaternary volcanic island of Lipari (Aeolian Archipelago, southern Italy). Stratigraphy and geology of volcanic areas. Geol Soc Am Spec Paper 464, 1-32.

Marriner, N. – Morhange, C. 2007: Geoscience of ancient Mediterranean harbours. Earth-Science Reviews 80(3), 137-194.

Mattia, M. – Palano, M. – Bruno, V. et al. 2008: Tectonic features of the Lipari-Vulcano complex (Aeolian archipelago, Italy) from 10 years (1996-2006) of GPS data. Terra Nova 20, 370-377. DOI: 10.1111/j.1365.3121.2008.00830.x.

Mazzuoli, R. – Tortorici, L. – Ventura, G. 1995: Oblique rifting in Salina, Lipari and Vulcano Islands (Aeolian Islands, Southern Tyrrhenian Sea, Italy). Terra Nova 7, 444-452.

Neri, G. – Caccamo, D. – Cocina, O. et al. 1991: Shallow earthquake features on the Southern Tyrrhenian region: geostructural and tectonic implications. Bollettino di Geofisica Teorica ed Applicata 33, 129, 47-60.

Neri, G. – Barberi, G. – Oliva, G. et al. 2005: Spatial variations of seismogenic stress orientations in Sicily, south Italy. Physics of the Earth and Planetary Interiors 148(2-4), 175-191. DOI:10.1016/j.pepi.2004.08.009.

Obrizzo, F. 1998: Vertical ground movements at Vulcano: precise levelings. Acta Vulcanologica 10, 127-129.

Peccerillo, A. – Dallai, L. – Frezzotti, M.L. et al. 2004: Sr-Nd-Pb-O isotopic evidence for decreasing crustal contamination with ongoing magma evolution at Alicudi volcano (Aeolian arc, Italy): implications for style of magma-crust interaction and for mantle source compositions. Lithos 78, 217-233.

Pichler, H. 1980: The Island of Lipari. Rendiconti della Società Italiana di Mineralogia e Petrologia 26, 415-440.

Pirazzoli, P.A. 1986: Marine notches. Sea level research: a manual for the collection and evaluation of data, in: Van de Plassche, O. (Ed.), Geobooks (Norwich) 361-400.

Pondrelli, S. – Piromallo, C. – Serpelloni, E. 2004: Convergence vs. retreat in Southern Tyrrhenian Sea: Insights from kinematics. Geophysical Research letters 31(6), L06611.

Presti, D. – Billi, A. – Orecchio, B. et al. 2013: Earthquake focal mechanisms, seismogenic stress, and seismotectonics of the Calabrian Arc, Italy. Tectonophysics, DOI:10.1016/j.tecto.2013.01.030.

Ramírez–Herrera, M.T. – Kostoglodov, V. – Urrutia–Fucugauchi, J. 2004: Holocene-emerged notches and tectonic uplift along the Jalisco coast, Southwest Mexico. Geomorphology 58(1), 291-304.

Revil, A. – Johnson, T.C. – Finizola, A. 2010: Three-dimensional resistivity tomography of Vulcan's forge, Vulcano Island, southern Italy. Geophysical Research Letters 37(15), DOI:10.1029/ 2010GL043983.

Santo, A. 2000: Volcanological and geochemical evolution of Filicudi (Aeolian Islands, south Tyrrhenian Sea, Italy). *JVGR* 96, 79-101.

Scicchitano, G. – Antonioli, F. – Berlinghieri, E.F.C. et al. 2008: Submerged archaeological sites along the Ionian coast of southeastern Sicily (Italy) and implications for the Holocene relative sea-level change. Quaternary Research 70(1) 26-39.

Scicchitano, G. – Lo Presti, V. – Spampinato, C.R. et al. 2011: Millstones as indicators of relative sea-level changes in northern Sicily and southern Calabria coastlines, Italy. *QuInt* 232(1-2) 92-104. Smartcom Software. Tide Wizard. http://www.marinecomputing.com.

Tallarico, A. – Dragoni, M. – Anzidei, M. et al. 2003: Modeling long-term ground deformation due to the cooling of a magma chamber: Case of Basiluzzo island, Aeolian Islands, Italy. *JGR* 108(B12), 2568. DOI:10.1029/2002JB002376.

Tisseyre, P. 2010: Attività della Soprintendenza del Mare Province di Catania, Messina, e Isole Minori, Atti del IV Convegno di Archeologia Sottomarina, Genova 2010. https://www.academia.edu/12264350/Attivit%C3%A0_della_Soprintendenza_del_Mare_Messina_Catania_isole_Eolie_2007-2010.

Tortorici, L. – Monaco, C. – Tansi, C. et al. 1995: Recent and active tectonics in the Calabrian arc (Southern Italy). Tectonophysics 243(1-2), 37-55. DOI:10.1016/0040-1951(94)00190-K.

Tranne, C.A. – Lucchi, F. – Calanchi, N. et al. 2002: Geological map of the island of Lipari (Aeolian Islands). University of Bologna and INGV (Firenze).

Tusa, S. 2010: Arte e storia nei mari di Sicilia (Udine).

Ventura, G. 1994: Tectonics, Structural evolution and caldera formation on Vulcano Island (AeolianArchipelago, Southern Tyrrhenian Sea). *JVGR* 60, 207-224.

Ventura, G. – Vilardo, G. – Milano, G. et al. 1999: Relationships among crustal structure, volcanism and strike-slip tectonics in the Lipari-Vulcano Volcanic Complex (Aeolian Islands, Southern Tyrrhenian Sea, Italy). Physics of the Earth and Planetary Interiors 116, 31-52.

Wang, C.Y. – Hwang, W.T. – Shi, Y. 1989: Thermal evolution of a rift basin: the Tyrrhenian Sea. *JGR* 94, 3991-4006.

Credits of figures

Figs. 1a-c: modified after De Rosa et al. 2003; Mazzuoli et al. 1995; Fig. 2: modified after Tranne et al. 2002; Lucchi et al. 2004; Gioncada et al. 2003; 2005; Fig. 3: De Rosa, modified De Guidi; Figs. 4-5, 8-9: Photos De Guidi; Fig. 6: Courtesy of: Soprintendenza del Mare, Palermo (Sicily); Fig. 7a-b: Photos De Guidi; 7c: Photo P. Tisseyre, 7d: elaborated by Salvo Emma, Soprintendenza del Mare; Figs. 10-11: De Guidi/old postcards; Fig. 11a: State Museum Zarskoje Selo; Fig. 12: Data from Lambeck et al. 2004; Fig. 13a: Data from Cucinotta 2013; 13b: Anzidei 2015; Table 1: Antonioli et al. 2007.

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